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Surface and Groundwater Modelling of the Ganga River Basin

GRBMP: Ganga River Basin Management Plan

by

Indian Institutes of Technology

IIT Bombay | IIT Delhi | IIT Guwahati | IIT Kanpur | IIT Kharagpur | IIT Madras | IIT Roorkee

Preface

In exercise of the powers conferred by sub-sections (1) and (3) of Section 3 of the Environment (Protection) Act, 1986 (29 of 1986), the Central Government has constituted National Ganga River Basin Authority (NGRBA) as a planning, financing, monitoring and coordinating authority for strengthening the collective efforts of the Central and State Government for effective abatement of pollution and conservation of the river Ganga. One of the important functions of the NGRBA is to prepare and implement a Ganga River Basin Management Plan (GRBMP).

A Consortium of 7 Indian Institute of Technology (IIT) has been given the responsibility of preparing Ganga River Basin Management Plan (GRBMP) by the Ministry of Environment and Forests (MoEF), GOI, New Delhi. Memorandum of Agreement (MoA) has been signed between 7 IITs (Bombay, Delhi, Guwahati, Kanpur, Kharagpur, Madras and Roorkee) and MoEF for this purpose on July 6, 2010.

This report is one of the many reports prepared by IITs to describe the strategy, information, methodology, analysis and suggestions and recommendations in developing Ganga River Basin Management Plan (GRBMP). The overall Frame Work for documentation of GRB EMP and Indexing of Reports is presented on the inside cover page.

There are two aspects to the development of GRBMP. Dedicated people spent hours discussing concerns, issues and potential solutions to problems. This dedication leads to the preparation of reports that hope to articulate the outcome of the dialog in a way that is useful. Many people contributed to the preparation of this report directly or indirectly. This report is therefore truly a collective effort that reflects the cooperation of many, particularly those who are members of the IIT Team. Lists of persons who have contributed directly and those who have taken lead in preparing this report is given on the reverse side.

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Introduction

Chapter 1 - Introduction

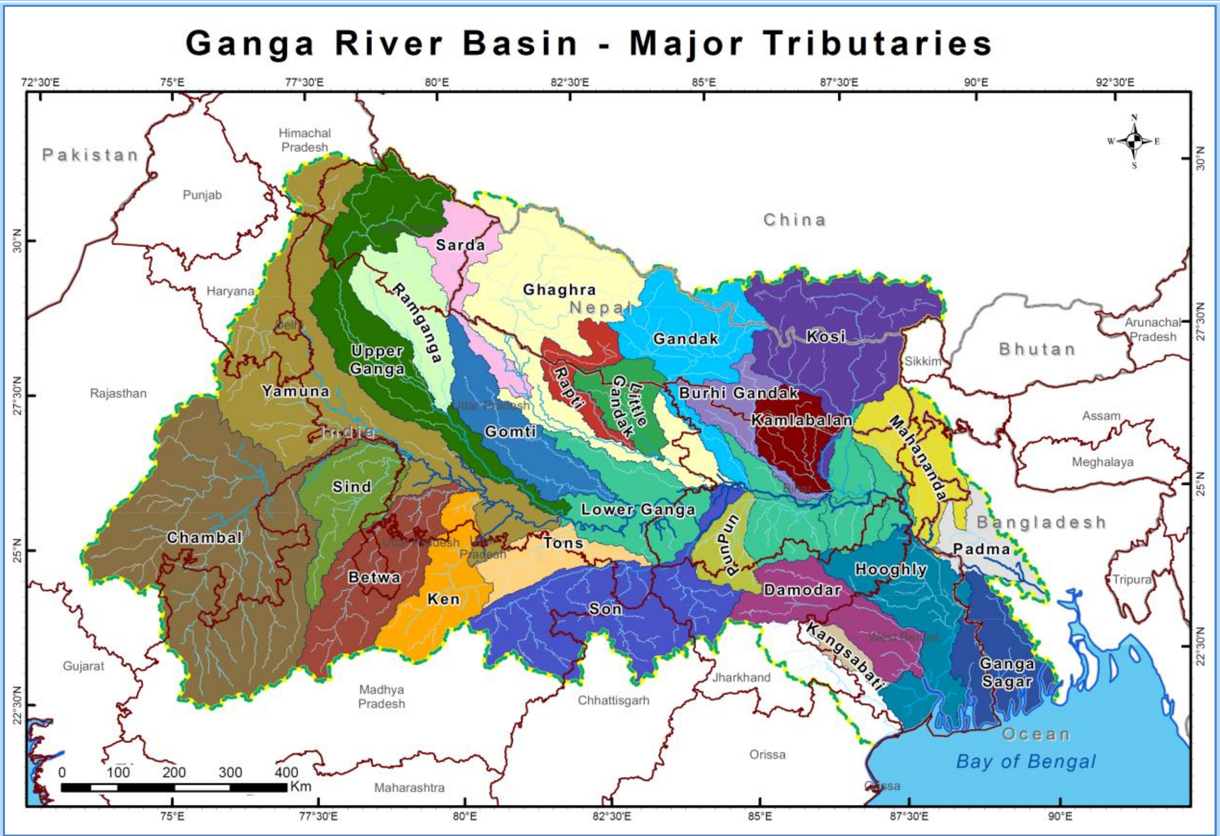
The Ganga River Basin profile

The river Ganga is a part of the composite Ganga-Brahmaputra-Meghna basin draining 1,086,000square kilometres in China, Nepal, India and Bangladesh the Ganga-Brahmaputra divide. The Ganga originates as the Bhagirathi at an elevation of about 3,892 m above mean sea level in the ice cave of Gaumukh at the snout of the Gangotri glacier. The Bhagirathi and the Alaknanda, joins at Devaprayag to continue as the River Ganga. The entire basin drains through 11 states: Bihar, Delhi, Haryana, Himachal Pradesh, Uttar Pradesh, Madhya Pradesh, Rajasthan, West Bengal, Uttrakhand, Jharkhand and Chhattisgarh. The Ganga originates as Bhagirathi from the Gangotri glaciers in the Himalayas at an elevation of about 7010 m in Uttarkashi district of Uttrakhand and flows for a total length of about 2525 km up to its outfall into the Bay of Bengal through the former main course of Bhagirathi-Hooghly. The principal tributaries joining the river are the Yamuna, the Ramganga, the Ghaghra, the Gandak, the Kosi, the Mahananda and the Sone. Chambal and Betwa are the two important sub-tributaries.

Physiography

The Ganga river basin is situated in the northern part of the country between 22°30' and 31°30' N latitude and 73°30' and 89°00' E longitude. The total drainage area is 1,086,000 sq. km extending over China, Nepal, India and Bangladesh. About 79% area of the Ganga river basin is in India (Figure 1).

Figure 1: Geographical Context of the Ganga river basin



On the west, the Ganga river basin borders the Indus basin and then the Aravalli ridge. Southern limits are the Vindhyas and Chota Nagpur Plateau. On the east the Ganga merges with the Brahmaputra through a complex a system of common distributaries into the Bay of Bengal[1]. The altitude ranges from Mean Sea level at Sundarbans, Bay of Bengal, to 200 to 375m above MSL in Haryana, 150-450m above MSL in Rajasthan and 600-900m above MSL in Madhya Pradesh.

On a physiographic basis the Ganga river basin is divided into three physiographic divisions, namely, the Himalayan fold mountains/the Central Indian highlands, the Peninsular shield, and the Gangetic plain. The Ganga river basin has eight physiographic sub-divisions, namely, Trans-Yamuna Plain, Ganga-Yamuna Doab, Rohilkhand, Avadh Plain, North Bihar Plain, North Bengal Plain and Bengal Basin.

The central part of Ganga Basin in the state of Uttar Pradesh can be divided physiographically into a) Himalayas b) Sub-Himalaya c) Alluvial Plains and d) Bundelkhand and Vindhyan Plateau.

The Himalayan unit forms the northern most part of the state covering the districts of Uttarkashi, Tehri, Pauri, Chamoli, Pithoragarh, Almora and parts of Nainital. The zone is underlain by metamorphic sedimentary rocks and form hill ranges with high relief, deep gorges and narrow deep valleys.

Sub-Himalayan unit is lying between Himalayan unit as northern and alluvial plain as southern limit. The unit comprises Doon Valley, river terraces and low relief hilly tracts of Shivaliks.

The third, alluvial unit of this area can be sub-divided into five zones:

Bhabhar: It is highly porous dry zone and forms the southern limit of Sub-Himalayan unit. It varies in width between 10-30 km all along the foothills from Uttar Pradesh to West Bengal.

Tarai: This zone lies between Bhabhar in the north and central Ganga plain in the south and has a varying width of 8-16kms. It is characterised by change in surface slope.

Central Alluvial Tract : The vast alluvial tract south of Tarai belt and extending up to Yamuna river and Chhota Nagpur plateau, Palamu plateau in the east, covers the largest, about 40-50% part of the basin and is highly cultivated throughout the area.

Marginal Alluvial zone: It occupies the southern fringe area of the Ganga plain lying south of Yamuna close to plateau region. It has slope from south to north towards Ganga River.

The Southern Plateau: This unit occupies the extreme southern fringe of the basin. It is characterized by plain table land of Vidhyans and residual conical hills in Bundelkhand region. The entire plateau region forms the cratonic part of Ganga basin.

Climate

The climate of the Ganga river basin belongs predominantly to tropical and subtropical temperature zones. The climate is hot and humid in summer and cool in winter. The temperature in the Ganga plains varies from 5° to 25°C in winter and from 20°C to more than 40°C during summer. The average annual rainfall in the Ganga river basin varies from 350 mm at the western end to 2000 mm near the

[1]http://en.wikipedia.org/wiki/Ganges_Basin

delta. Major part of the rains is by the south-western monsoon from July to October. Part of the flow comes from melting Himalayan snows, in the hot season from April to June. Some mountain peaks in the head water reaches of the river are permanently covered with snow and glaciers. In the upper Gangeatic Plain in Uttar Pradesh average rainfall varies from 762 to 1016 mm. The headwater area receives large amount (1200 to 2200 mm) of precipitation composed of substantial amount of snow fall.

Drainage and Major Tributaries

Drainage in Ganga basin is governed mainly by rainfall, physiography and lithology. Drainage in mountains and hills are mainly dendritic and structurally controlled. On hill slopes drainage is mostly characterized by parallel to sub-parallel drainage, which persists in the Central Ganga plain and continues up to Bay of Bengal.

The Himalayan rivers are mainly rainfed and snow-fed while rivers originating from Aravali and Vindhyan mountains are mainly rainfed and groundwater fed.

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 (Figure 1). The Himalayan Rivers are mainly rain and snow-fed while rivers originating from Aravali and Vindhyan mountains are mainly rainfed and ground water fed.

Geotectonic Framework

The southern and western parts of the basin are occupied by the Achaean, Proterozoic and Vindhyan folded self-zones, which extend into the ocean beneath the narrow strip of sedimentary cover in the east. In the Ganga valley, the northern edge of the peninsular shield slopes with a low gradient. In the western part of the basin a marginal depression possibly connecting the Himalayan foredeep. The southern part is essentially composed of archean basement complex i.e. Bundelkhand gneisses, schists, meta-sedimentaries and meta-basics of Aravali Super group and Delhi group in the West, and Bijawars and iron ore group of rocks in the southern Uttar Pradesh and Bihar, and West Bengal possess Archaeans of eastern ghats. In southern and south-eastern part, the basin platforms are composed of late Palaeozoic and Mesozoic sediments deposited on the ancient basement along rift basins, elongate narrow sags and these form intra-cratonic basins. These are represented by Gondwana Super group of rocks. Extensive volcanic efflusives (basalts), commonly known as Deccan trap, on west southern part of the basin, in the MP and Rajasthan, are due to volcanic activity in a marginal depression, and suffered warping consequent to Himalayan orogeny. Their present platform like deposition is attributed to renewed volcanic activity during Himalayan orogeny. In extra-Peninsular region, the entire northern part of the basin is occupied by the great Himalayan geosynclinals belt. The greater part of the Himalayan belt, is covered by reworked massifs of Archaean-hercynian folded belts comprising meta-sediments, efflusives and intrusive. Folded sequence of Cretaceous-Eocene along with reworked basement and gneiss constituted a eugeosynclinal area. This belt is characterised by sandstones, subgreywackes containing metamorphic rock fragments, shales, limestones, coal and petroleum bearing formation.

The Himalayan foredeep occupied by Ganga-Yamuna alluvium is believed to be constituted of Post-tectonic molassic sediments above Cainozoic Sediments known as Shivaliks, Dharamsala and Subathus deposited over Vindhyan Super groups of rocks.

Sedimentation in the Ganga Basin:

Alluviation in the Ganga foreland basin took place in similar way as it is taking place today. Alluvial fans and fluvial deposits are two different patterns which are active in the entire basin. Alluvial fans mostly occur to the south of the frontal folded belt and extending 30 to 50km in their surfacial extents. Some mega-alluvial fans are Kosi fans, Gola fan etc. Fluvial deposits in the form of channel bar, natural levee, floodplains, back swamps are very common along the present existing rivers. Further, the presence of paleo-channels, abandoned channels, meander-scars and several other fluvial landforms present in the vast alluvial plain indicate a similar environmental condition in the past.

Soils

Soil types in the Ganga basin are grouped into various classes, namely Entisols, Vertisols, Inceptisols, aridisols, Mollisols, Alfisols, Ultisols and Histosols. The classification is based on presence of Pedons and the rock types from which they have originated.

Besides these, there are younger alluvial soils, older alluvial soils, lateritic soils, red, yellow and black soils. The brown soils of sub-mountain region and desert region occur in Rajasthan and Haryana. It also occurs in the foothills of Himalayas. The red acidic lateritic soils are very prominent in the southern part of Bihar and south-western part of West Bengal. The alluvial soils are most dominant soil type and occur in the alluvial flats from west in Uttar Pradesh to east in West Bengal. They are also known as Bhangar-Bhabhar on flat plains and khaddar soils in black swamps of major rivers flowing through the central Ganga Plain.

Texture of the soil plays important role in surface water movement and development of quality characteristics. These soils are termed as sandy, silty, loamy etc. The soils of Haryana and Rajasthan can be grouped into Loamy sand, Sandy loam, Sandy soil and loamy soil. In case of Bihar and UP, the major soil groups are alluvial.

The important soil types found in the basin are sand, loam, clay and their combinations such as sandy loam, silty clay etc. Alluvial soils covers about 58% followed by red soils (12%) and deep to shallow black soil (20%), mixed red and yellow soils (6%)2.

Landuse

Major land use is agriculture (51%), and Forest (17 %), about 14 % land not available for cultivation and fallow land (8%). Wheat, sugarcane, jowar, bajra and rice are the main crops of the basin. Rice and jute are the main crops in Bihar and West Bengal.

Agricultural activity in the basin is mainly restricted to the plains of Ganga which possess highly fertile land from West Bengal in the east to western Uttar Pradesh, Haryana in the west. The part of plains of Uttar Pradesh, Haryana and Rajasthan are affected by saline tracts with Usar lands. The hilly

[2]Status Paper on River Ganga, Central Pollution Control Board, National River Conservation Directorate (MoEF) (2009)

terrains of the entire states are covered by forests of various categories i.e. reserve forests, protected forests etc. The major land use in Ganga Basin are urban areas, arable land, Forest, Grassland, wasteland and water bodies, marshes etc.

The central plain of the basin has some 28 million ha of land suitable for irrigation cropping. The wasteland and grassland are mainly localised in the hilly terrains of Aravalies, Vindhyan Plateau and in the plains of Rajasthan, Haryana, Uttar Pradesh and Bihar. Shrublands in plains of Uttar Pradesh are generally salt affected. The marshy land and water bodies in the area are either natural depressions or manmade water bodies on the rivers. The marshy and waterlogged areas also develop along canals and in canal command areas. The entire alluvial tract of the basin has network of canals originated from total live storage capacity of almost 38 BCM with 23.41 M ha irrigated area.

Demography

The Ganga river 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 world3. Ganga river 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 Ganga river basin is one of the most densely populated with about 300 million people. Average population density in the Ganga river basin is 520 persons per square km as compared to 312 for India (2001 census).

Irrigation

The annual surface water potential of the Ganga river basin has been assessed as 525 km^3 in India, out of which 250 km^3 is utilizable water. 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 Ganga river basin has a substantial groundwater, replenished every year at a very high rate. The conjunctive use of groundwater for irrigation, even within the canal command areas is highly prevalent. The groundwater usage for irrigation in the states falling under the Ganga river basin exceeded 104.7 billion cum per year as of 2008 and accounted for nearly 50 per cent of the groundwater irrigated area of the entire country. Therefore, it is important to understand the interaction between the surface water and groundwater. For the purpose, it is essential to deploy the surface water and groundwater models for the Ganga basin. The following sections describe these models and their calibration and validation for the Ganga basin.

[3]moef.nic.in/downloads/public.../Status%20Paper%20-Ganga.pdf

Chapter 2

Surface Water Modelling Calibration and Validation

Chapter 2 - Surface Water Modelling (SWAT) - for the Ganga river basin: Calibration and Validation

Objective of the Study

Following are the overall objectives defined with respect to the water resources management of the Ganga basin

1. Understand the Surface water system of the Ganga River Basin by performing hydrological modelling of the Surface water dynamics of the basin
2. Study the water balance of the entire basin as a single entity
3. Developing suitable management practices and policies for sustainable development of water resources in the basin

The first two objectives are achieved through hydrological modelling taking entire Ganga river basin as a single entity and is the main focus of this report. The following sections gives details of the same.

Methodology

Hydrological model has been set up to simulate all the natural processes prevalent in the basin as well as to represent the manmade activities in the basin. Once the model is set up and proven through the process of calibration and validation then only it shall be possible to generate scenarios that can possibly be used to bring back the hydrological health of the basin.

A brief description of the SWAT hydrological model is given in the following paragraphs.

Soil and Water Assessment Tool (SWAT) Model

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998[4], Neitsch et al., 2002[5]) is a distributed parameter and continuous time simulation model. The SWAT model has been developed to predict the hydrological response of un-gauged catchments to natural inputs as well as the manmade interventions. Water and sediment yields can be assessed as well as water quality. 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 un-gauged 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 land management practices 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 sub-watersheds. Major model components include weather, hydrology, soil

[4]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

[5]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.

temperature, plant growth, nutrients, pesticides, and land management. The model has been validated for several watersheds.

In SWAT, a watershed is divided into multiple sub-watersheds, 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 sub-watershed 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[6]).

SWAT also simulates the nutrient dynamics. Sediment yield is calculated based on the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975[7]). 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 subsurface flow is calculated from 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[8]). 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)[9]

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

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

[8]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

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

Advantages of the SWAT model

The SWAT model possesses most of the attributes which are identified to be the desirable attributes that 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 the land management practices being followed in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modelled by SWAT using these input data. This approach results in major advantages, such as:

- Un-gauged watersheds with no monitoring data (e.g. stream gauge data) can be successfully modelled.
- 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 of change.
- The model has gained a wide global acceptability. Currently 720 peer reviewed papers have been published based on the SWAT model (http://swatmodel.tamu.edu). The current rate of publication is about 120 peer reviewed papers 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.
- IIT Delhi has a MoU with the SWAT group for the past 16 years and has been engaged in the improvement of many segments of the model.

Development of hydrological model for the Ganga river basin

In the present model set up, the entire Ganga river basin including Nepal part is used. The Ganga river basin is shown in Figure 2.

Figure 2: The Ganga river basin

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

Data Used

The model requires two types of data; static and dynamic data. Spatial static data and the source of data used for the study area include:

Digital Elevation Model: SRTM 90m Digital Elevation Data[10]
Drainage Network – Hydroshed[11]
Soil maps and associated soil characteristics (source: NBSSLUP and FAO Global soil)[12]

[10]http://srtm.csi.cgiar.org/
[11]http://hydrosheds.cr.usgs.gov/
[12]http://www.lib.berkeley.edu/EART/fao.html

Land use: NRSC Landuse (2007-08) merged with IWMI's Global Map of Irrigated Areas (GMIA) (source: IWMI) [13]

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

IMD Reanalysis regridded weather data (1965–2006) – initial 4 years of weather data was used as warmup/setup period for the Ganga river basin model thus outputs were available from 1969 to 2006

Water demand and abstraction data

Current management/operation practices, existing irrigation as per crop demand. (Note: Current crop management practices include irrigation sources from Surface and Ground water)

Model Performance

Once the model was set up, the model was calibrated by changing the model parameters to represent the observed flow at the point of observation as closely as possible. The performance of the SWAT model was evaluated using statistical parameters namely regression coefficients (R^2) and Nash Sutcliffe coefficient (NS) on monthly basis.

Model Evaluation Statistics (Dimensionless)

Nash-Sutcliffe efficiency (NSE): 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[14]). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as

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

where Y_i^{obs} is the ith observation for the constituent being evaluated, Y_i^{sim} is the ith 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[15]

Coefficient of determination (R^2): Coefficient of determination (R^2) describes the degree of co-linearity between simulated and measured data. R^2 describes the proportion of the variance in

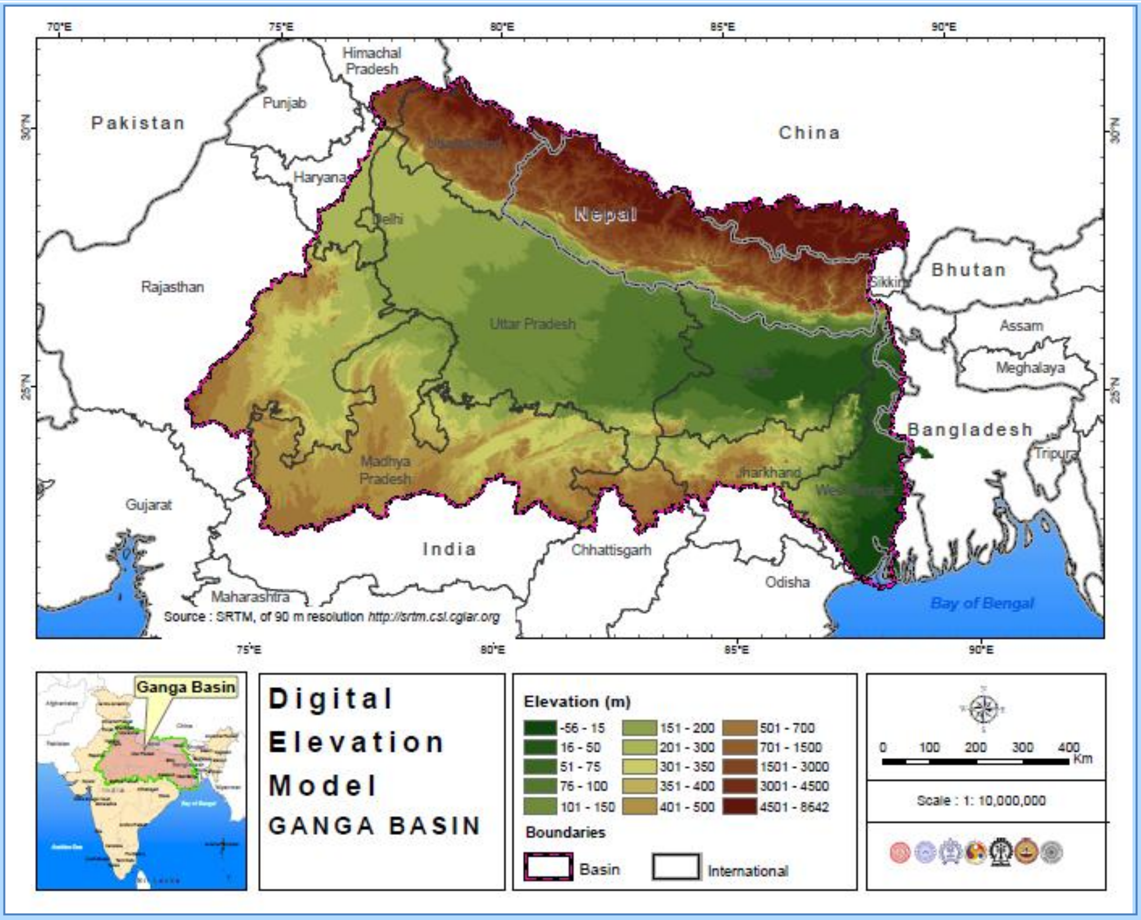
[13] http://www.iwmigiam.org/info/main/index.asp
[14] Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part 1. A discussion of principles. J. Hydrology 10(3): 282-290
[15] Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith, 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, Transactions of the ASABE, Vol. 50(3): 885–900 2007

measured data explained by the model. R^2 ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable (Santhi et al., 2001[16], Van Liew et al., 2003[17]). However,R^2 is very sensitiveto extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data (Legates and McCabe, 1999[18]).

Mapping the Ganga river basin

The ArcSWAT interface has been used to pre-process the spatial data for the river system. A digital elevation model (DEM) from the SRTM[19] was used for basin delineation and is shown in Figure 3. The SRTM DEM with 90 m resolution was preferred over the CARTOSAT data set because of high degree of error reported in the latter.

Figure 3: Digital Elevation Model of the Ganga river basin



[16]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

[17]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

[18]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

[19]http://srtm.csi.cgiar.org

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

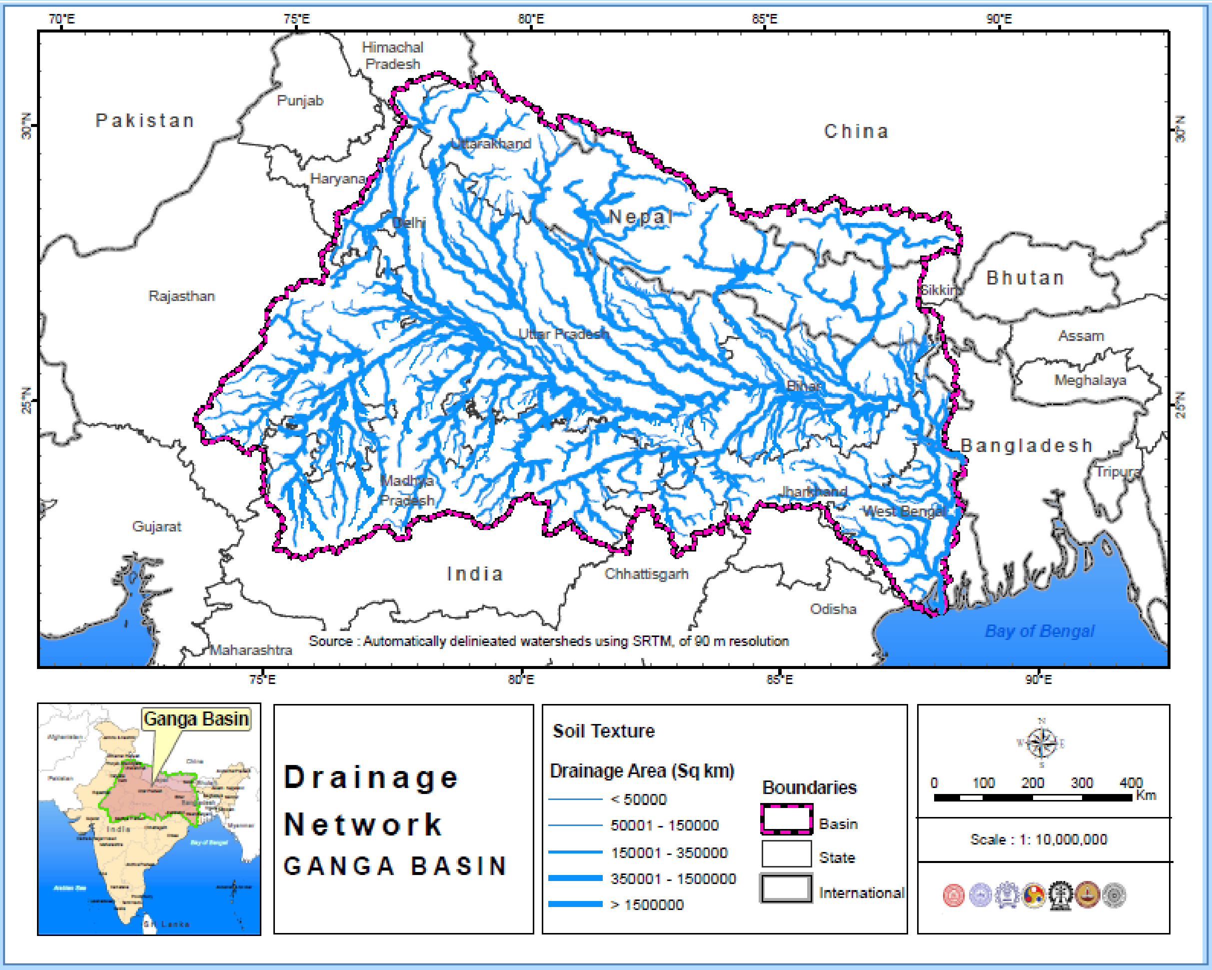
Table 1: Elevation Summary – Ganga Basin

Parameter	Elevation (m)
Minimum Elevation	1
Maximum Elevation	8752
Mean Elevation	949

Basin Demarcation

Figure 4 shows the delineated Ganga catchment with the generated drainage network using the DEM. The watershed boundary of Ganga basin was delineated using the ArcView interface of SWAT.

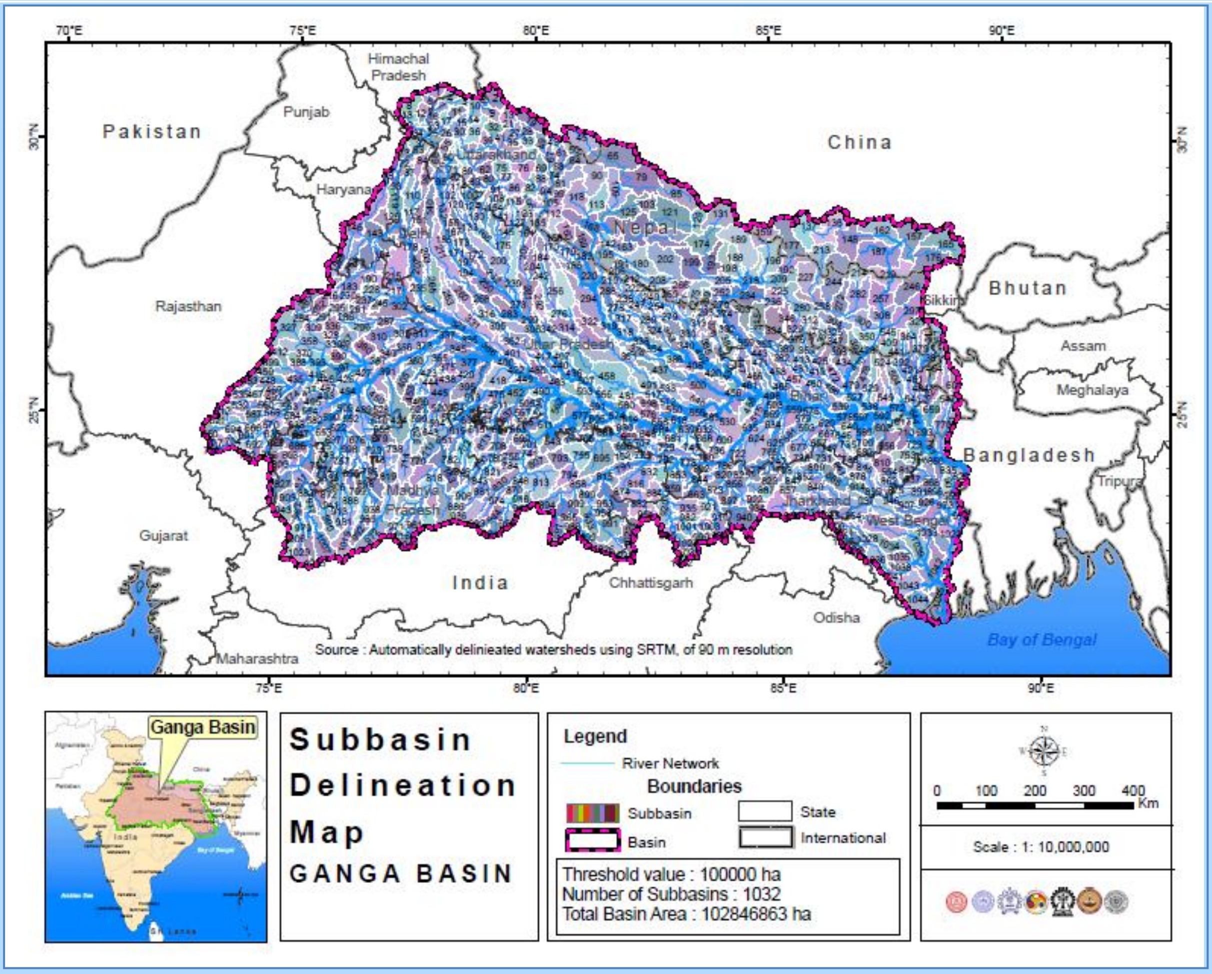
Figure 4: Basin delineation using DEM for the Ganga river basin



Watershed (sub-basin) Delineation

Automatic delineation of watersheds was done by using the DEM as input. The target outflow point is interactively selected. The Ganga river basin has been delineated and has resulted in 1038 sub-basins (Figure 5). Basin area of the Ganga up to the basin outflow point in India without considering the Bangladesh part is 1,028,468,63 sq km. Care was also taken to incorporate the locations of major dams, reservoirs and diversion structures while undertaking the delineation process.

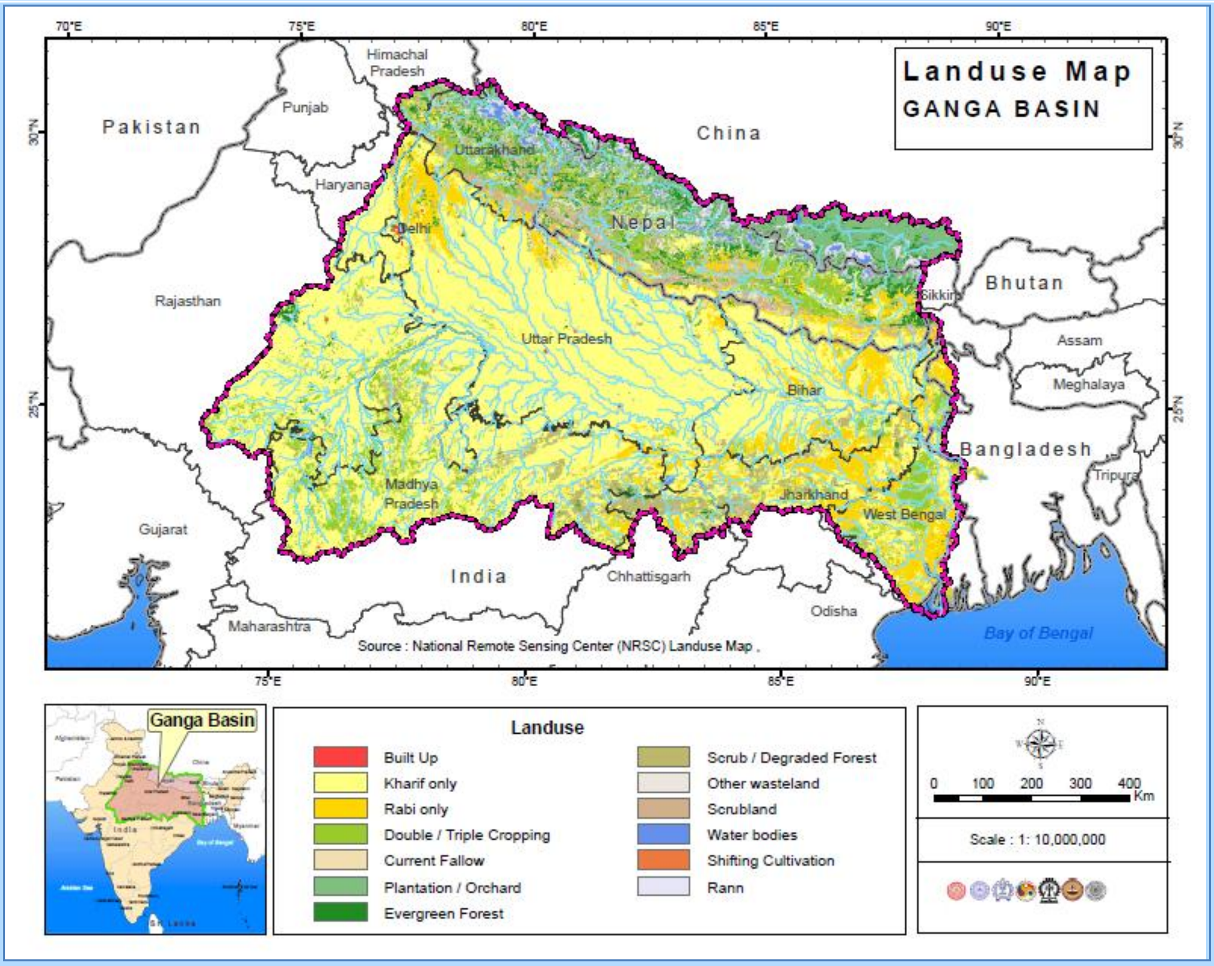
Figure 5: Sub basin delineation using DEM for the Ganga river basin



Land Cover/Land Use Layer

Land Use/Land Cover is another important segment of data that is required for hydrological simulation of the basin. The merged landuse and irrigation source map from NRSC and IWMI, as shown in Figure 6, used for the present study. IWMI derived the Ganges River Basin Irrigated Area product using MODIS 500-m and AVHRR 10-km satellite sensor data merged with NRSC Landuse/landcover map 2007-2008, to derive a new landuse map with agriculture landuse as well as sources of irrigation.

Figure 6:Landuse map for the Ganga river basin

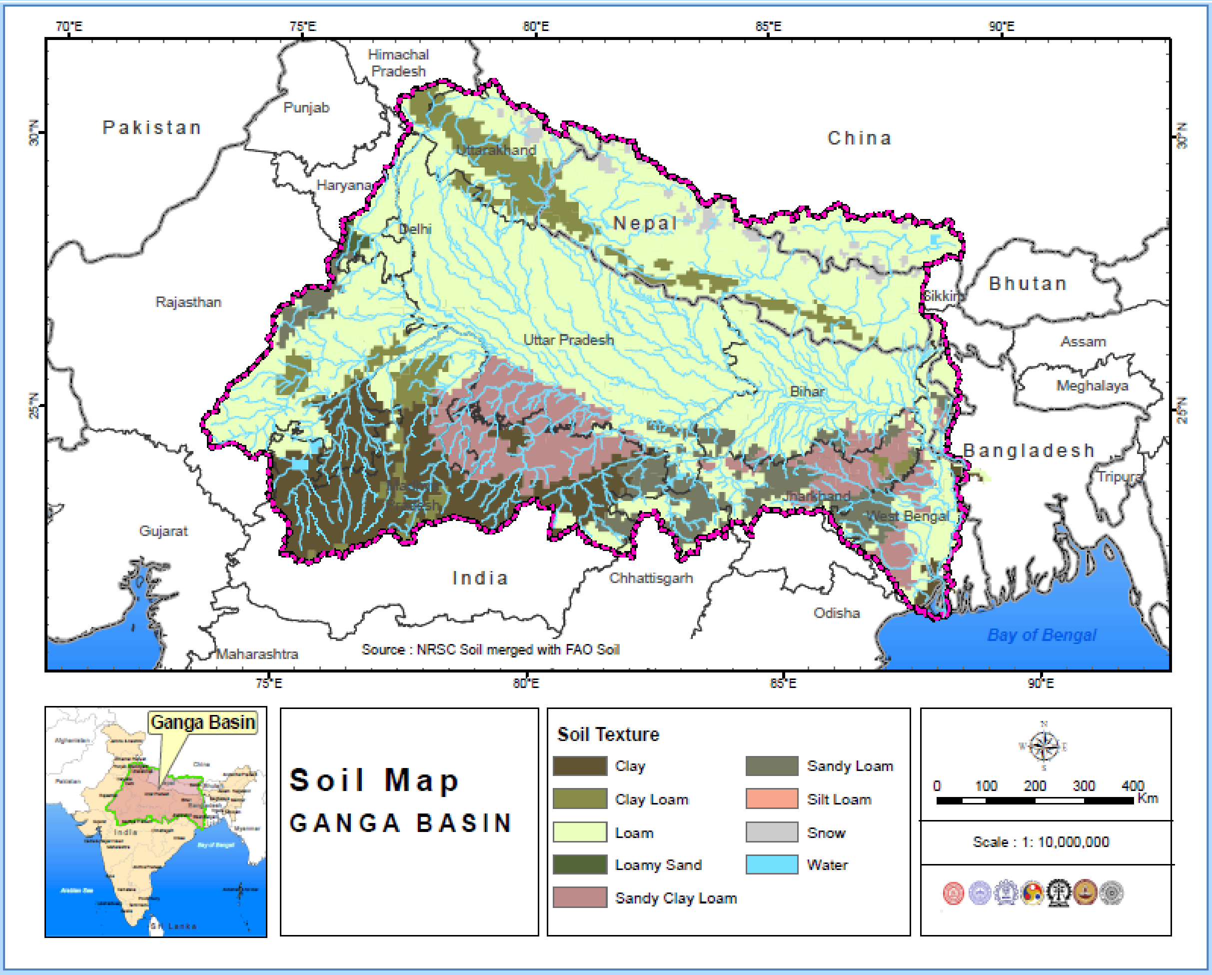


The major part of the basin is under agriculture land use (80%) with large portion under the irrigated agriculture, and rice, wheat, sugarcane and pulses are the predominant crops.

Soil Layer

Information on the soil profile is also required for simulating the hydrological character of the basin. Digitised soil map from NBSSLUP merged with the FAO global soil map has been used for the modelling. The soil map is shown in Figure 7.

Figure 7: Soil map for the Ganga river basin



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

Hydro-Meteorological and Water resources structures data

The daily reanalysis and re-gridded weather data from IMD (rainfall, temperature) has been used. Daily rainfall data are at a resolution of 0.5° X 0.5° latitude by longitude grid points (represented by black dots in Figure 8). 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 $1^{o}x1^{o}$ resolution (represented by red cross in Figure 8) for the entire basin. The weather grids were superimposed on the sub basins for deriving the weighted means of the inputs for each of the sub basins.

Figure 8: IMD Gridded Rainfall and Temperature grid locations for the Ganga river basin

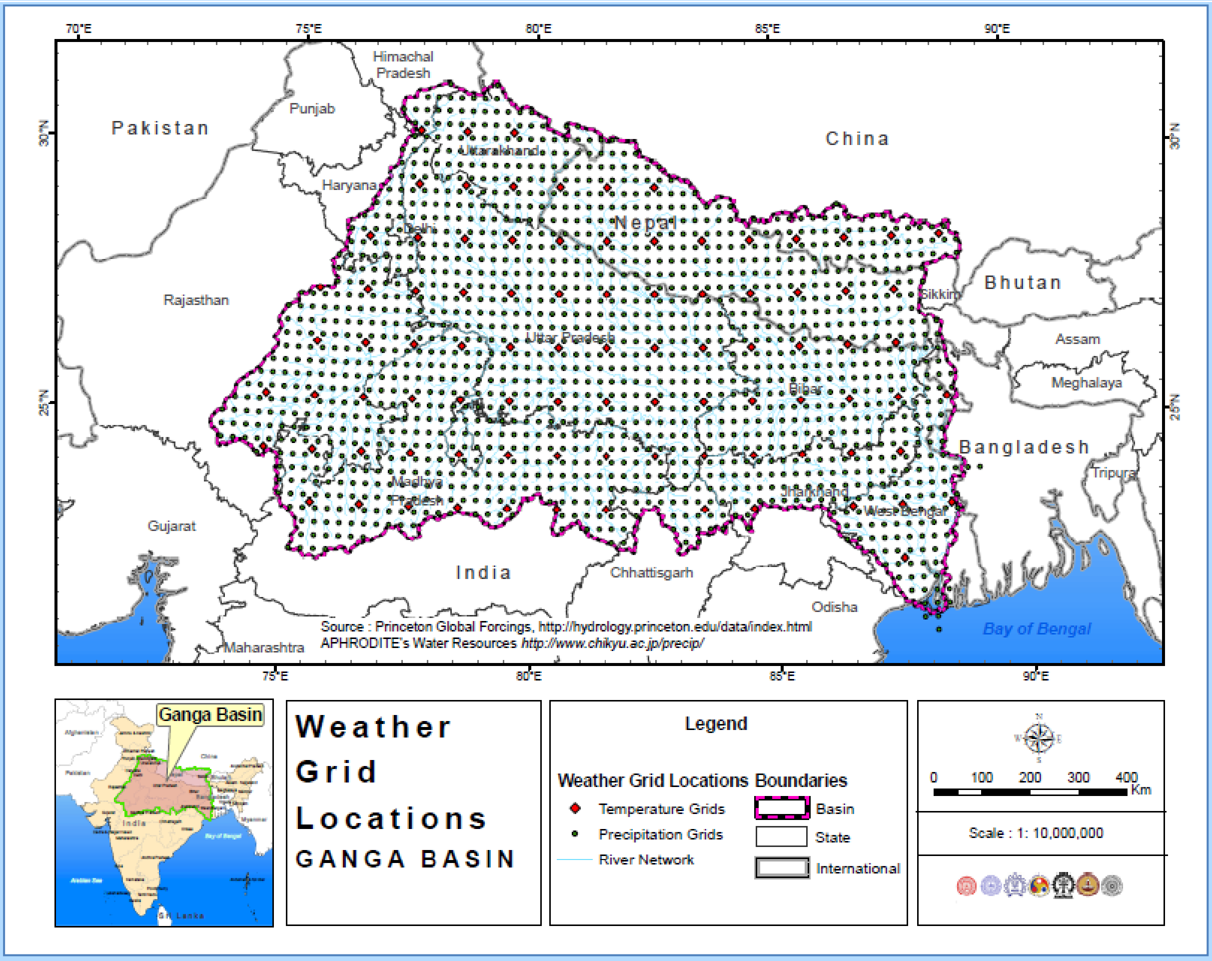
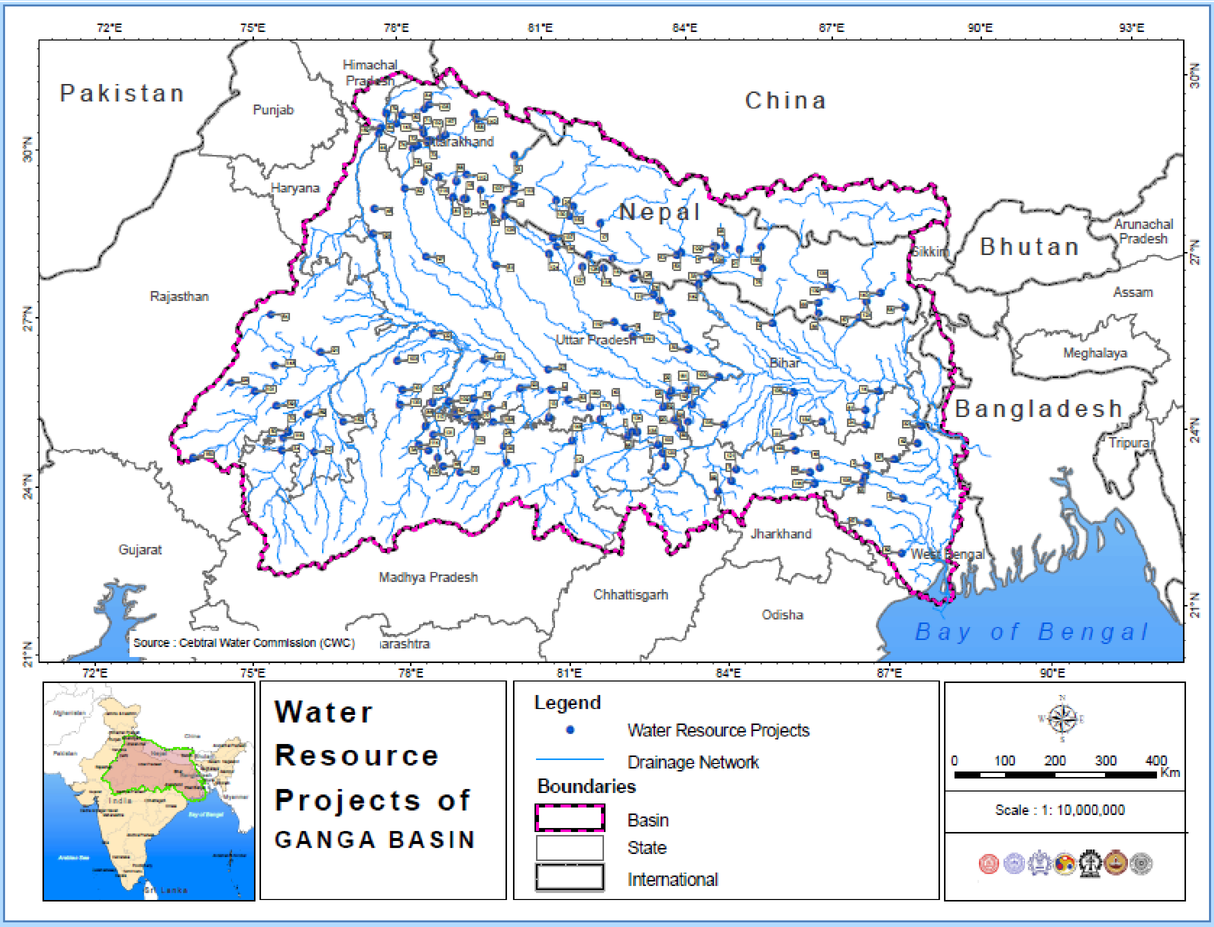


Figure 9 shows the locations of the water resources structures which include, major, medium projects, weir, canal diversion locations and other similar structures. Even though the location of these projects are available, ironically, none of the details such as the operating policy, rule curves, height-volume relationship were made available to the modelling group.

Figure 9: Water resources structure locations for the Ganga river basin



Model Assumptions

In the absence of precipitation data availability for higher elevation areas, elevation corrections were applied for rainfall and temperature stations available at lower elevations to simulate snow hydrology. Maps of canal command areas[20], irrigation sources[21] and district crop production[22]were used to arrive at close representation of current crop management practices to be incorporated for crop simulation in the SWAT model. In the part of the basin area with the elevation ranging from 7000m to 2000 m, elevation bands have been used. 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. The SWAT model is capable of using elevation band to adjust the temperature and rainfall as the altitude changes. A literature based value of -6.5^{o}C/km increase was used as temperature lapse rate and 100 mm/Km was used as precipitation lapse rate for those subbasins where the elevation bands were incorporated. These correction factors are necessary to account for change in precipitation and temperature at higher altitudes since the observations of rainfall and temperatures were very limited. In addition, there was no data on the spatial pattern of glacier depth and snow pack. Hence, in this modelling setup a glacier depth of 100

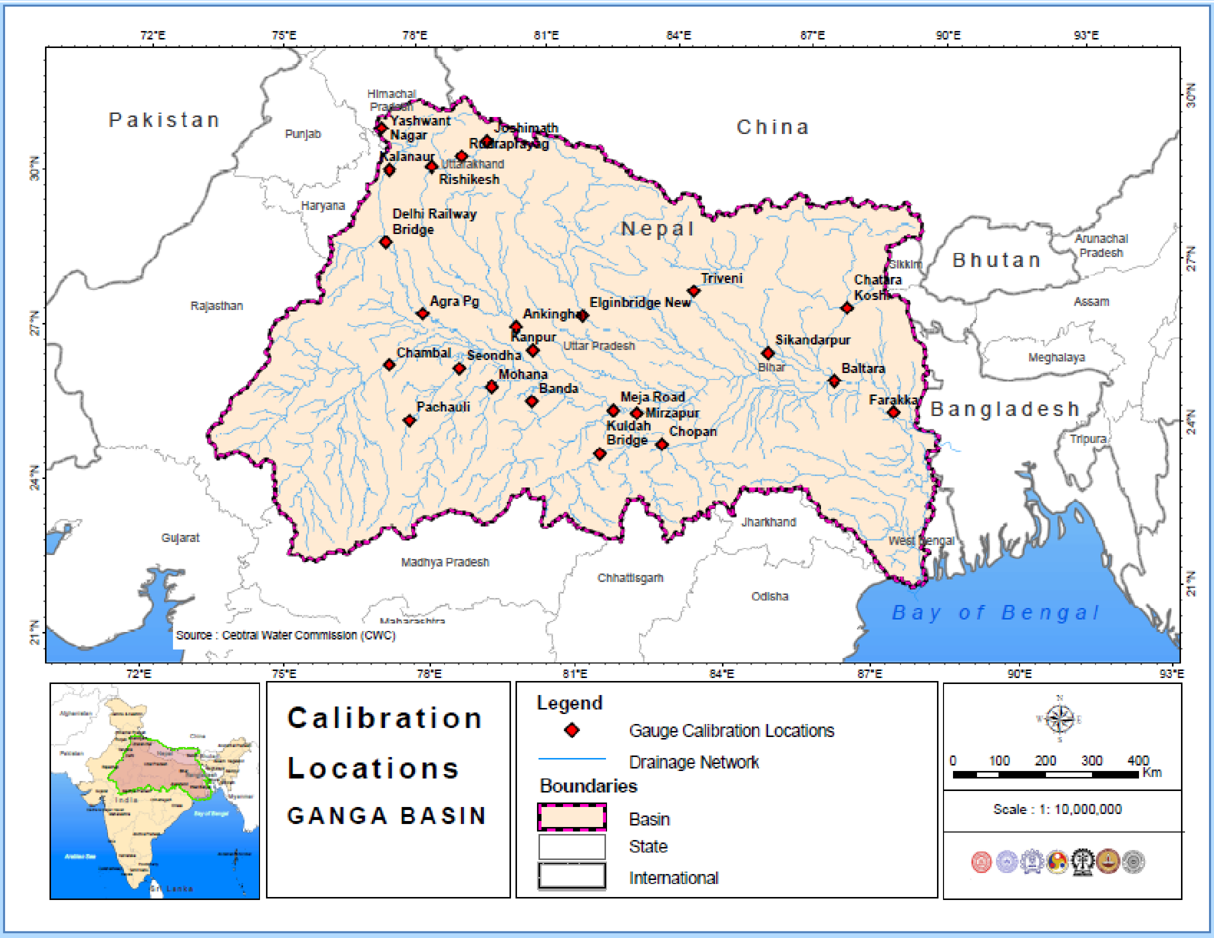
[20]www.india-wris.nrsc.gov.in/
[21]IWMI: http://www.iwmigiam.org/info/main/index.asp
[22]http://www.icrisat.org/vdsa/vdsa-mesodoc.htm

m was assumed for altitudes above4500 m above MSL. The 100 m initial depth was setup after a calibration process where various initial depths were assumed iteratively to ascertain the depth that shall provide reasonable streamflow during leanflow season that is mainly due to glacial melt. The model can provide the change in glacier depth over time to predict the loss of glacier due to climatic factors.

SWAT Model Performance for the Study area

Although the SWAT model does not require elaborate calibration (Gosain et al., 2005[23]), limited model validation has been made using the observed data for the period 1990-2004 at monthly scale. The stream flow data were provided for various time periods by CWC[24]. Figure 10 shows the locations where the SWAT model performance has been verified.

Figure 10: SWAT Calibration Locations for the Ganga river basin



Statistical parameters namely regression coefficients (R^2) and Nash Sutcliffe coefficient (NS) were used to assess the model efficiency for monthly streamflow predictions. Before performing statistical comparison of streamflows, the reasonableness of the model for general

[23]Gosain, A.K., Sandhya Rao, Srinivasan, R. and Gopal Reddy, N., 2005. “Return-Flow Assessment for Irrigation Command in the Palleru River Basin Using SWAT Model”.Hydrological Processess 19, 673-682.
[24]Central Water Commission, MoWR

evapotranspiration, runoff, base flow/return flow, and crop yields against district averages were analyzed as additional check points for satisfactory simulation.

The SWAT model has been setup in this study with elevation bands, temperature and precipitation lapse rates along with an assumedglacier depth.All the manmade structures in the form of major and medium irrigation projects, diversions and other utilizations have also been incorporated indirectly in the absence of the required data from the respective State governments.

Model calibration and validation is performed at some of the snow catchments and on all the major tributaries of the Ganga river, namely, Alaknanda, Yamuna and its tributaries, main Ganga, and other tributarties of the Ganga. Figure 11 shows the line diagram of the locations where calibration and validation has been performed.

Figure 11: Line Diagram of Calibration Locations for the Ganga river basin

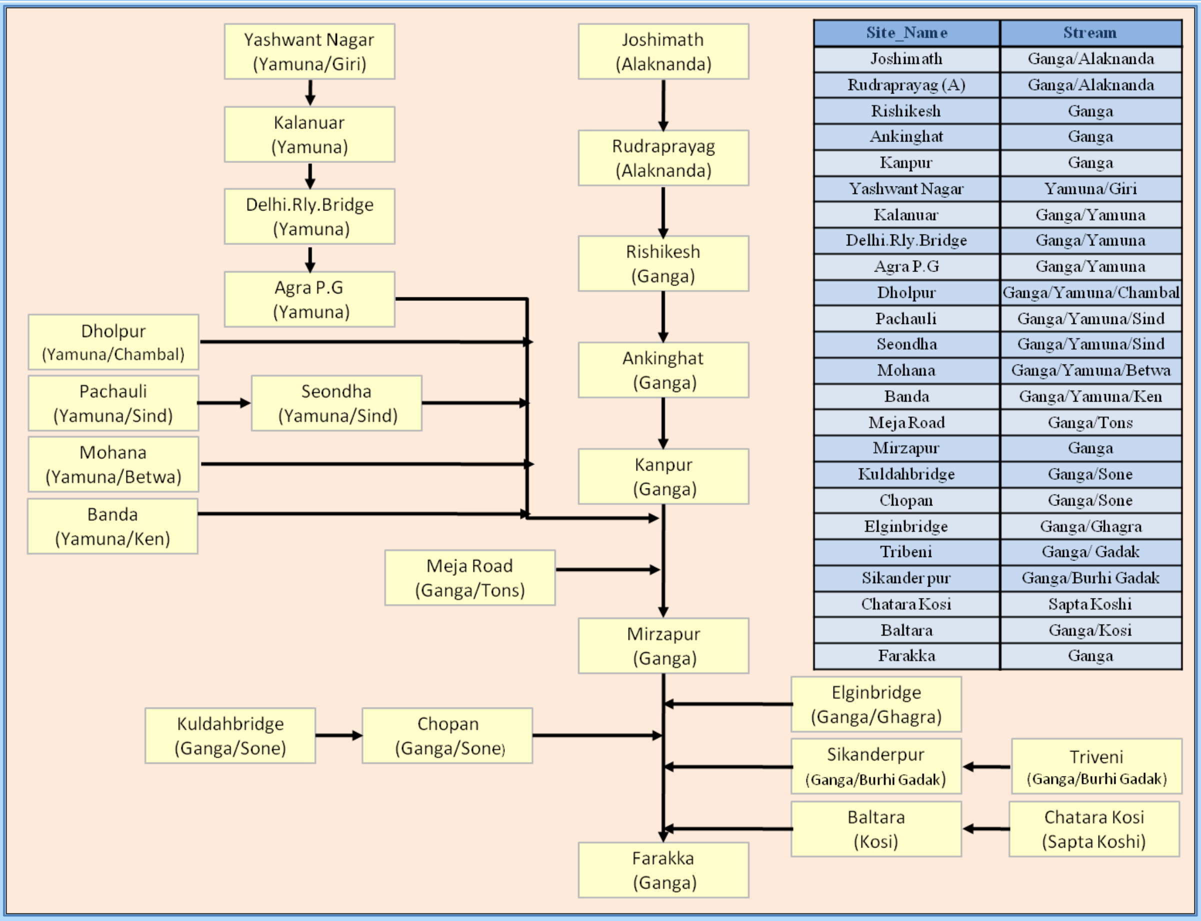
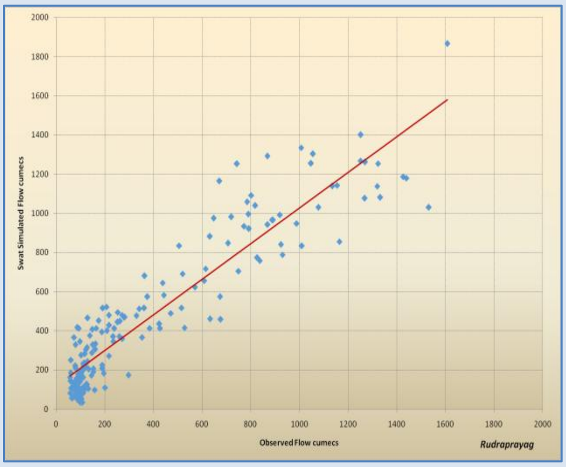


Figure 12 shows the 24 locations where model performance has been validatedon the major tributaries of the Ganga river. Time series plots of observed and simulated have not been provided because the data is classified. Therefore, only scattered plots for the observed vs. simulated monthly discharge have been provided.

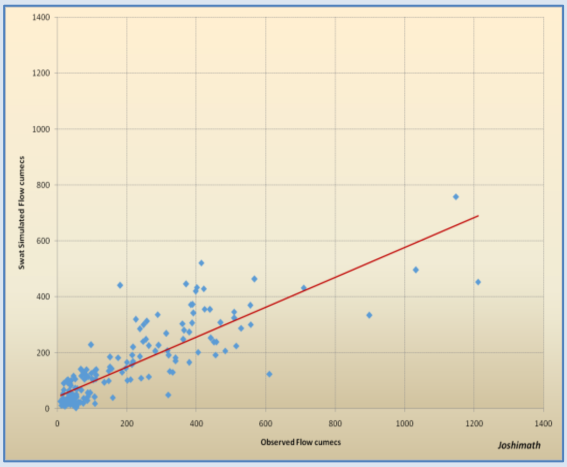
Figure 12: SWAT Calibration Locations for the Ganga river basin

Observed Vs. Simulated Scatter Plots

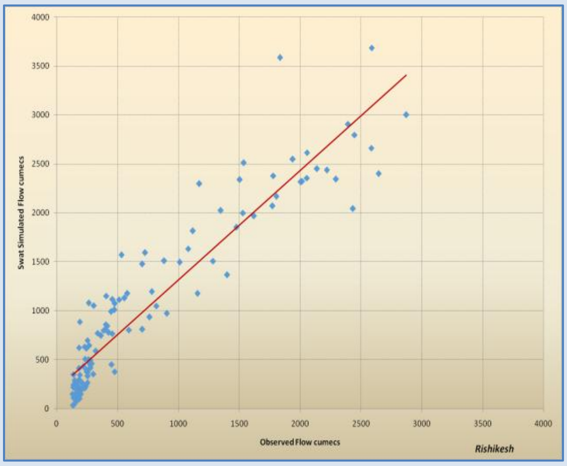
Rudraprayag on Alaknanda (Ganga/Alaknanda) river



Joshimath on Alaknanda (Ganga/Alaknanda) river



Rishikesh on Ganga river



Yashwant Nagar on Giri (Yamuna/Giri) river

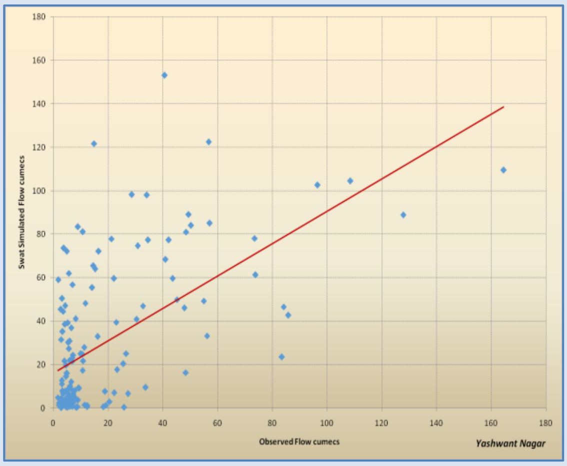
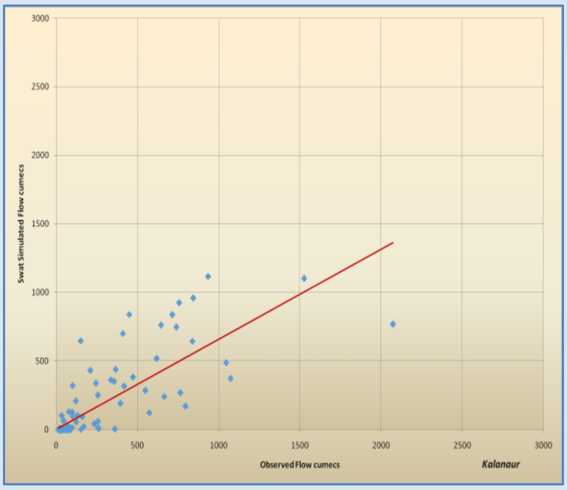
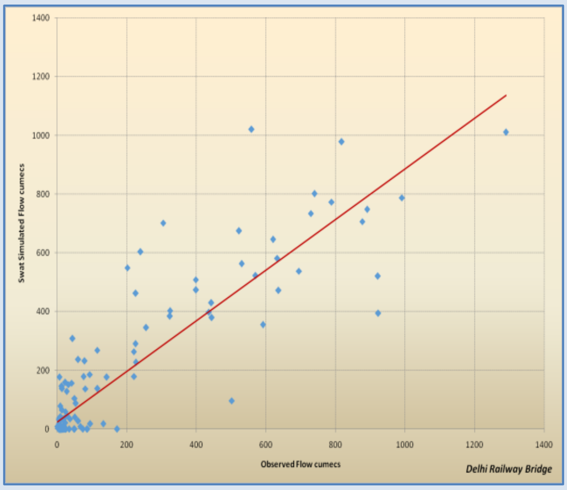


Figure 12: SWAT Calibration Locations for the Ganga river basin

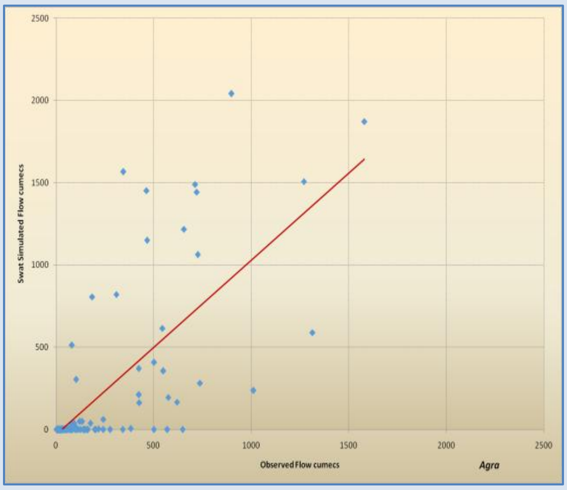
Kalanaur on Yamuna (Ganga/Yamuna) river



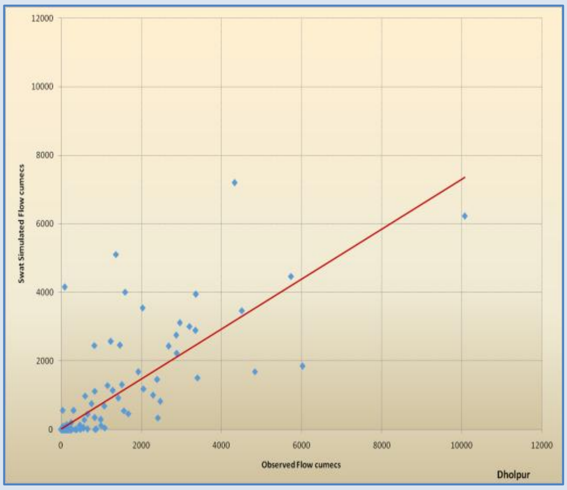
Delhi Railway Bridge on Yamuna (Ganga/Yamuna) river



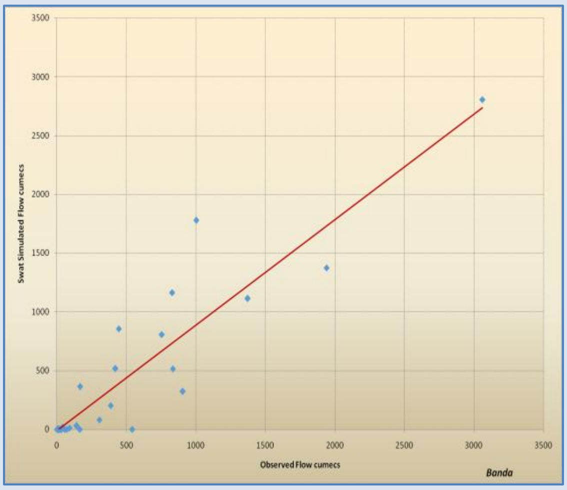
Agra P.G. on Yamuna (Ganga/Yamuna) river



Dholpur on Chambal (Ganga/Yamuna/Chambal) river



Banda on Ken (Ganga/Yamuna/Ken) river



Mohana on Betwa (Ganga/Yamuna/Betwa) river

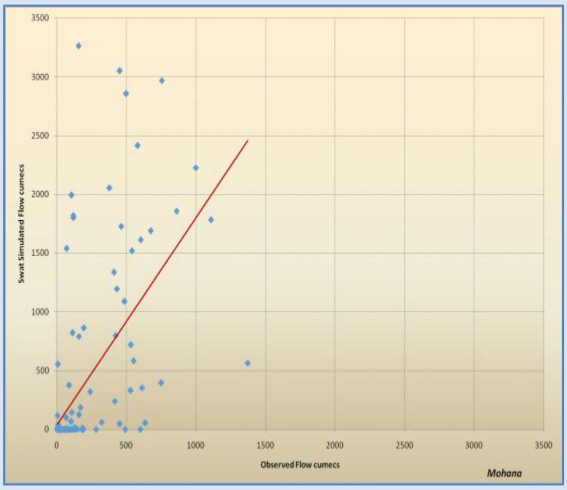
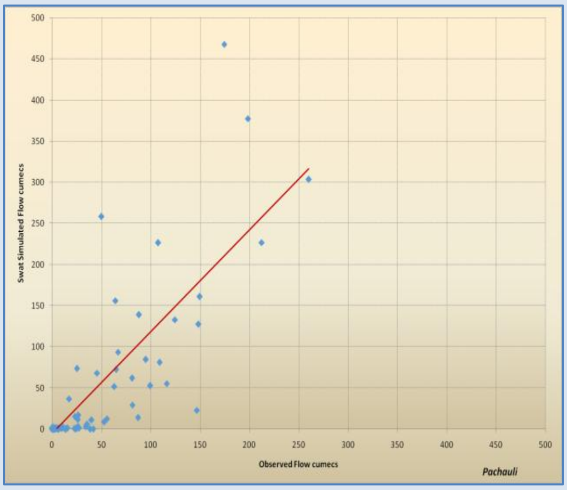
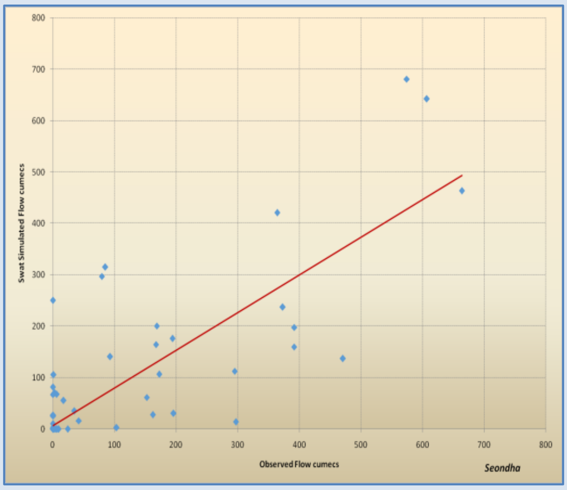


Figure 12: SWAT Calibration Locations for the Ganga river basin

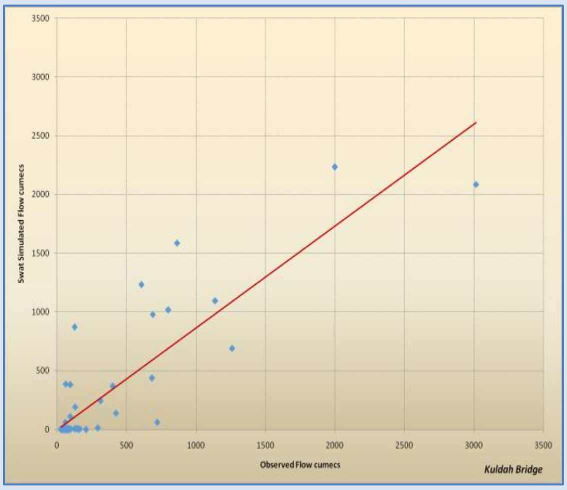
Pachauli on Sind (Ganga/Yamuna/Sind) river



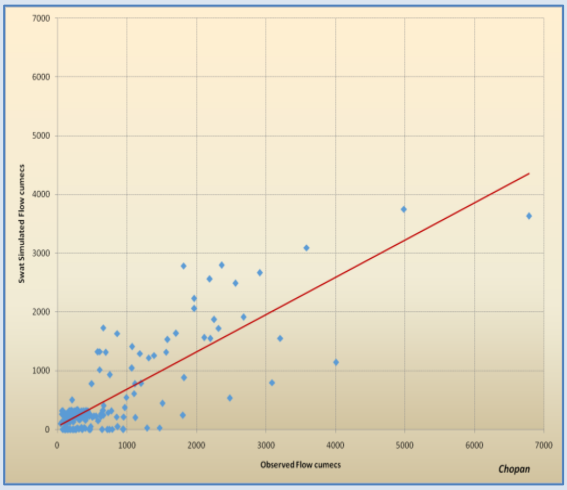
Seondha on Sone (Ganga/Yamuna/Sind) river



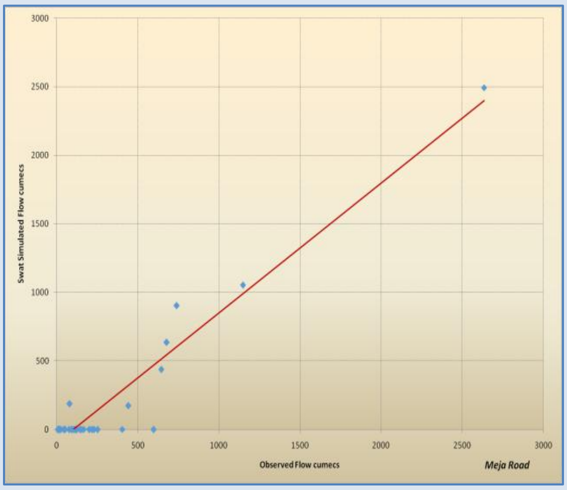
Kuldahbridge on Sind (Ganga/Sone) river



Chopan on Sind (Ganga/Sone) river



Meja Road on Tons (Ganga/Tons) river



Elginbridge on Ghagra (Ganga/Ghagra) river

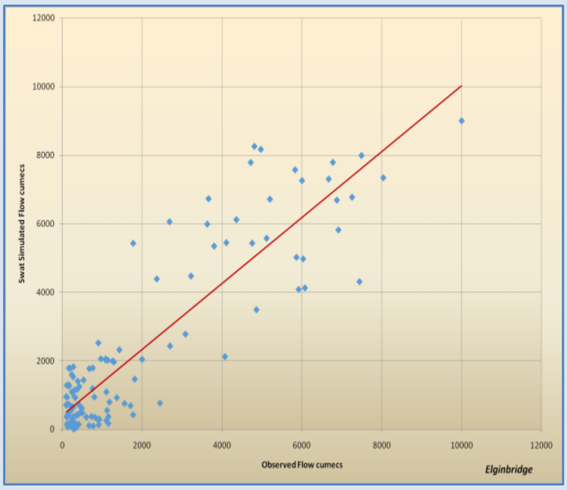
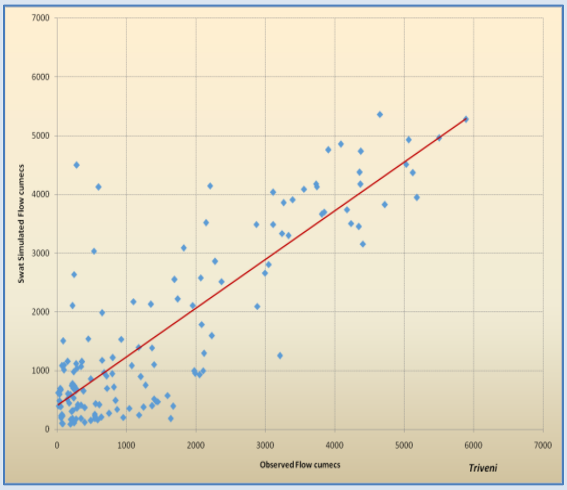
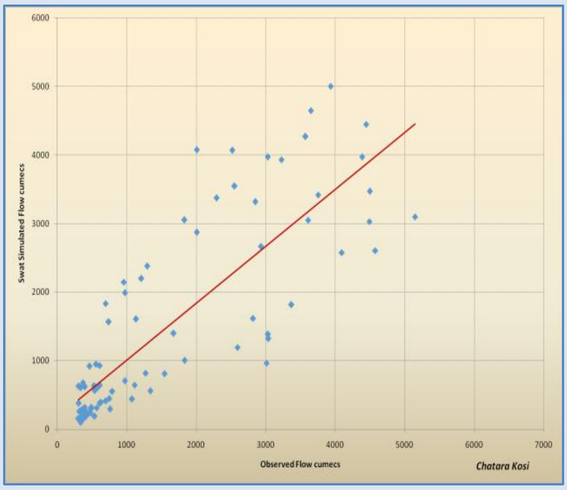


Figure 12: SWAT Calibration Locations for the Ganga river basin

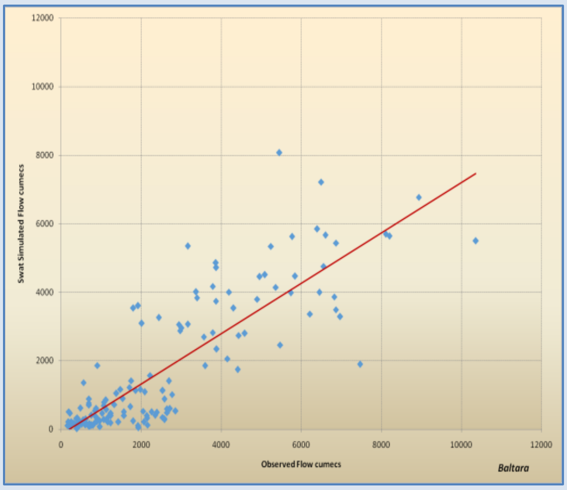
Tribeni on Gandak (Ganga/Gandak) river



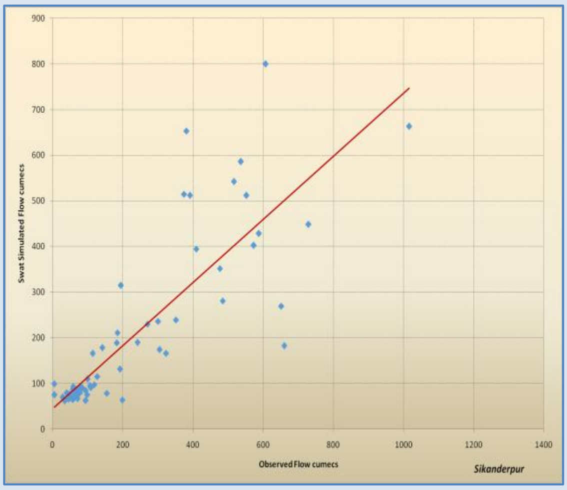
Chatara Kosi on Kosi (Ganga/Kosi) river



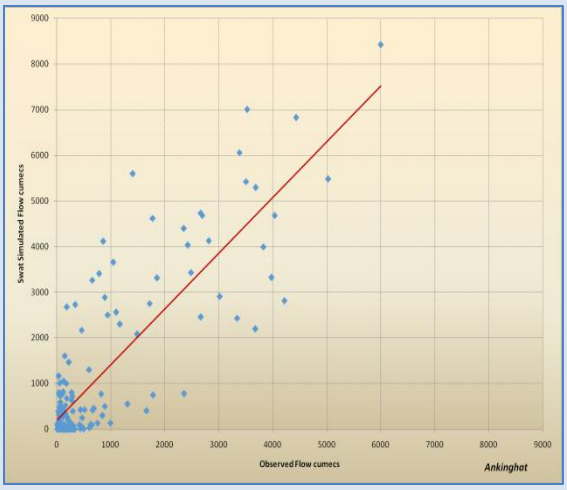
Baltara on Kosi (Ganga/Kosi) river



Sikanderpur on Burhi Gandak (Ganga/Burhi Gandak) river



Ankinghat on Ganga river



Kanpur on Ganga river

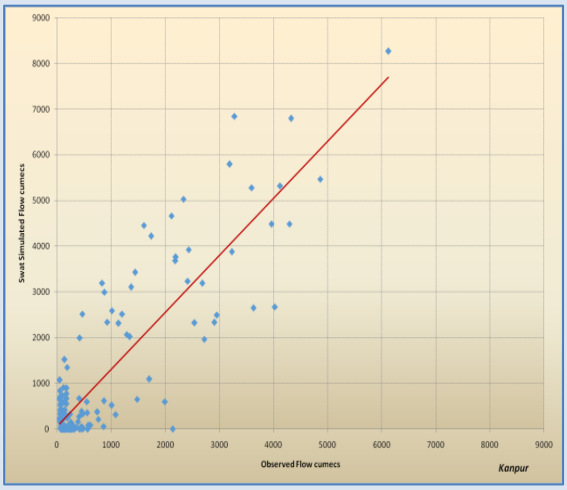
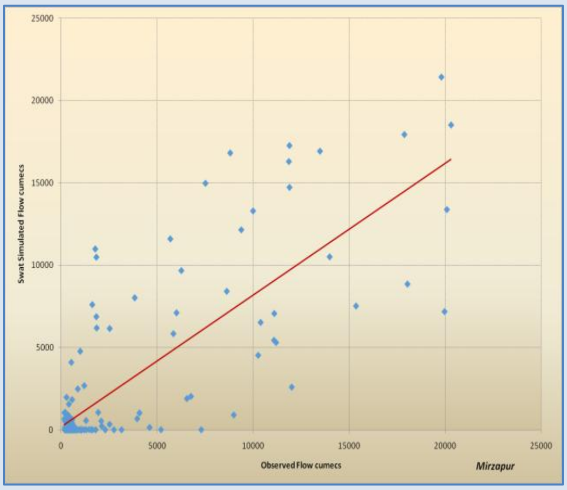
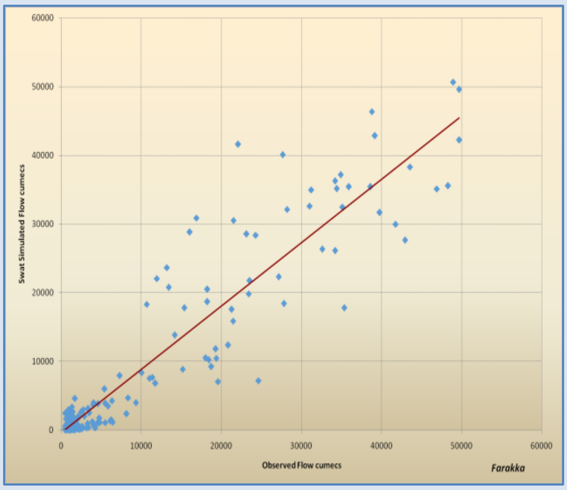


Figure 12: SWAT Calibration Locations for the Ganga river basin

Mirzapur on Ganga river



Farakka on Ganga river

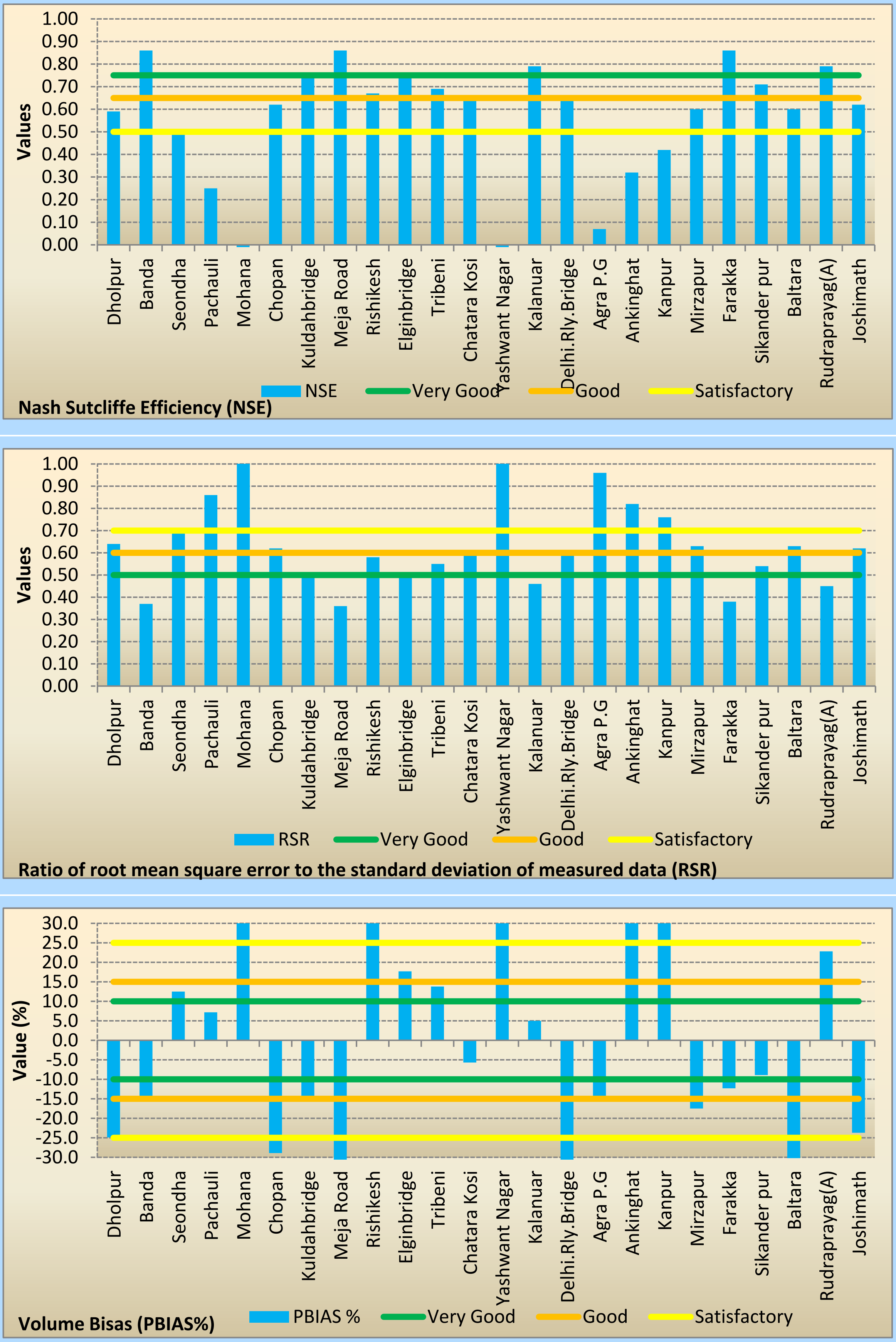


The total period of 37 years of data has been used for calibration of the model. Although the overall performance of the model to simulate the Upper Ganga basin which are snow/glacier fed is very good in terms of the performance statistics, the base flow has been simulated very well. This is mainly due to the inadequate information on the snow and glacier data that is mainly responsible for the base flow component in this basin. Similarly, simulation of the monsoon fed tributaries joining from the right side show good simulation barring a few. Inadequate simulations in some cases are also attributed to lack of appropriate information on canal releases, command area and crop management practices.

In the present case, in the absence of the data on snow/glacier depths assumptions made regarding these depths and thus were part of the calibration process. It is very likely that with additional information on snow and glacier and also with better precipitation network in the hilly area the simulation performance shall further improve in the snowfed part of the basin.

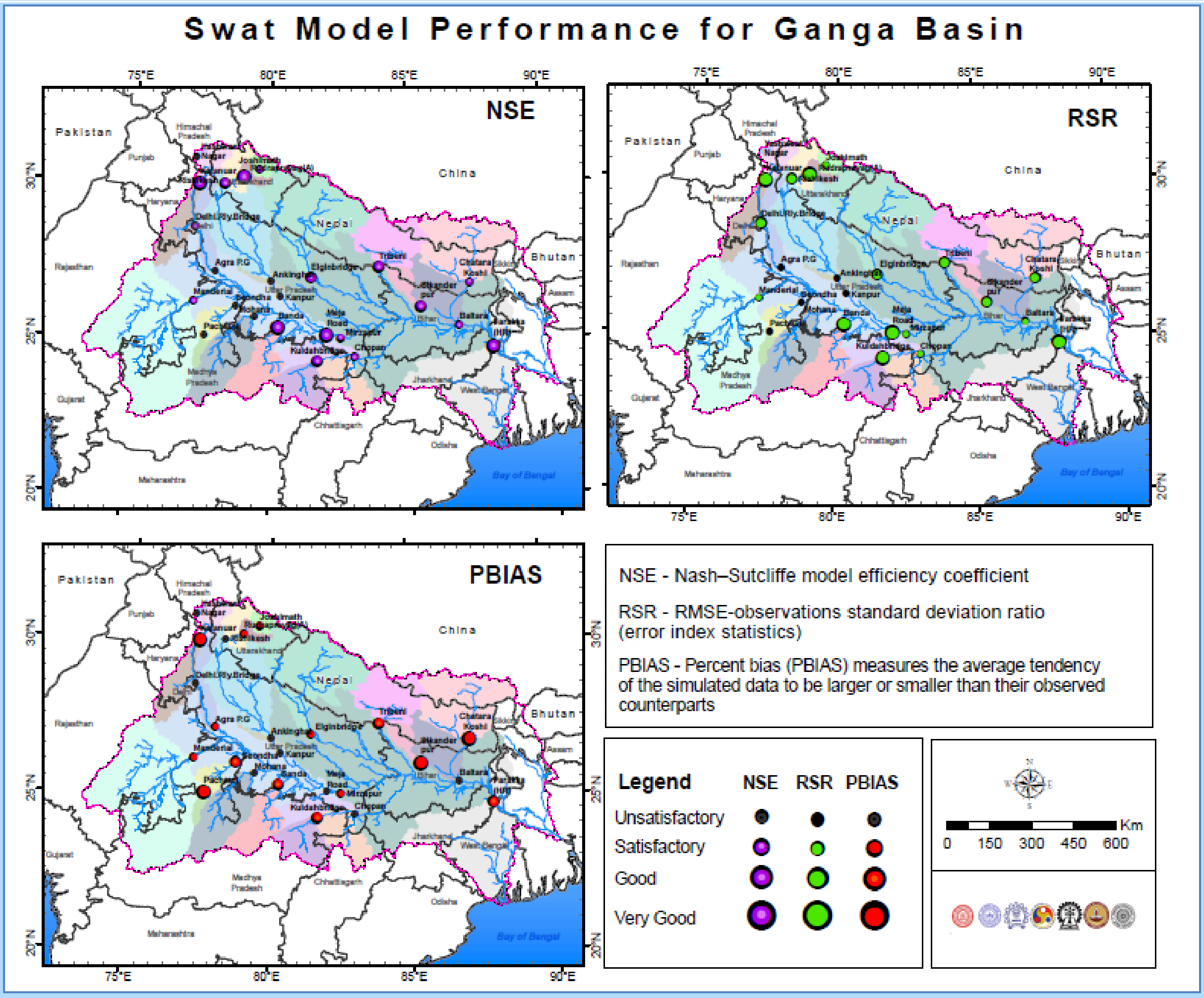
Figure 13 shows graphical representation of these three model performance parameters namely, NSE*(Nash-Sutcliffe efficiency)*, RSR*(ratio of the root mean square error to the standarddeviation of measured data)*and PBIAS*(percent bias)* for various locations in the Ganga basin.

Figure 13: Model performance graph for the Ganga river basin



Characteristics of the 3 model performance parameters has also been depicted for each of the station spatially in a qualitative term in Figure 14.

Figure 14:SWAT Model Performance for the Ganga river basin



Water Balance estimates based on the calibrated SWAT model

Following model setup, the available weather data was used to make simulation runs for a period of 37 years (1969-2006) with 4 years period used as model warm-up period. Manual calibration process has been resorted to for validation of the model.

The model was run on continuous basis at daily interval for all the sub-basins the Ganga. 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 used for analyses, include:

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

The outputs can be depicted in many ways depending on the focus and requirement. Although detailed outputs for each of the 1038 sub-areas are available, a spatially and temporally aggregated information is presented here for overall understanding of the issues. Figure 15 presents the snapshot long-term variability of the key water balance elements for the whole Ganga river basin as a single unit. These components are expressed in terms of total annual depth of water in mm over the total basin area. In other words, the total water yield is the equivalent depth in mm, of flow past the outlet of the basin on average annual basis. Figure 15 shows the average annual and average seasonal water balance components for the Ganga river basin.

Water Yield is composed of surface runoff, lateral flow and groundwater contribution to the stream flow. Adding up of the subcomponents of the water balance provided in the tables should be avoided since groundwater recharge is the total recharge contributing to the lateral flow and the deep percolation and also the carryover storage shall also have an impact.

Figure 15: Annual and seasonal water balance components for the Ganga river basin

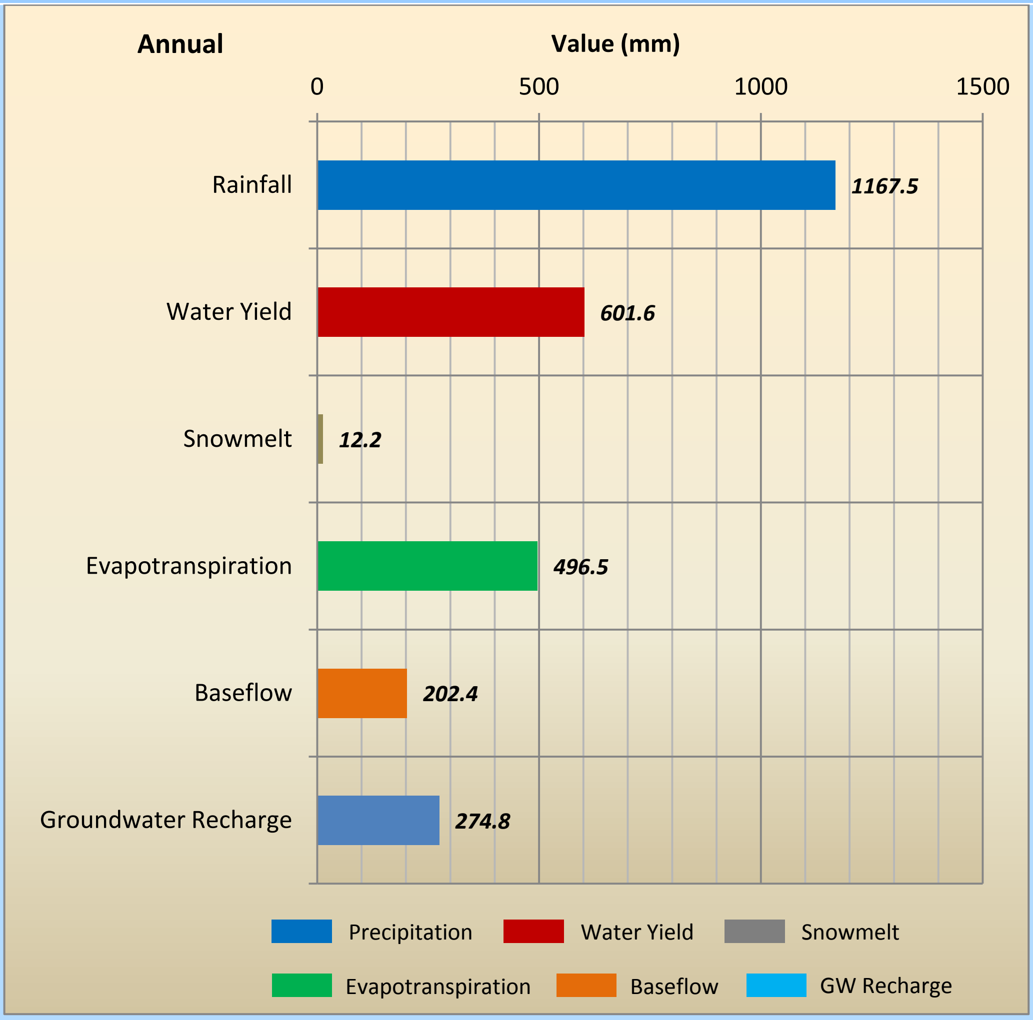
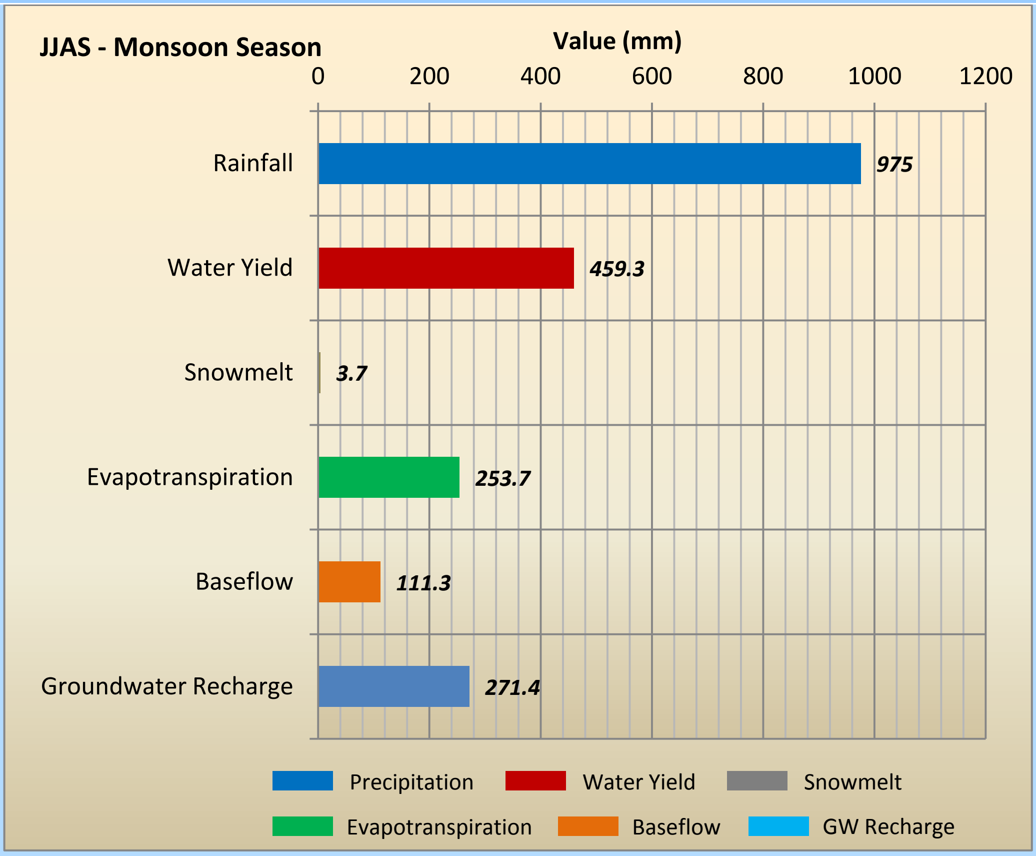
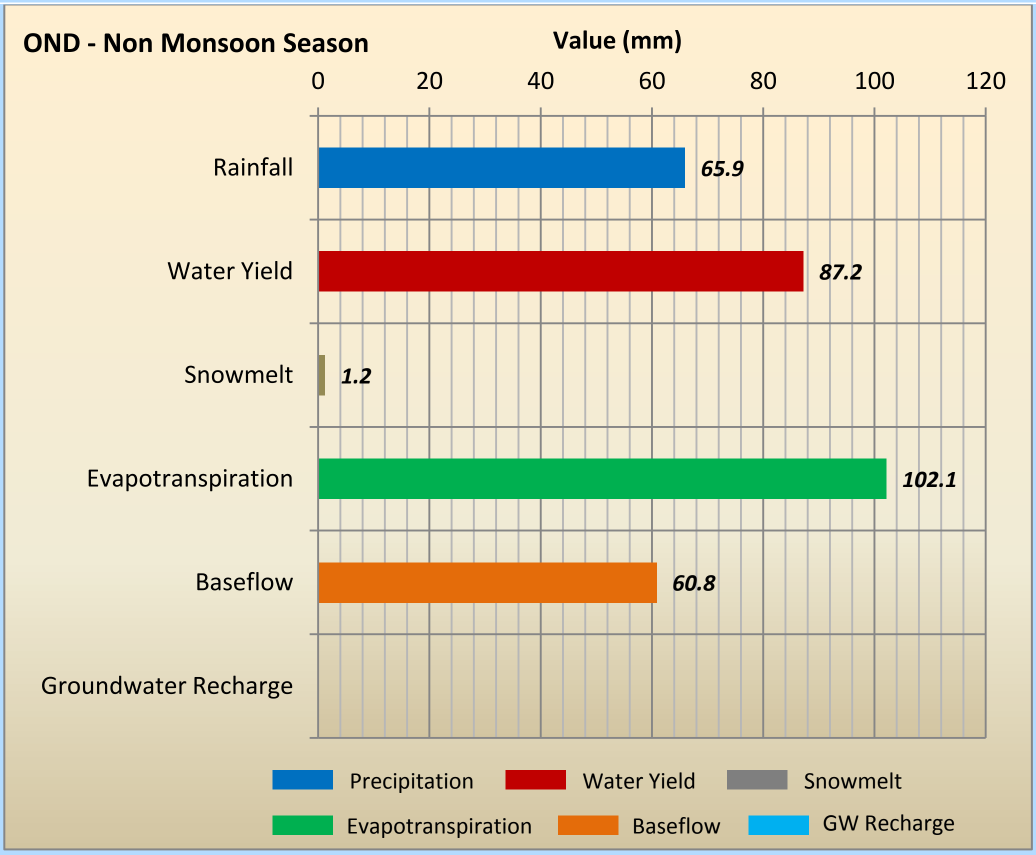


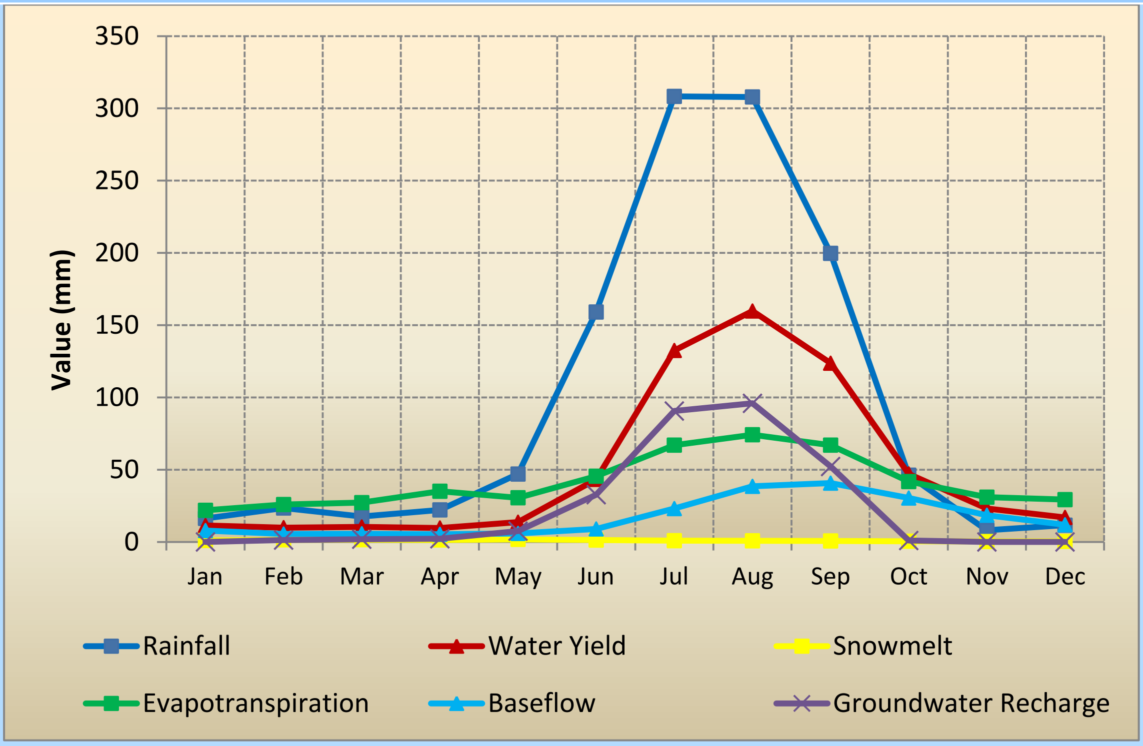
Figure 15: Annual and seasonal water balance components for the Ganga river basin





Long-term monthly distribution of the major water balance components is shown in Figure 16.

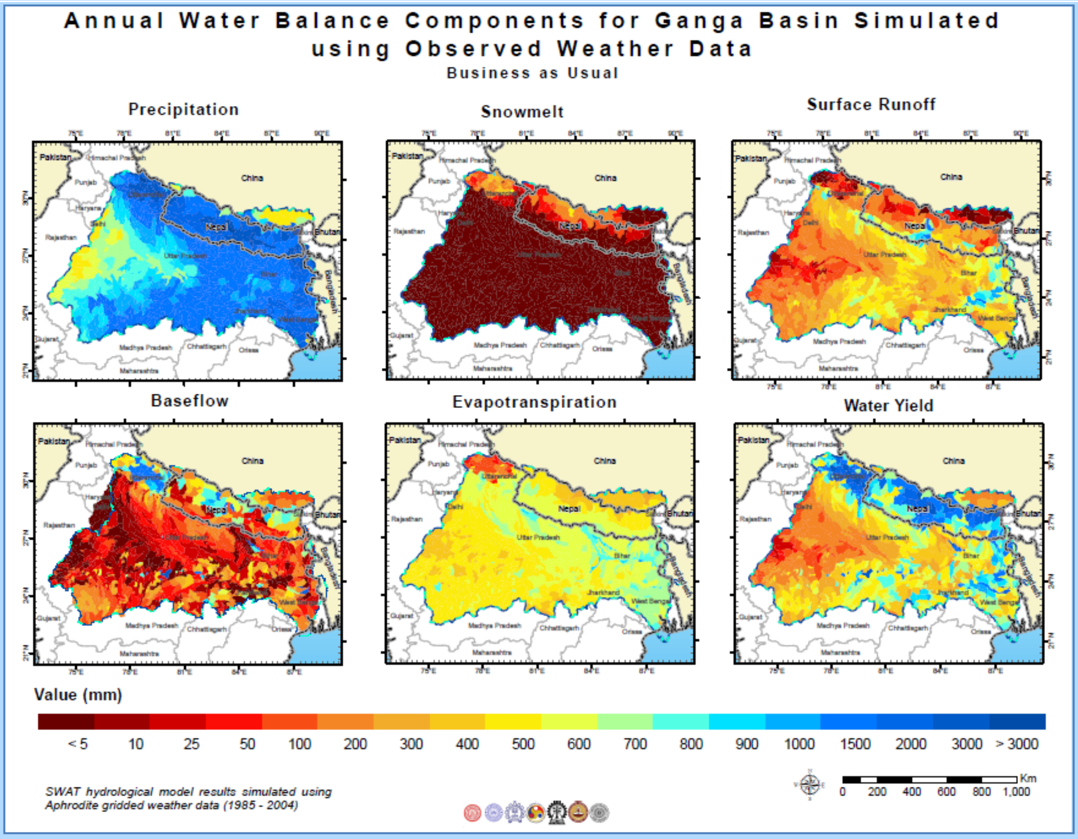
Figure 16: Long-term Monthly water balance componentsforthe Ganga river basin



The precipitation varies both spatially and temporally. The average annual precipitation shown in Figure 17, ranges from less than 600 mm per year in the Chambal basins and some of the rain shadow regions of Himalayas to over 4000 mm per year in the Kosi and Gandak basins. The average annual rainfall for the entire basin is about 1168 mm. The general spatial trend is that rainfall increases from west to east of the Ganga river basin. The major part of the rainfall occurs during monsoon months of June, July, August and September and ranges from 225 mm to 3045 mm in these 4 months. Winter rain (October, November and December) ranges from 7 mm to 415 mm. It can be seen from the figure that during monsoon months of June through September the rainfall is higher than the evapotranspiration requirement and able to meet most of the crop water requirements. However during non-monsoon months, the evapotranspiration is higher than rainfall, suggesting the required additional water has been either diverted through storage or shallow/deep aquifer withdrawal to meet the crop production demand.

In addition to precipitation, the spatial variation of other key water balance components derived through the simulation process namely, snowmelt, surface runoff, baseflow, evapotranspiration and water yield has also been depicted in Figure 17 for annual, monsoon and non-monsoon periods.

Figure 17: Spatial distribution of Annual and seasonal water balance componentsforthe Ganga river basin



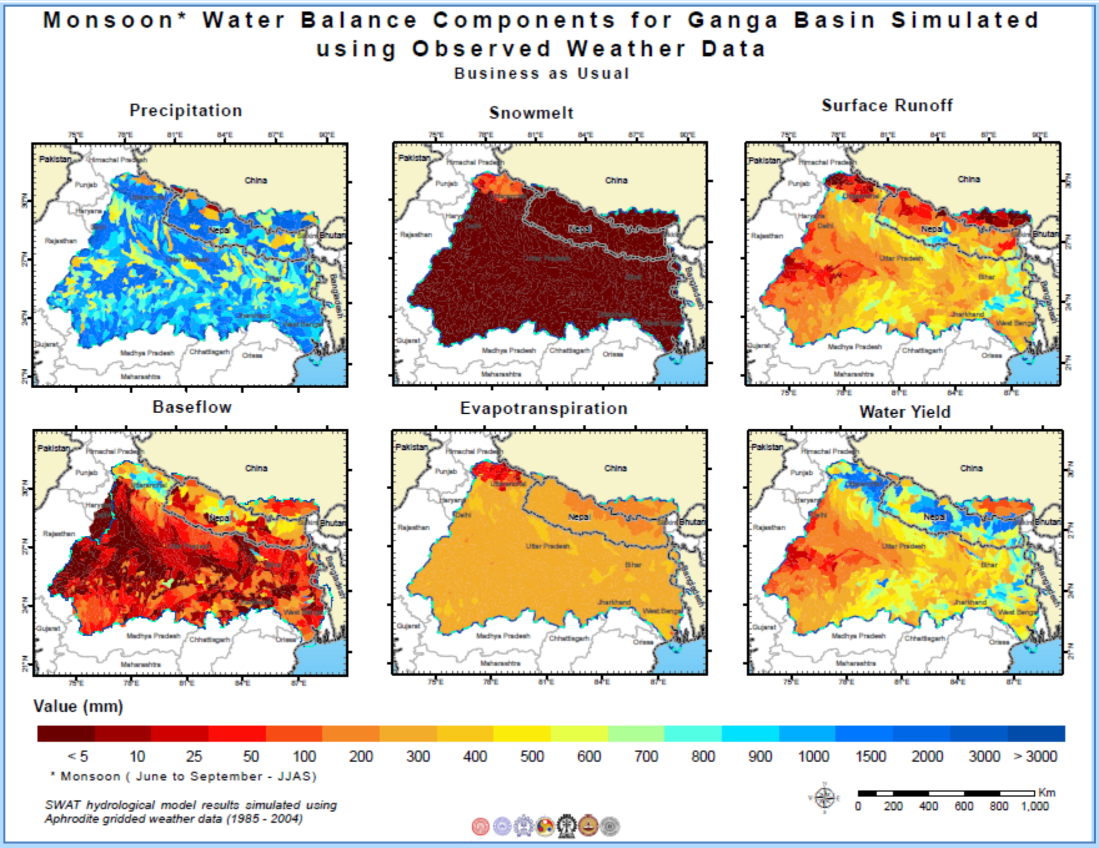
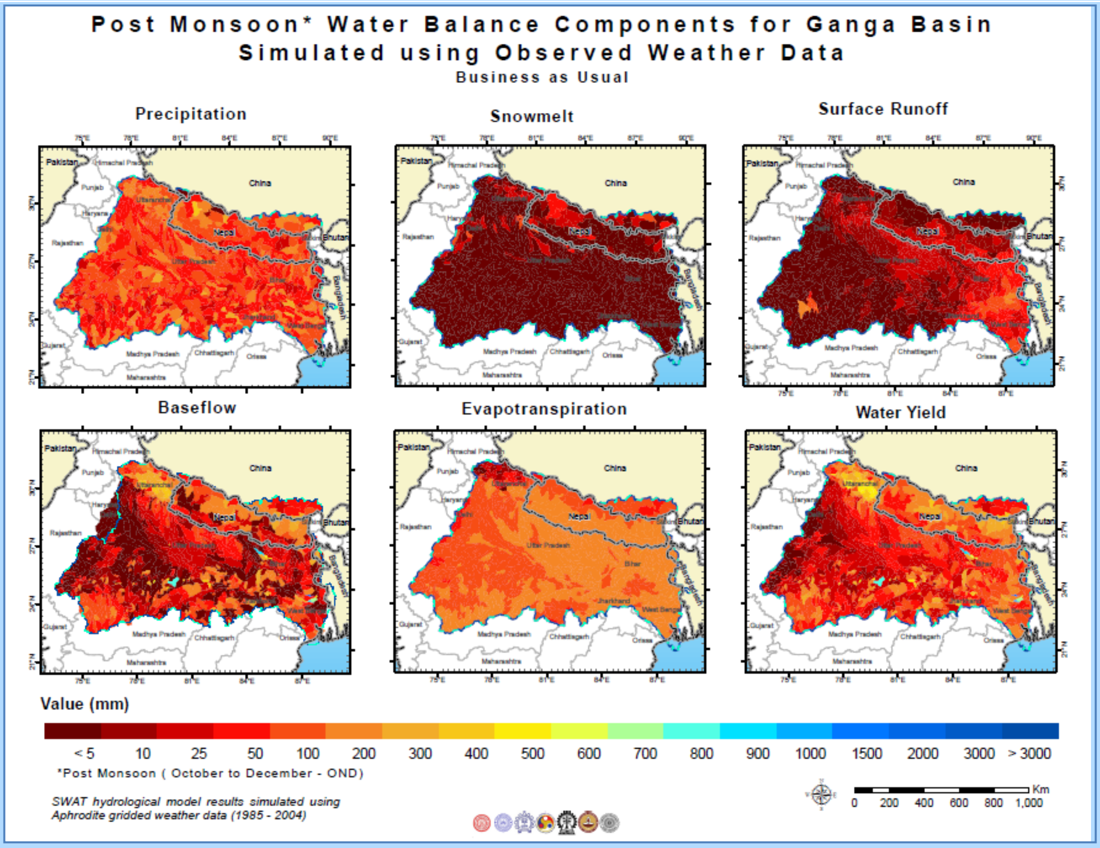


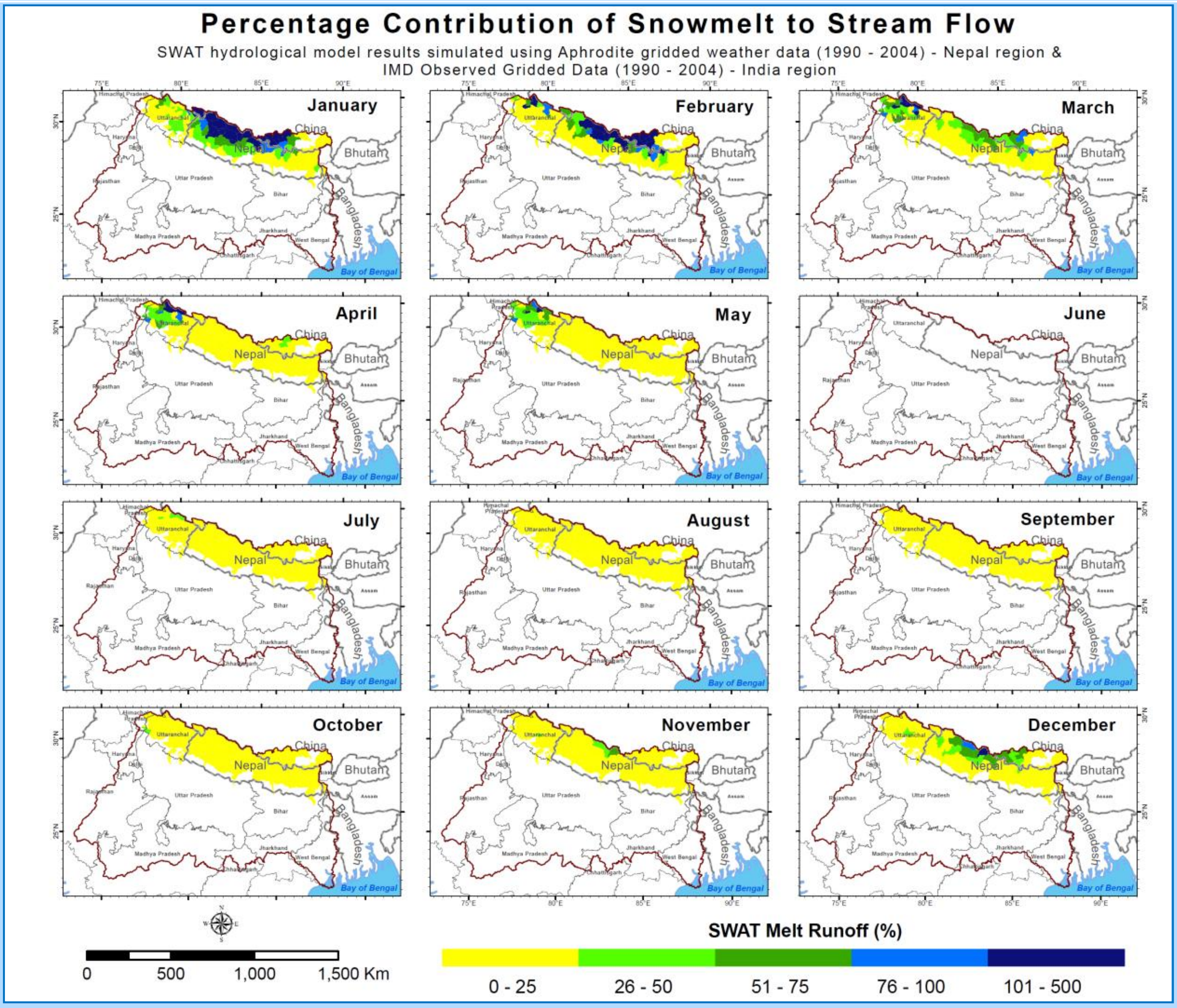
Figure 17: Spatial distribution of Annual and seasonal water balance componentsforthe Ganga river basin



It is desirable to mention that it was very tricky to simulate the snowmelt in the absence of required observed data. SWAT model simulates snow hydrology and the model is capable of using elevation band to adjust the temperature and rainfall as the altitude changes. In the Ganga river basin the elevation range from 2000m to 8000 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 -2^{o}C/km to -6.5^{o}C/km raise was used as temperature lapse rate and 50 to 100 mm/km increase was used as precipitation lapse rate for those subbasin where the elevation bands were incorporated. These correction factors are necessary to account for 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 a glacier depth of 100 m for altitudes about 4500 m elevation has been assumed. The model provides the changing glacier depth over time on account of loss/gain of glacier due to climatic factors.

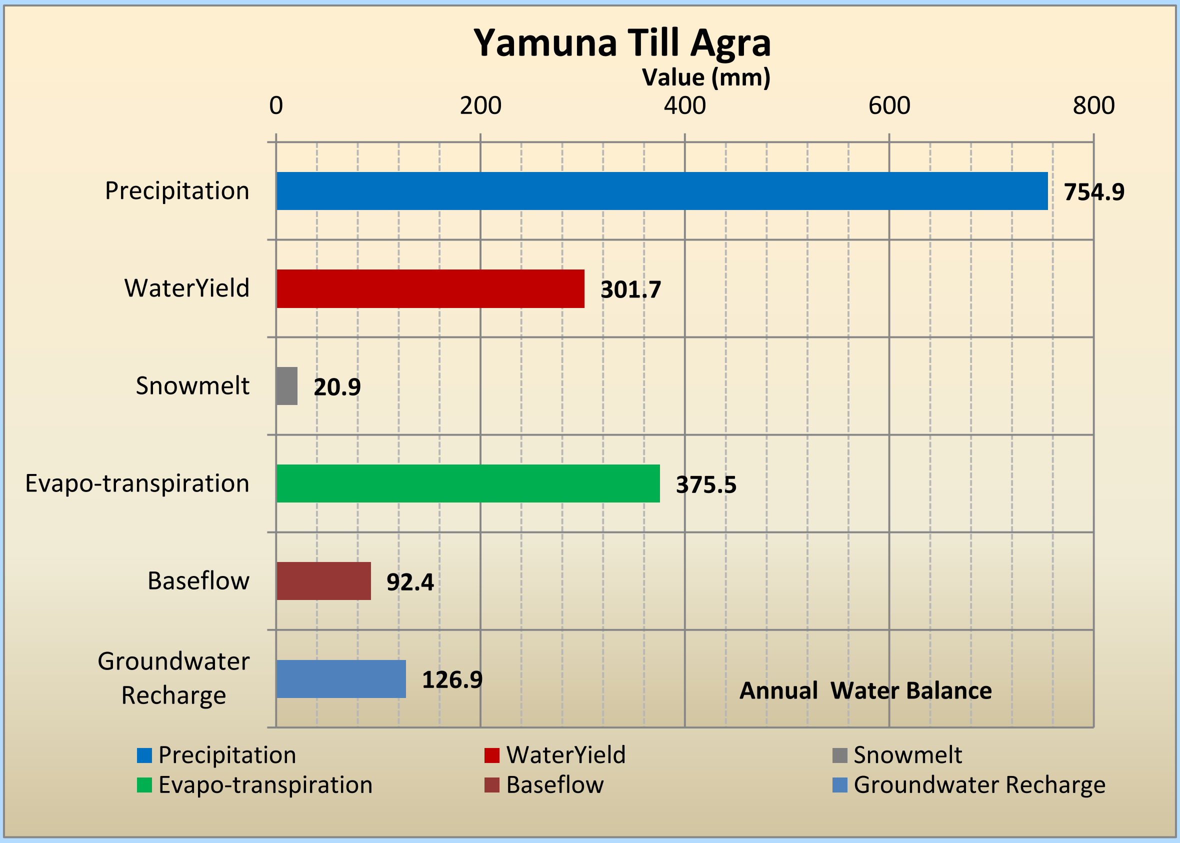
Mean monthly contribution of the snowmelt to the stream flow as percentage is shown in Figure 18. It can be seen that the maximum melt contribution occur during the summer months.

Figure 18: Spatial distribution of contribution of snowmelt to stream flow for the Ganga river basin



The water balance components of the major sub-basins of the entire Ganga basin are given in Figure 19.

Figure 19: Annual water balance components for major tributaries of the Ganga river basin



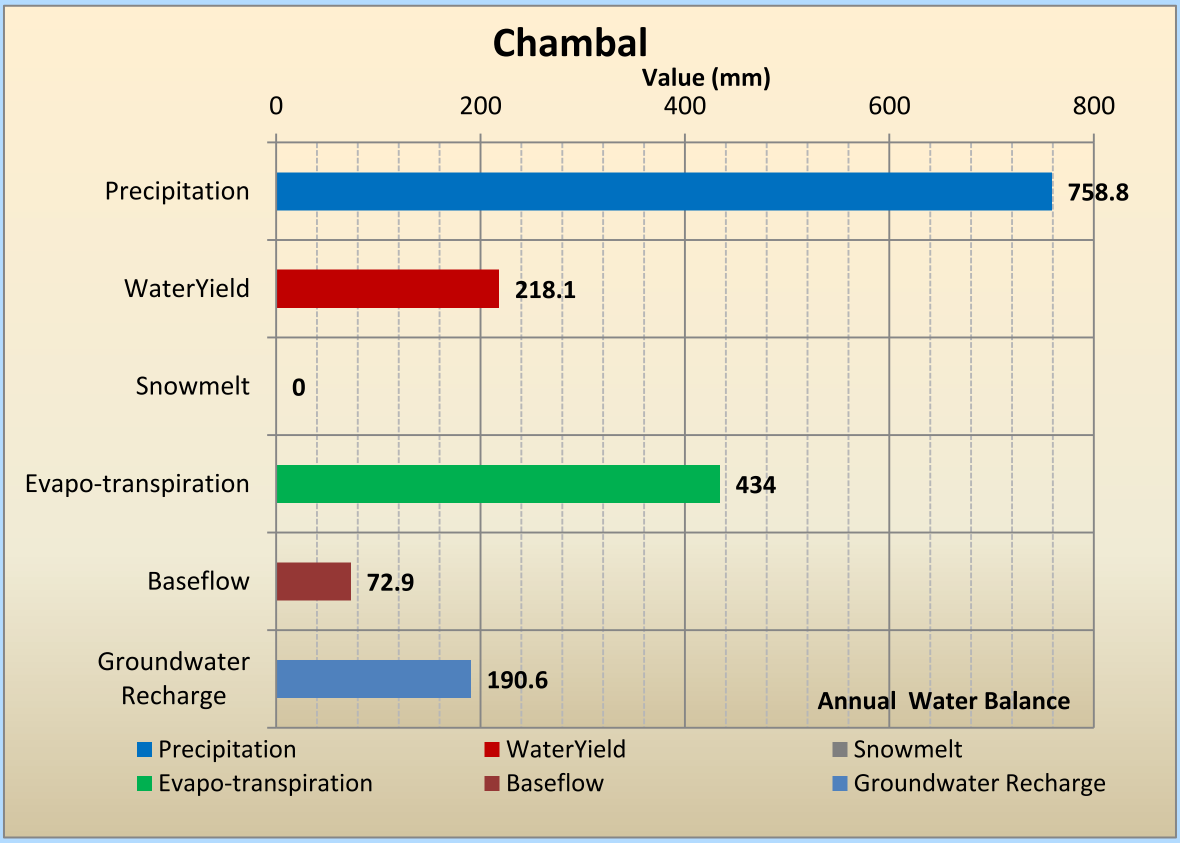


Figure 19: Annual water balance components for major tributaries of the Ganga river basin

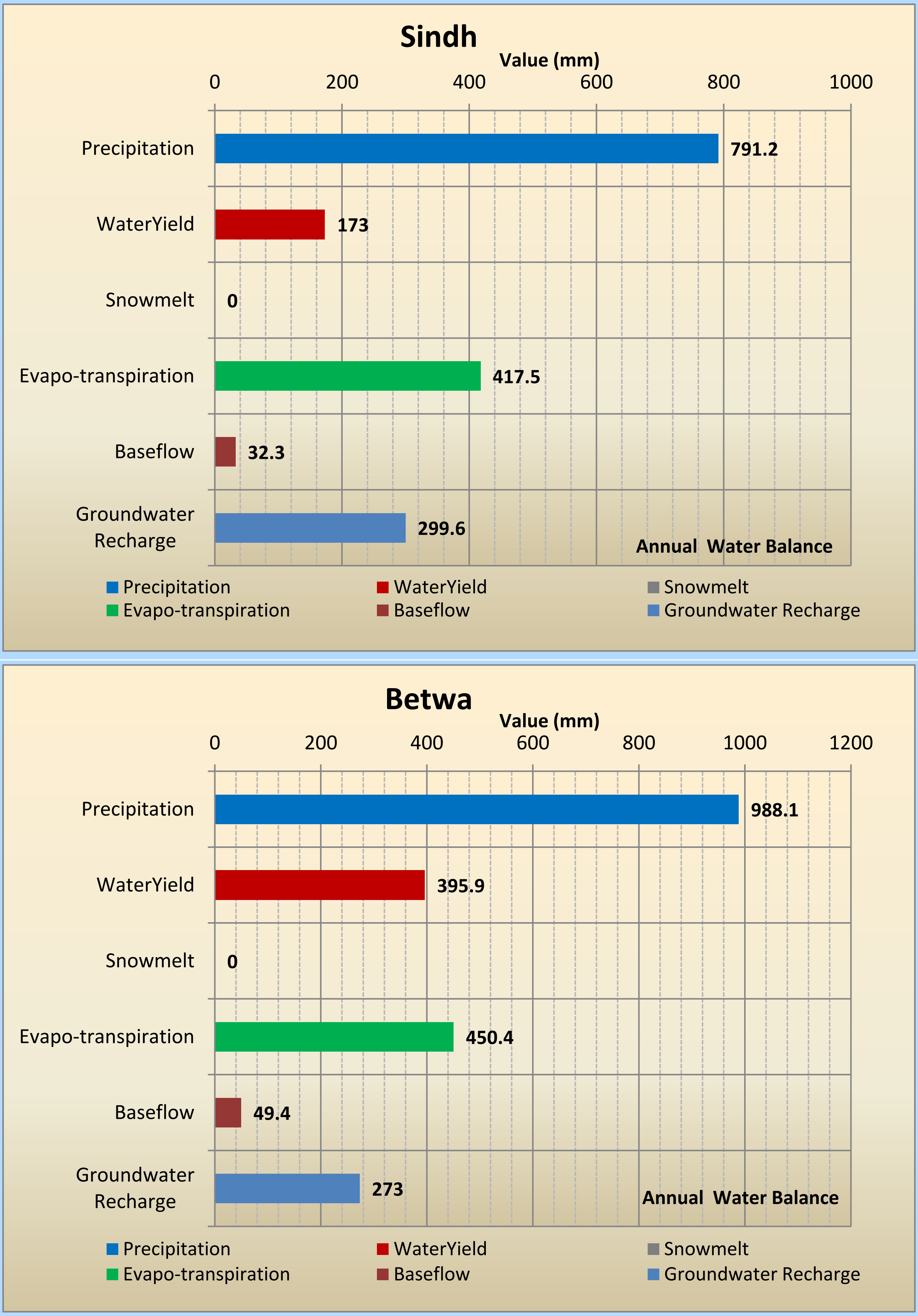
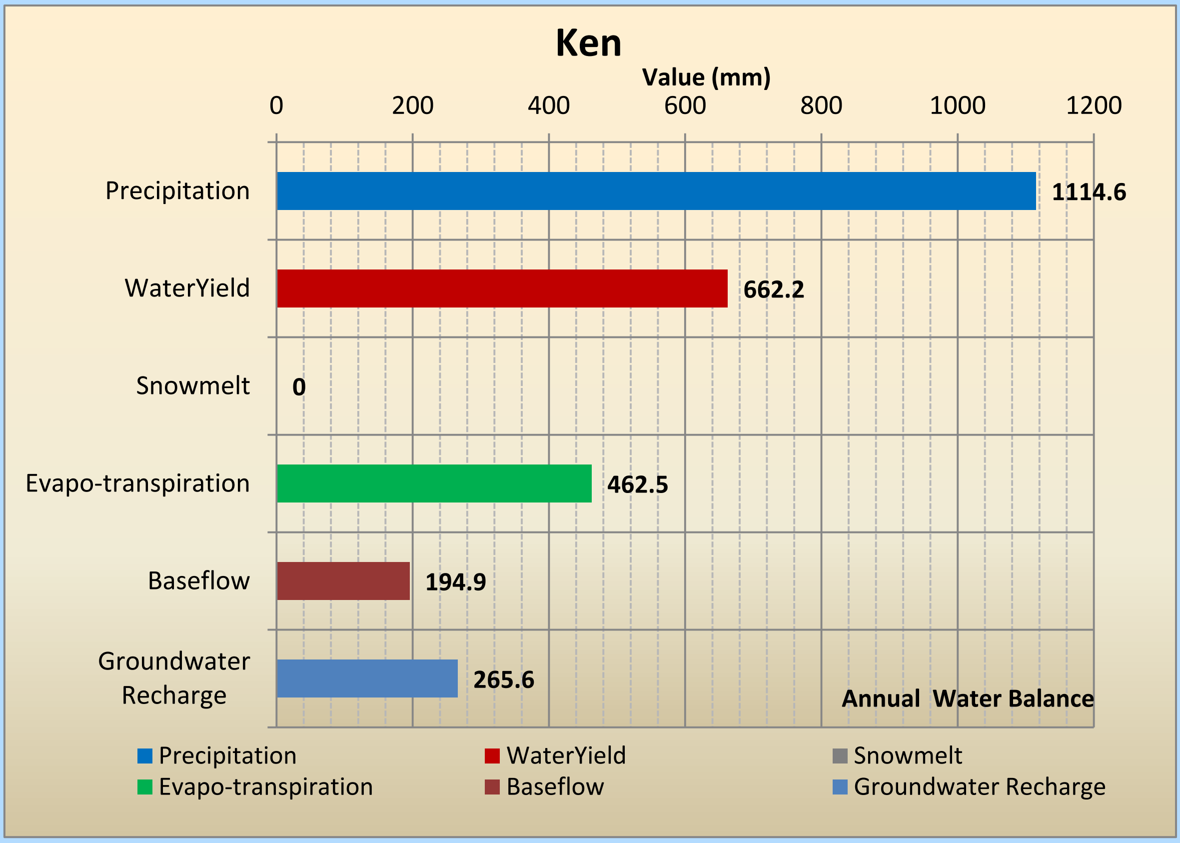


Figure 19: Annual water balance components for major tributaries of the Ganga river basin



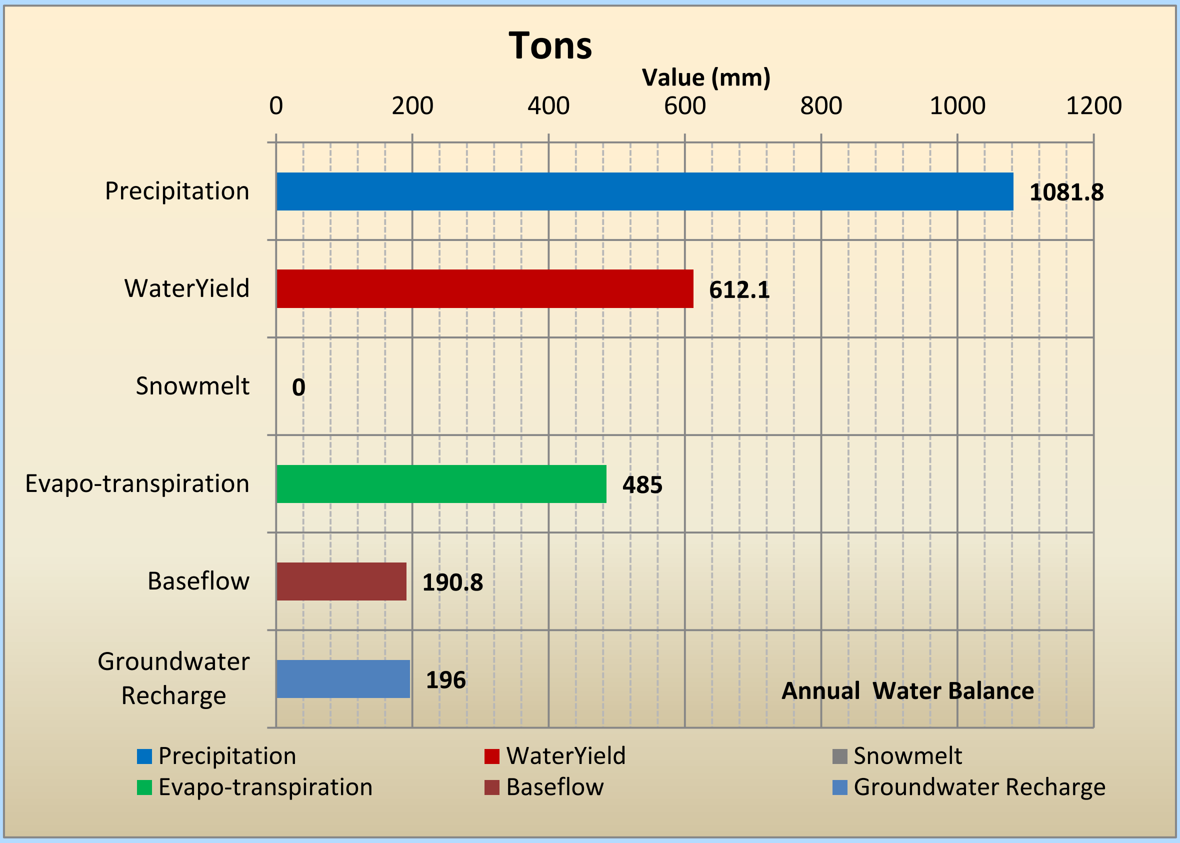
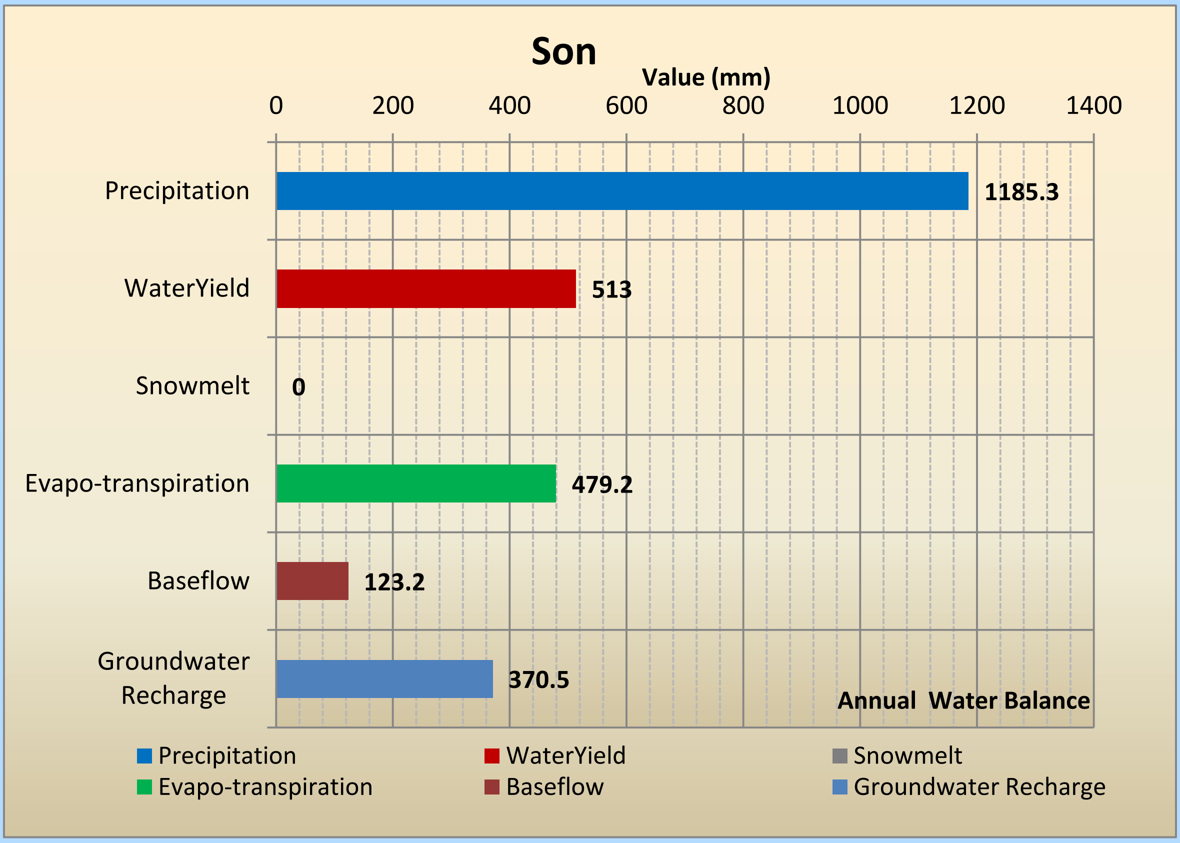


Figure 19: Annual water balance components for major tributaries of the Ganga river basin



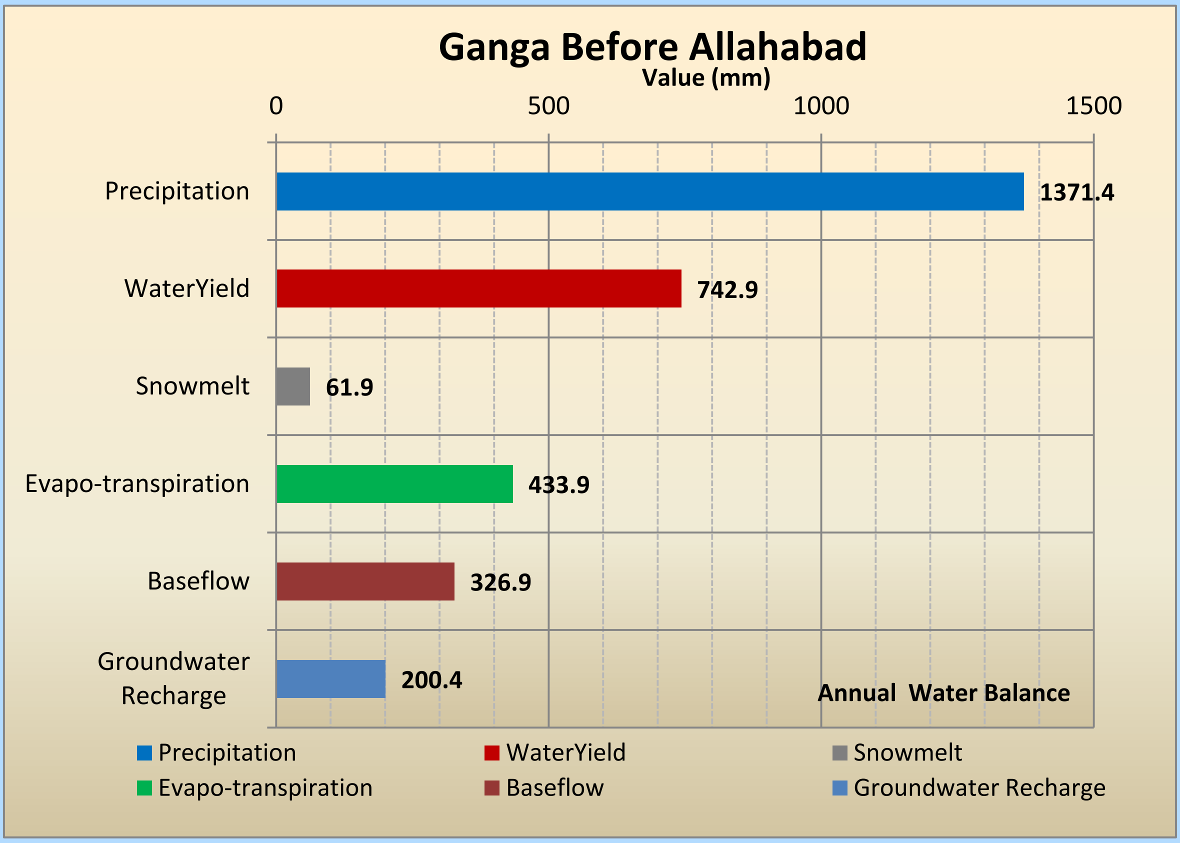
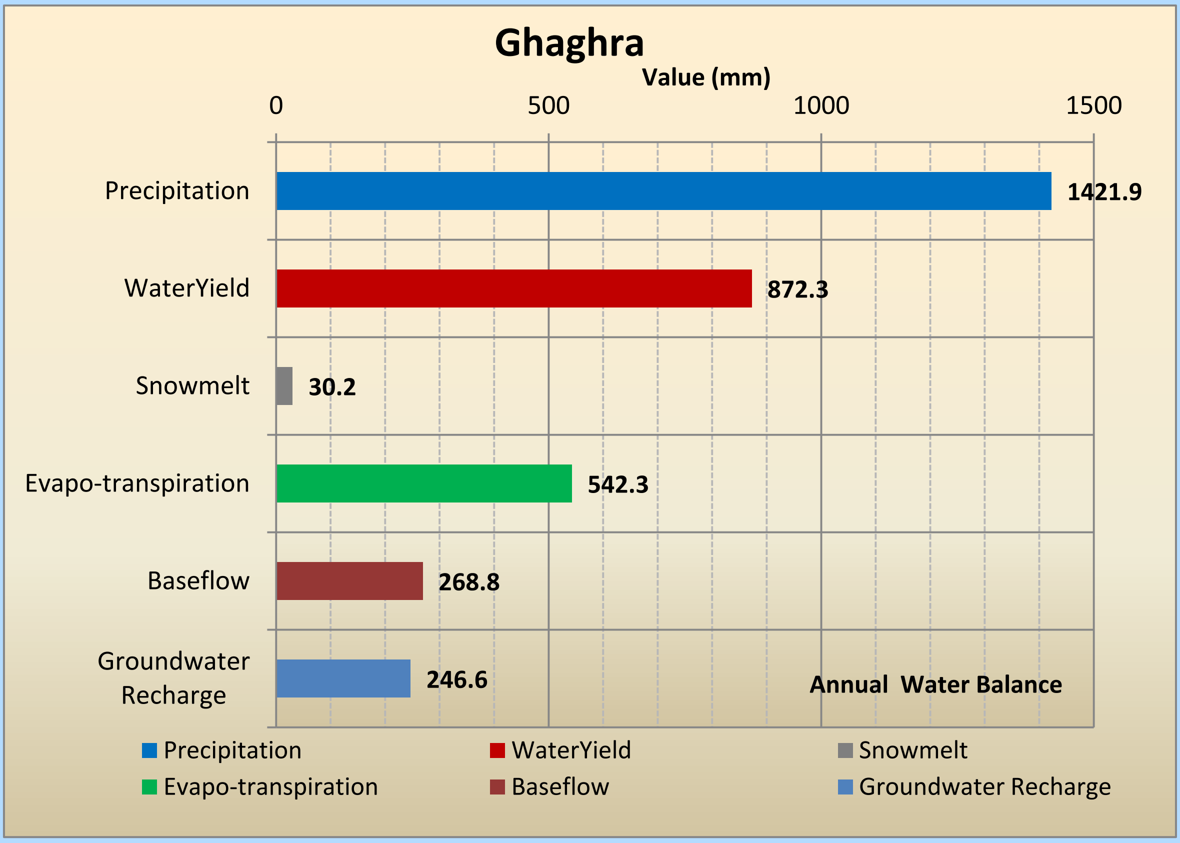


Figure 19: Annual water balance components for major tributaries of the Ganga river basin



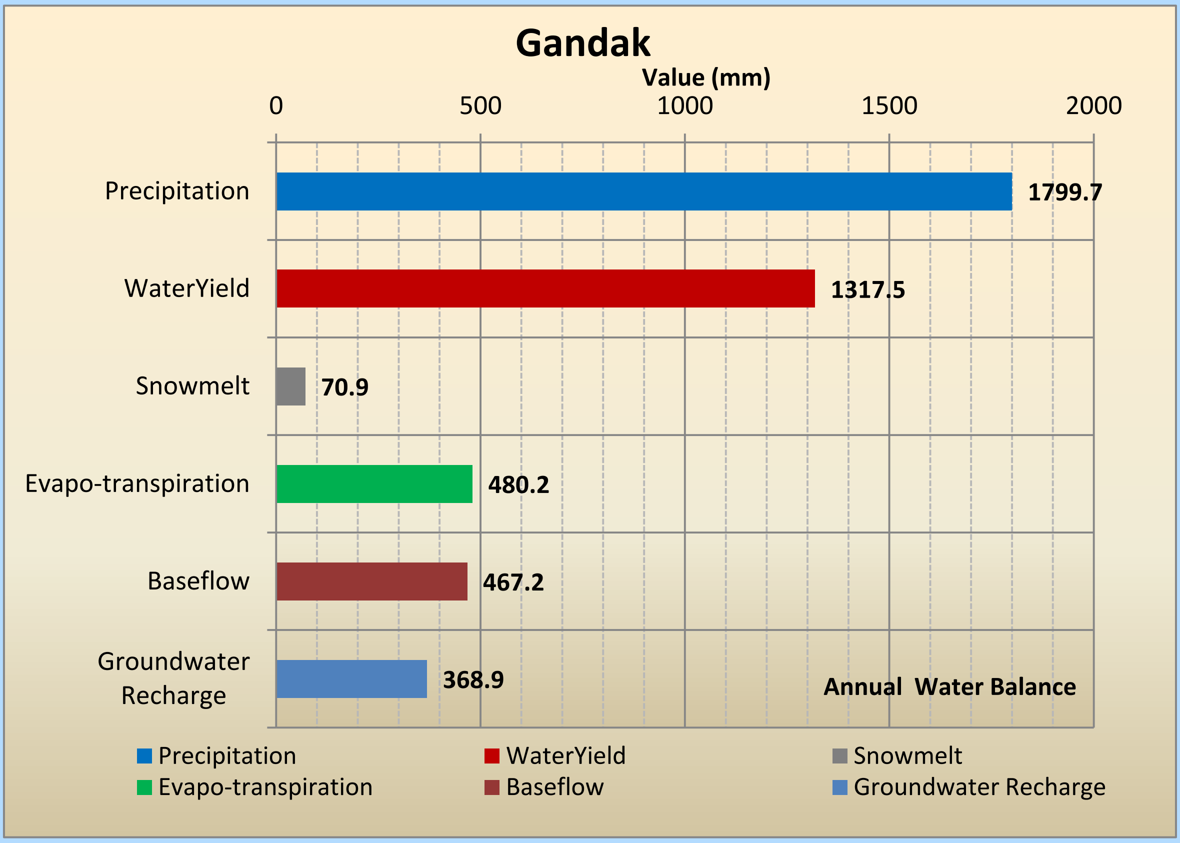
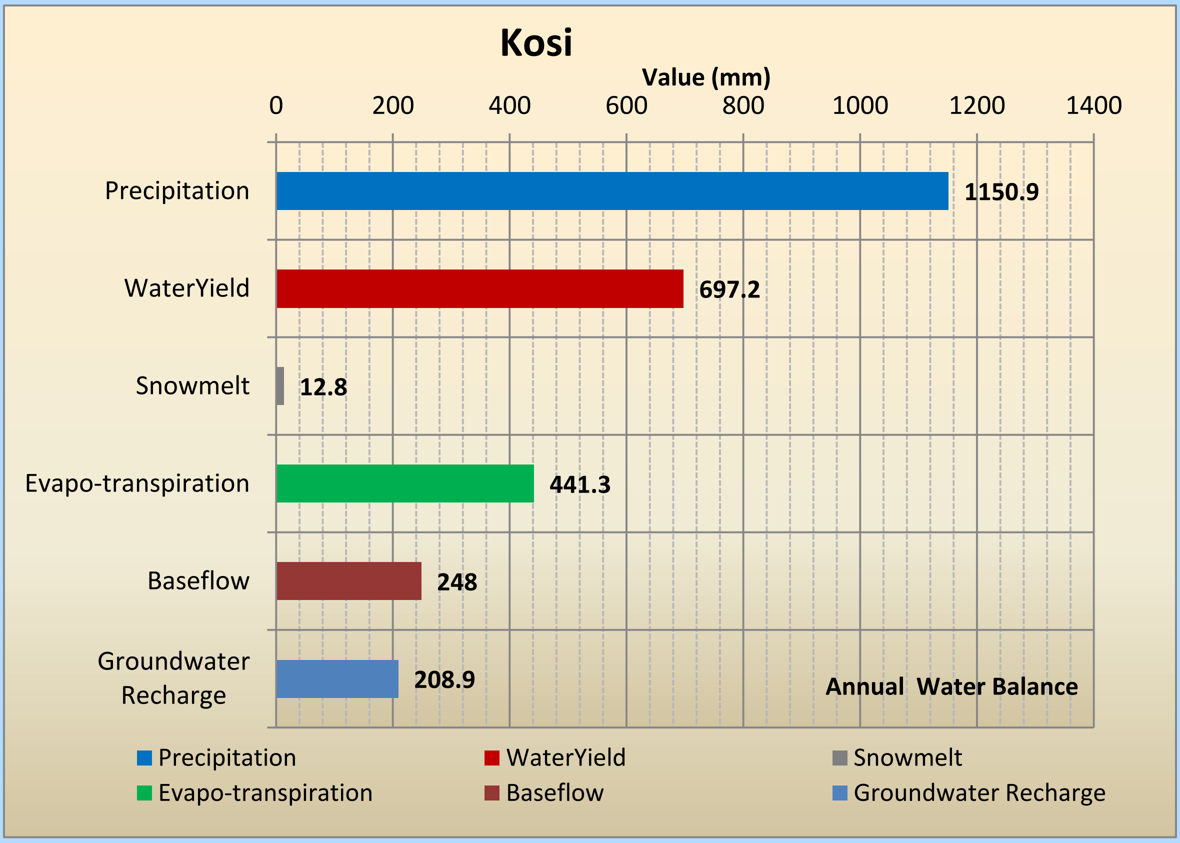


Figure 19: Annual water balance components for major tributaries of the Ganga river basin

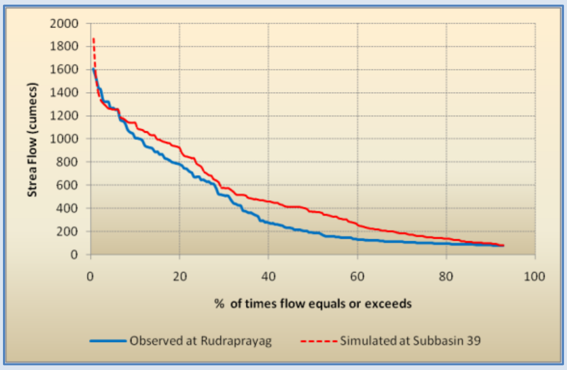


Flow Duration Curve and Flow Dependability

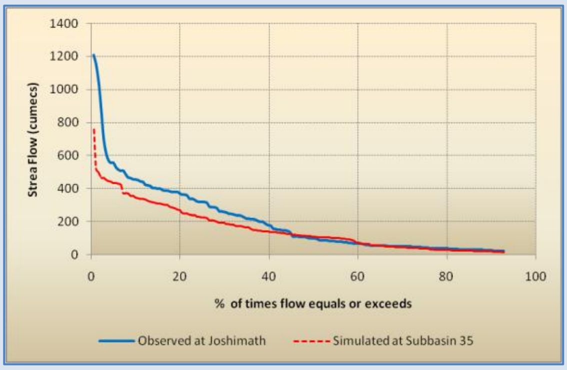
Assessment of dependable lean season flows along with their distribution in time is essential for planning and development of water supply schemes. The dependability of the water yield of the river system has been analyzed with respect to three levels of 50, 75 and 90% dependability. 90% probability level is considered safe for determining assured water supply. Figure 20shows the flow duration curves using the observed and simulated flows at locations where flow dependability is assessed. It may be observed that there are some stations where the simulation has not been good due to the absence of data on the utilization of water that could not be obtained from the states despite best of the efforts and instead proxies were used to simulate the prevailing conditions.

Figure 20: Flow Duration Curve at selected Locations for the Ganga river basin

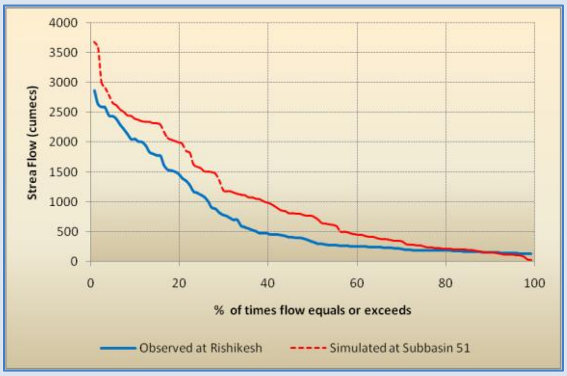
Rudraprayag on Alaknanda (Ganga/Alaknanda)



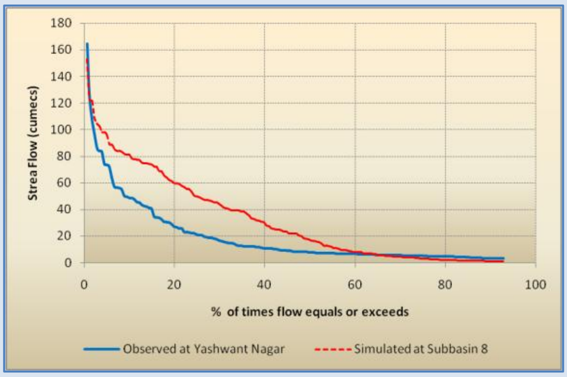
Joshimath on Alaknanda (Ganga/Alaknanda) river



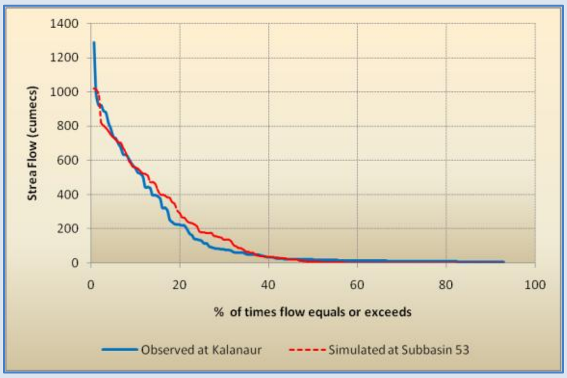
Rishikesh on Ganga river



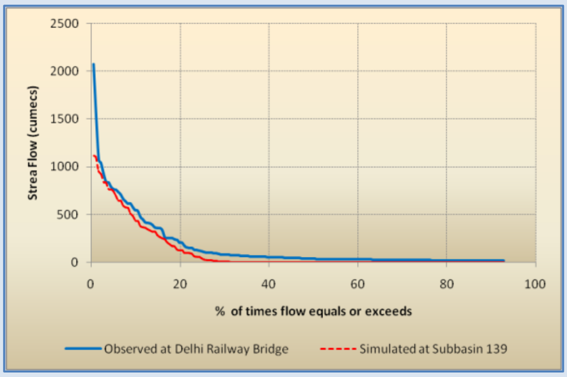
Yashwant Nagar on Giri (Yamuna/Giri) river



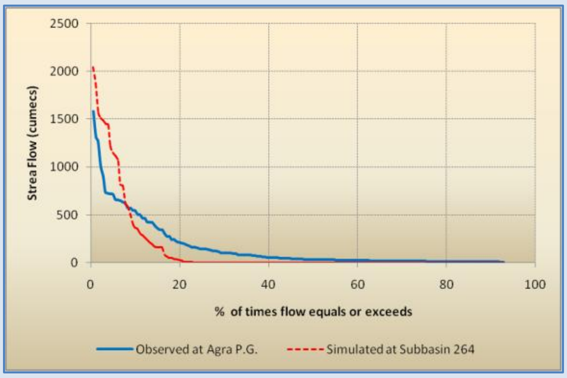
Kalanaur on Yamuna (Ganga/Yamuna) river



Delhi Rly Bridge on Yamuna (Ganga/Yamuna)



Agra P.G. on Yamuna (Ganga/Yamuna) river



Dholpur on Chambal (Yamuna/Chambal)

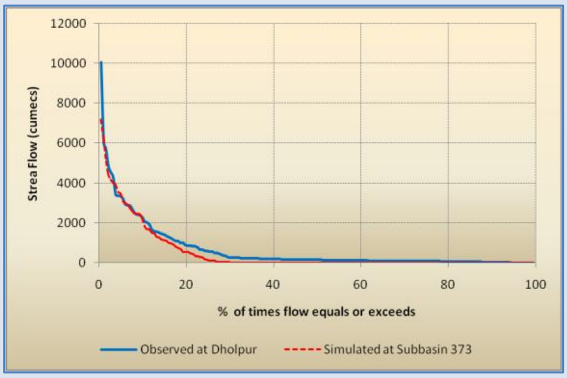
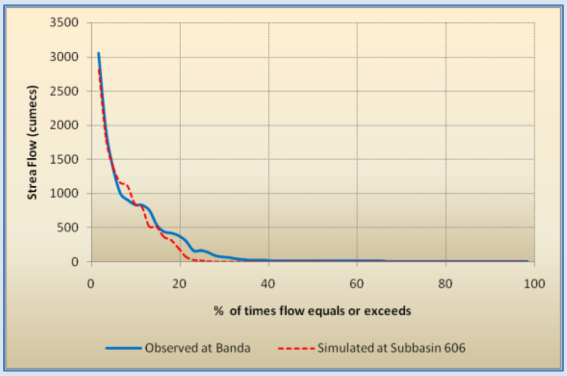
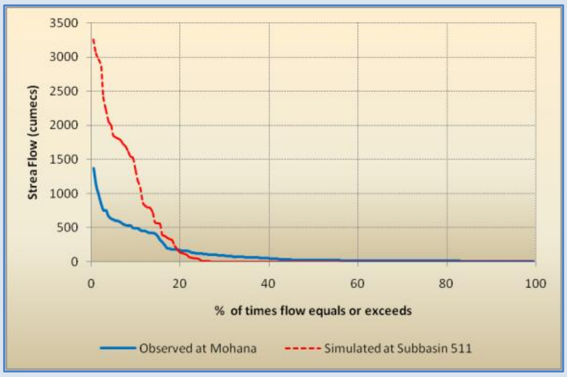


Figure 20: Flow Duration Curve at selected Locations for the Ganga river basin

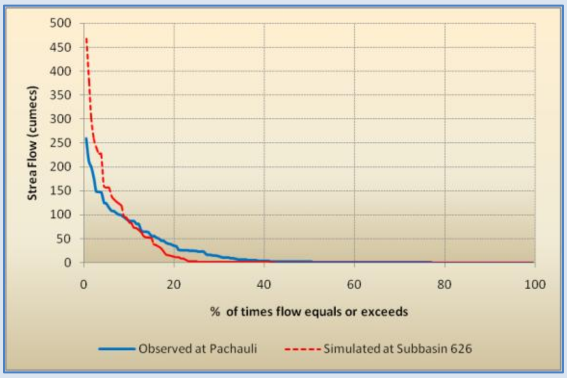
Banda on Ken (Ganga/Yamuna/Ken) river



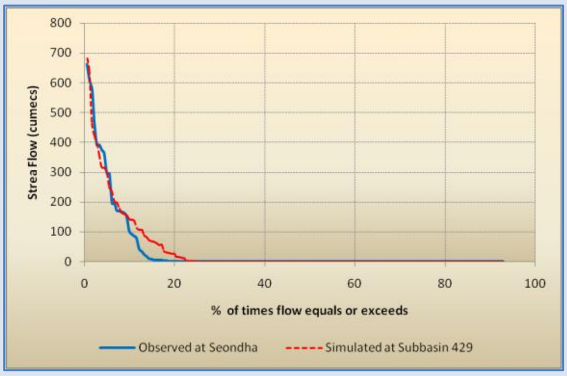
Mohana on Betwa (Ganga/Yamuna/Betwa)



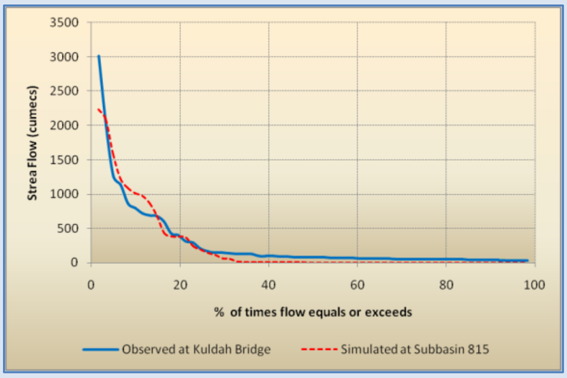
Pachauli on Sind (Ganga/Yamuna/Sind) river



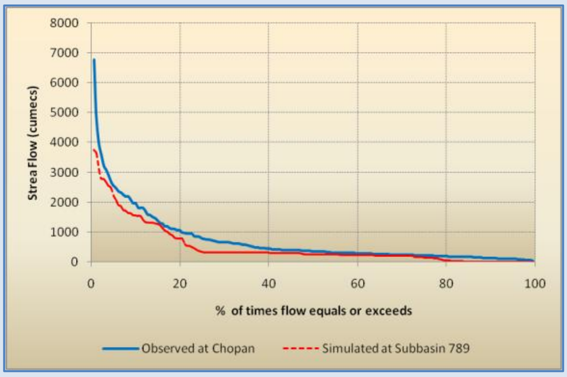
Seondha on Sone (Ganga/Yamuna/Sind) river



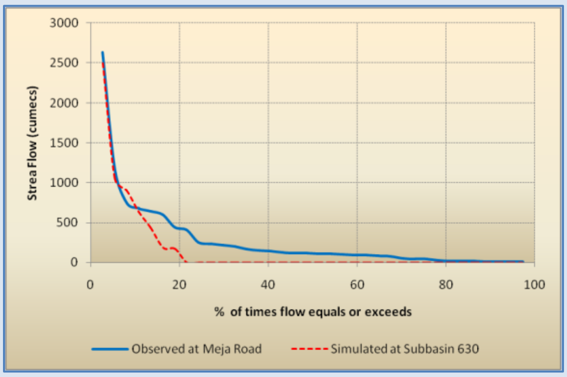
Kuldahbridge on Sind (Ganga/Sone) river



Chopan on Sind (Ganga/Sone) river



Meja Road on Tons (Ganga/Tons) river



Elginbridge on Ghagra (Ganga/Ghagra) river

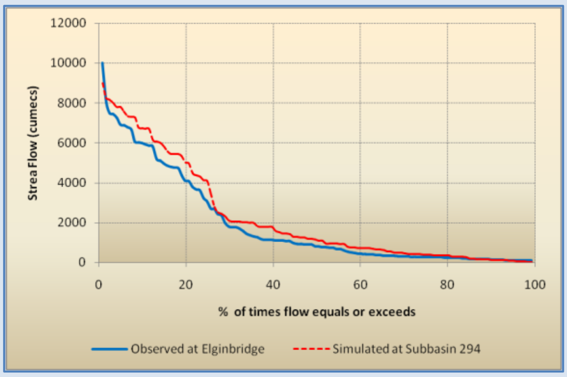
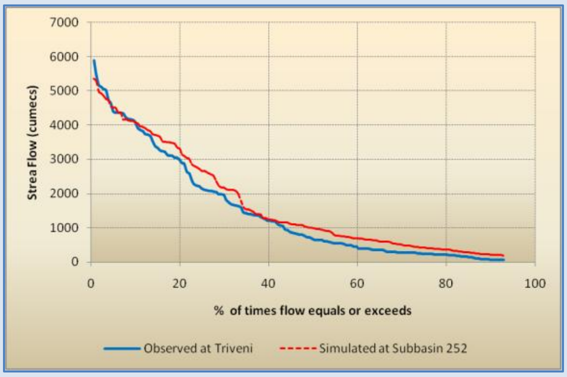
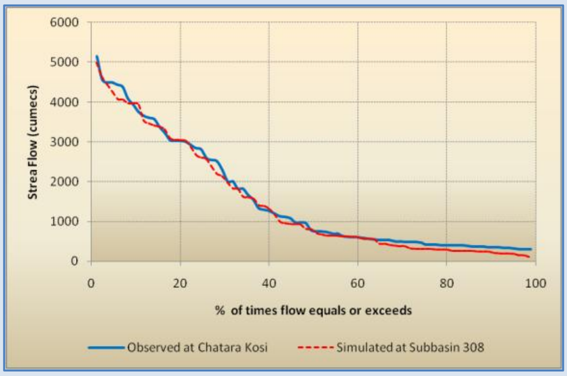


Figure 20: Flow Duration Curve at selected Locations for the Ganga river basin

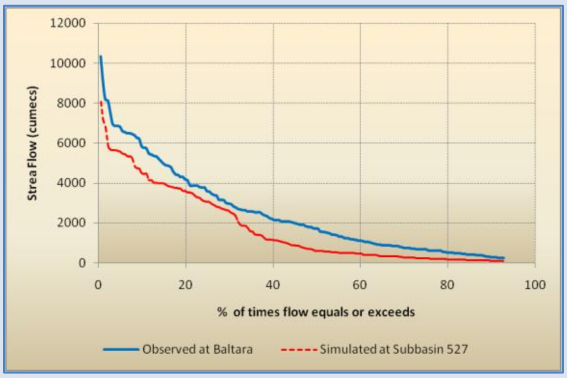
Tribeni on Gandak (Ganga/Gandak) river



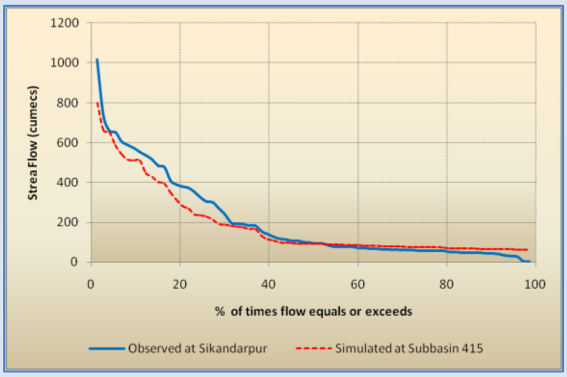
Chatara Kosi on Kosi (Ganga/Kosi) river



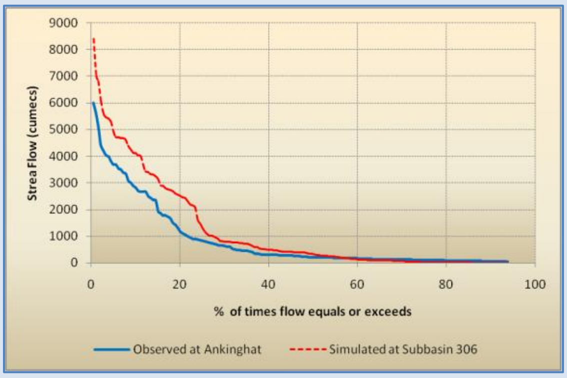
Baltara on Kosi (Ganga/Kosi) river



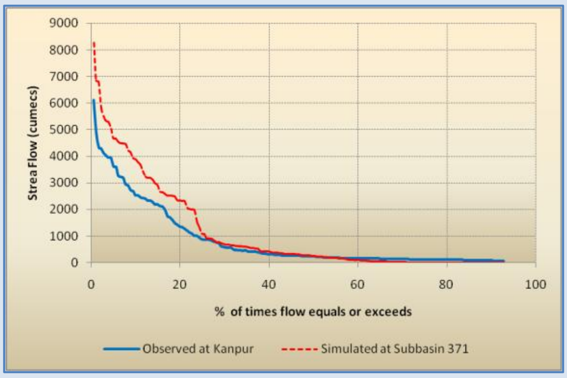
Sikanderpur on Burhi Gandak (Ganga/BurhiG)



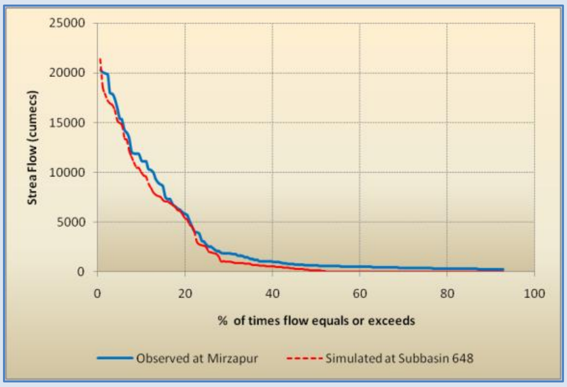
Ankinghat on Ganga river



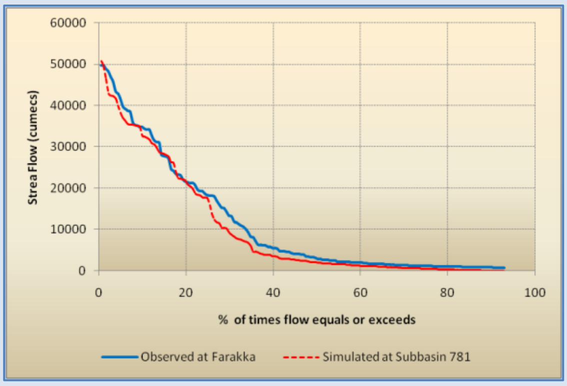
Kanpur on Ganga river



Mirzapur on Ganga river



Farakka on Ganga river



Conclusions

The hydrological model has been set up for the Ganga river basin using the SWAT hydrological model. The model has then been calibrated and validated using the stream flow data made available for various locations in the basin. This process has resulted in the complete understanding of the hydrological dynamics of the whole basin spatially and temporally. The calibrated model shall be used for generating and evaluating various scenarios which can possibly be used for restoring the hydrological health of the basin. The model shall also be used to simulate the virgin flows as were prevalent before the water resources development started in the basin. Such information is very useful for arriving at the environmental flows for various tributaries of River Ganga and their stretches thereof.

Very crucial output such as groundwater recharge has become available on daily basis and also in a distributed manner over the various sub-areas of the basin. This output is of immense value as an input to the next step of performing the groundwater modelling to understand the groundwater dynamics and its interaction with the surface water. Model setup and validation of groundwater modelling of the Ganga basin has been explained in the next section.

Limitations

The following were some of the limitations found while performing the hydrological modelling and were overcome by making appropriate assumptions:

- Absence of precipitation data for higher elevation areas
- Inadequate glacier and snow information for snow hydrology simulation
- About 206 dams/reservoirs are located in the basin, but only 104 structures could be 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 on the basis of irrigated land from landuse information was used as proxy to compute diversions
- 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
- Maps of canal command areas for certain regions were also missing and henceallocations were made by using the landuse information of the area which provided the area under irrigation along with the source of irrigation.

Chapter 3

Groundwater Modelling

Chapter3 - Groundwater Modelling

Introduction

The Ganga basin forms one of the largest ground water reservoirs with occurrence of multi-aquifer system down to depths of 2000m and larger extent falling in northern part of India particularly in UP, Bihar and West Bengal (CGWB,1996)[25]. As requirements of water are growing day by day due to increase in population, industrialisation and urbanisation, groundwater is no longer remaining an infinite replenishable resource. Already, there has been evidence from studies that the groundwater in Northern India is declining (Rodell, 2009)[26]. The groundwater resource in the Ganga basin is becoming scarce due to escalating water demand, acute competition for surface water that limits the overall availability of surface water across sectors and fast declining of ground water levels in upper aquifers. It is thus essential that the basin wise study should be conducted to work out strategies and options for optimal utilisation and to work out overall planning of sustainable development of groundwater resource and its management. It is known that proper assessment of the water potential is an essential requirement for efficient planning and development of water resources. For proper understanding of the system under investigation, groundwater models are developed as an alternative, but greatly simplified, representation of the inherently complex groundwater system. Groundwater models can be classified as physical or mathematical. A physical model (e.g. a sand tank) replicates physical processes, usually on a smaller scale than encountered in the field. A mathematical model describes the physical processes and boundaries of a groundwater system using one or more governing equations. An analytical model makes simplifying assumptions (e.g. properties of the aquifer are considered to be constant in space and time) to enable solution of a given problem. Analytical models are usually solved rapidly, sometimes using a computer, but sometimes by hand. A numerical model divides space and/or time into discrete pieces. Features of the governing equations and boundary conditions (e.g. aquifer geometry, hydro geological properties, pumping rates or sources of solute) can be specified as varying over space and time. This enables more complex, and potentially more realistic, representation of a groundwater system than could be achieved with an analytical model. Numerical models are usually solved by a computer and are usually computationally more demanding than analytical models. In this study, a numerical model has been developed for the Ganga basin for understanding the system and for planning and management of future developments. Visual MODFLOW Classic is used for groundwater modelling purposes.

Background

In most of the hydrogeological studies in alluvial aquifers, water balance studies are carried out using the norms provided by NABARD for evaluation of groundwater resources and thereby deciding its status of utilization. However, these norms are mostly adhoc and based on large number of assumptions (Umat R 2008[27]). Many facts are ignored just to simplify the procedure. For example, boundary flows are often not taken into account which practically implies that the system is always in steady state. Another important factor of exchange between river and aquifer are not considered

[25]Hydrogeology and Deep Groundwater Exploration in Ganga Basin(1996), CGWB, India.

[26]Rodell, M., I. Velicogna, et al. (2009). "Satellite-based estimates of groundwater depletion in India." Nature 460(7258): 999-1002.

[27]Umar R 2008 Groundwater Flow Modeling and Aquifer Vulnerability Assessment studies in Yamuna–Krishni sub-basin, Muzaffarnagar District, Ministry of Water Resources, Government of India (Report)

while this is quite common feature in the Ganga basin. Moreover, the status of utilization can be calculated only for present case and it is not always possible to project it to the future. Therefore, to overcome all these disadvantages and minimizing the error of estimation, the system should be evaluated through aquifer modeling where water balance is established using partial differential equation of groundwater flow and is solved with boundary and initial boundary conditions.

Objectives of the Groundwater Modelling

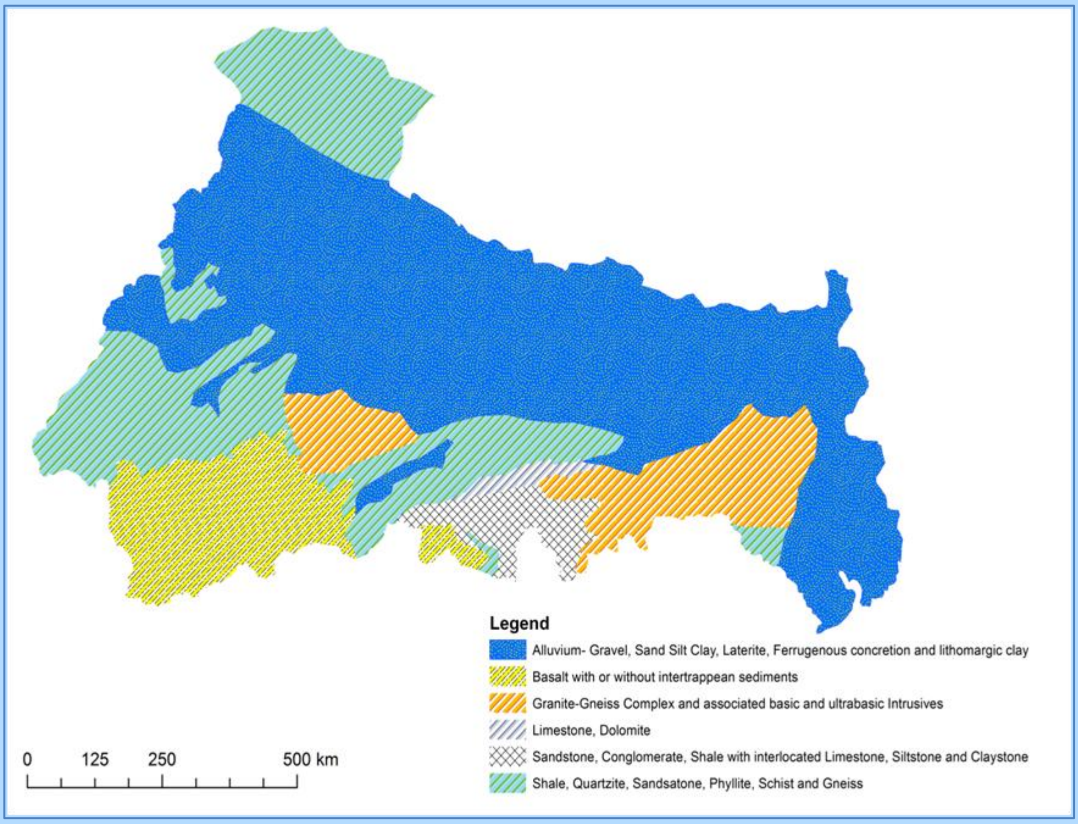
The following objectives are covered under the groundwater modelling:

1. Foster an understanding of the groundwater system of the Ganga River Basin and develop a modelling framework of its dynamic inter-relationship with the overall water cycle of the basin.
2. Develop a consistent water balance of the entire Ganga River Basin.
3. Identify influent and effluent river reaches within the Ganga River System and understand its implications with regard to current groundwater utilization and management practises.
4. Develop groundwater regime response scenarios under various prescribed management practices and understand corresponding implications with regard to sustainable groundwater use across the basin.

Hydrogeology

The hydro-geological conditions prevailing in the entire basin is highly diversified. Figure 21 shows the hydrogeology of the Ganga basin.

Figure 21: Hydrogeology of the Ganga river basin



Based on studies and mode of occurrence of ground water in similar geological formations, nature and extent of aquifer bodies and its hydro geological properties in relation to ground water flow characteristics under prevailing hydrodynamic and hydro chemical conditions, it is possible to broadly generalize the hydro geological framework of the basin. As such there are three categories:

- Area of unconsolidated formations
- Area of semi-consolidated formations.
- Area of consolidated formations.

Unconsolidated formations

The quaternary rocks comprising Recent Alluvium, Older Alluvium and Costal Alluvium at Bay of Bengal are by and large important unconsolidated formations. These sediments are essentially composed of clays, silts, sands, kankar etc. The areas of Haryana and Rajasthan with Aeolian cappings have also been included. Indo-Gangetic plains, Marusthalies, Bengal basin and Foredeep region, from western to eastern Himalayas on the northern flank of the basin, are occupied by these formations. They also occupy inter-montane valleys i.e. Doon Valley of Uttrakhand and Aeolian deposits of Haryana and Rajasthan.

Semi-consolidated formations

These belong to Palaeozoic-Mesozoic and Cenozoic rocks extending from Corboniferous to Mid-Pliocene in age. They mainly consist of shales, sandstones, limestones etc. this group of rocks are generally described as Tertiaries and Mesozoics of UP, West Bengal. Further, the terrestrial fresh water deposits belonging to Gondwana Super Groups of UP, MP, Bihar and West Bengal are also included under this category.

Consolidate formations

The consolidated formations which occupy almost half of the basin have been classified into four broad lithological units:

- Sedimentary and meta-sedimentaries
- Efflusives
- Intrusives
- Basal crytallines, which range in the age from Archaean to Tertiary.

The Sedimentaries and meta-sedimentaries belong to Cainozoic, unclassified Mesozoics belong to Cainozoic, unclassified Mesozoics and include formations from tertiary to upper pre-Cambrian age. These are mainly composed of sandstones, shales, slates, quartizites phyllite, dolomites and limestones. The compact sedimentary formations largely belong to Delhi and Vindhyan Super groups.

The basal crystallines belonging to Lower Pre-cambrian and Archaen age are represented by rocks of gneisses complex of Aravalies, Bundelkhand gneisses, Singhbhum granite and gneisses and Iron-ore formations. The intrusive Cainozoic group are tertiary granites, occurring in the north/west Himalayas. The efflusives are generally basaltic flows, chiefly represented by Dalma lava, Deccan trap and Rajmahal trap ranging in age from Paleozoic to Upper Mesozoic.

Aquifer geometry

A Fence diagram based on lithological logs of borehole drilled by State Tubewell Department has been prepared by the CGWB and has been made available for this study. The fence diagram reveals the vertical and lateral disposition of aquifers, aquiclude and aquitard in the study area down to depth of 122 m bgl. The aquifer structure was varying spatially across the Ganga Basin. The Figure 22 shows the fence diagrams for different areas viz. Yamuna, UP and Bihar and West Bengal respectively. It can be seen that the aquifer structure varies considerably spatially. But however, it is to be noted that most of the area is having the alluvium aquifer and reaches upto a depth greater than 700m. The variations are only in the formation of the clay layers.

In some areas such as North Bihar and West Bengal the top clay layer is persistent throughout the area varying in thickness from 3 to 20 m bgl. The top clay bed is underlain by granular zone, which extends downward to different depths varying up to 400 m bgl. The granular material is composed of fine, medium to coarse sand. The granular zone is subdivided at places into two to three sub-groups by occurrence of sub-regional clay beds, local clay lenses are also common throughout the area. By and large the aquifer down to 400 m appears to merge with each other and behaves as single bodied aquifer.

Figure 22: Fence diagrams for Yamuna, Uttar Pradesh, Bihar and West Bengal(CGWB Report,1996)

Parts of Yamuna Subbasin

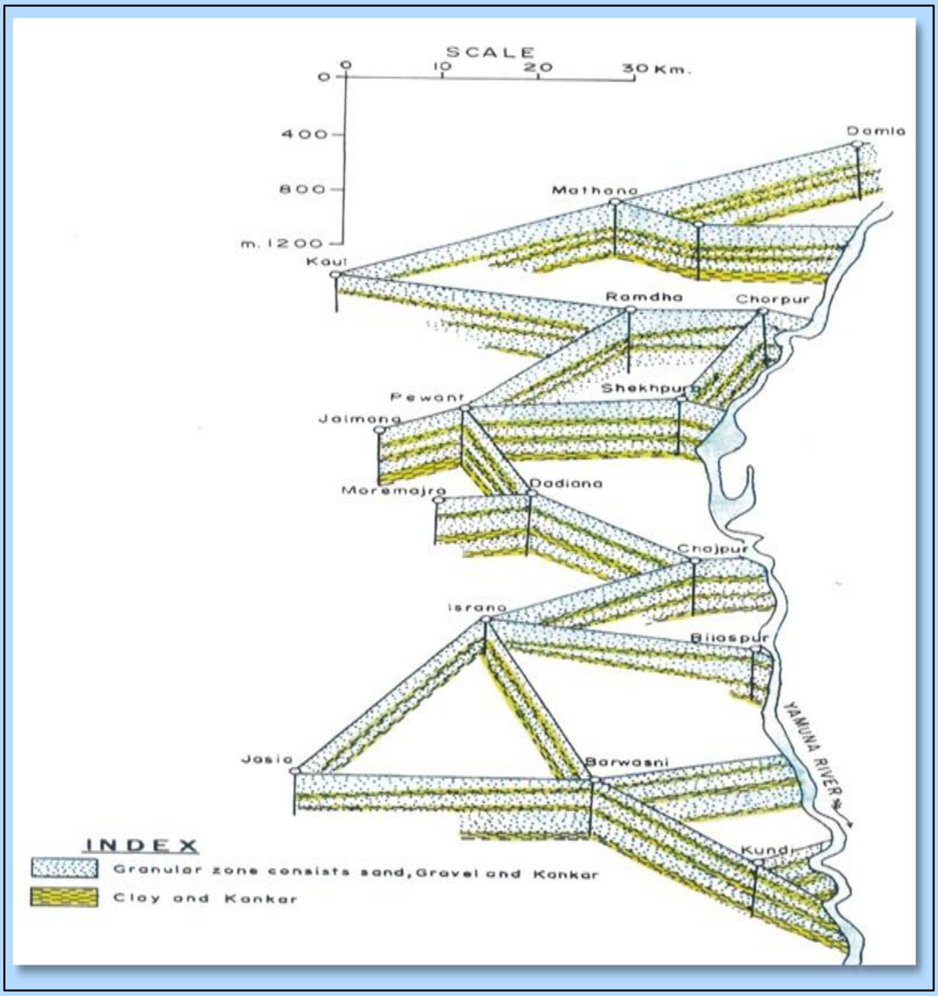
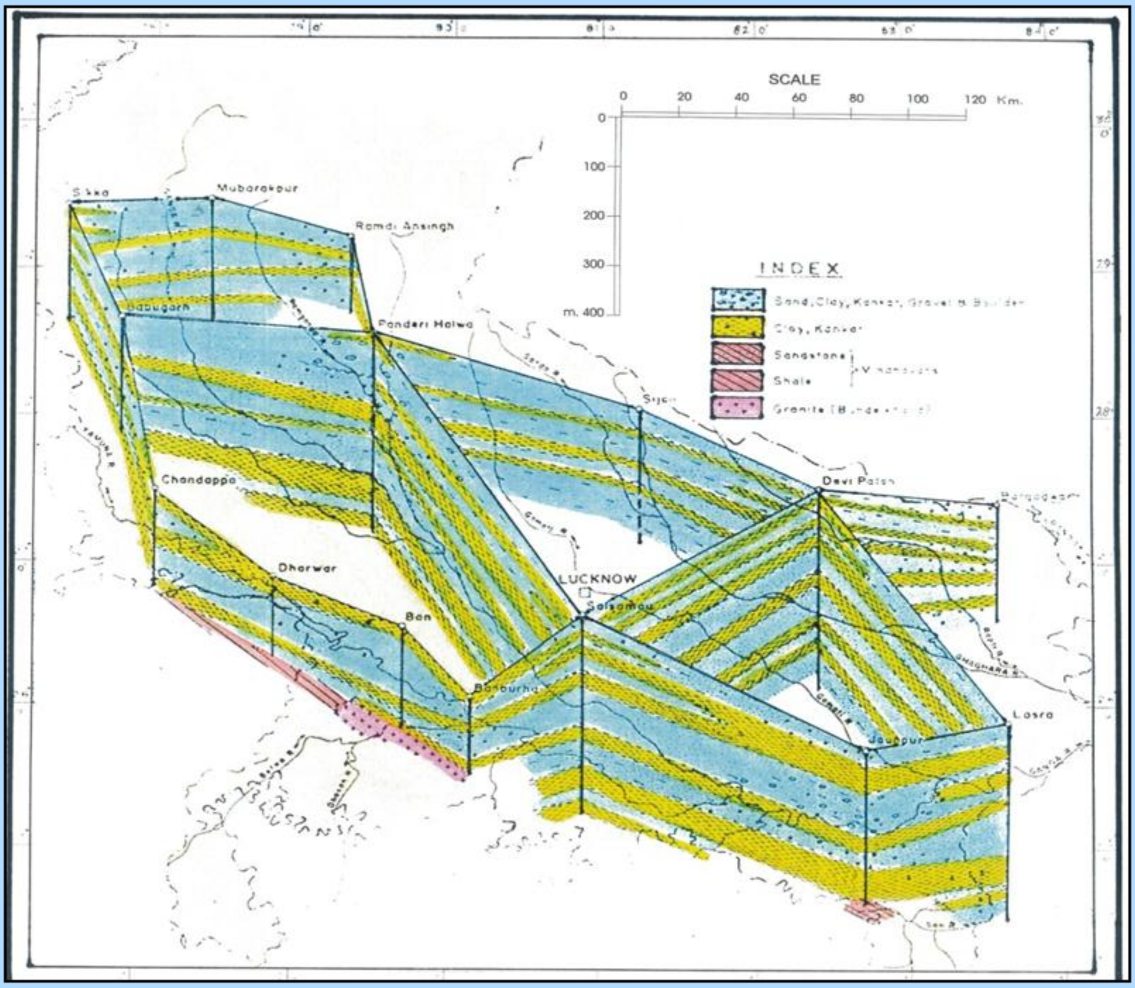


Figure 22: Fence diagrams for Yamuna, Uttar Pradesh, Bihar and West Bengal(CGWB Report,1996)
Parts of Ganga Basin in Uttar Pradesh



Parts of Ganga Basin in Bihar

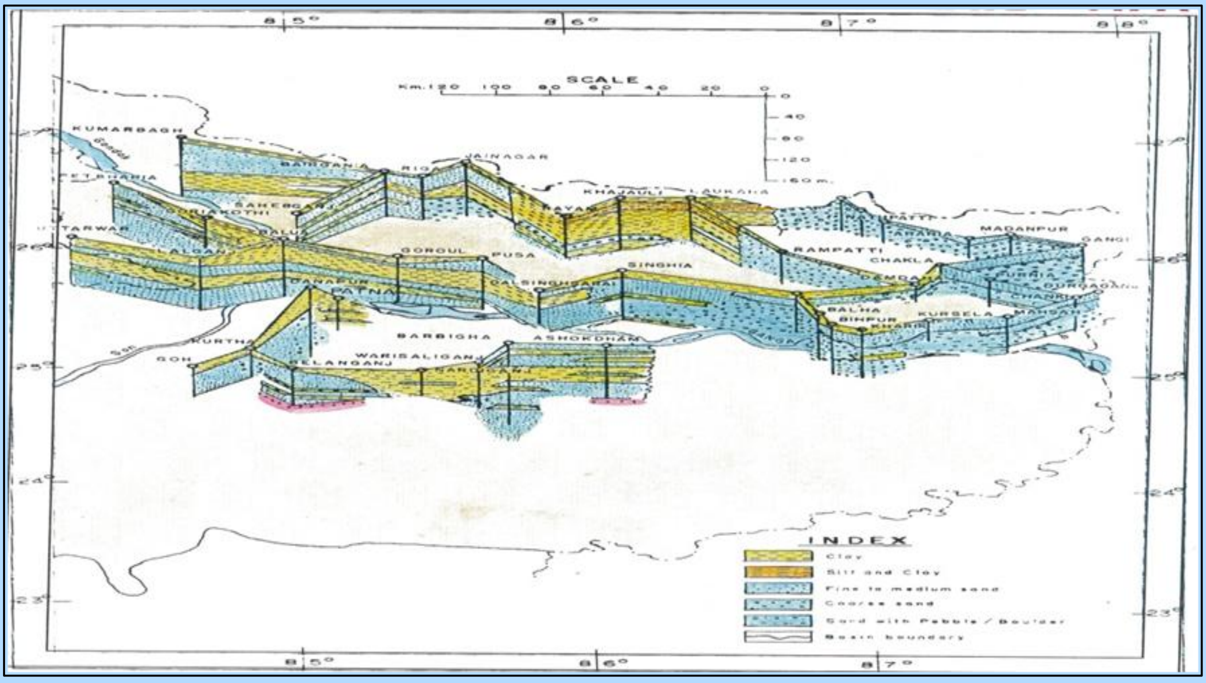
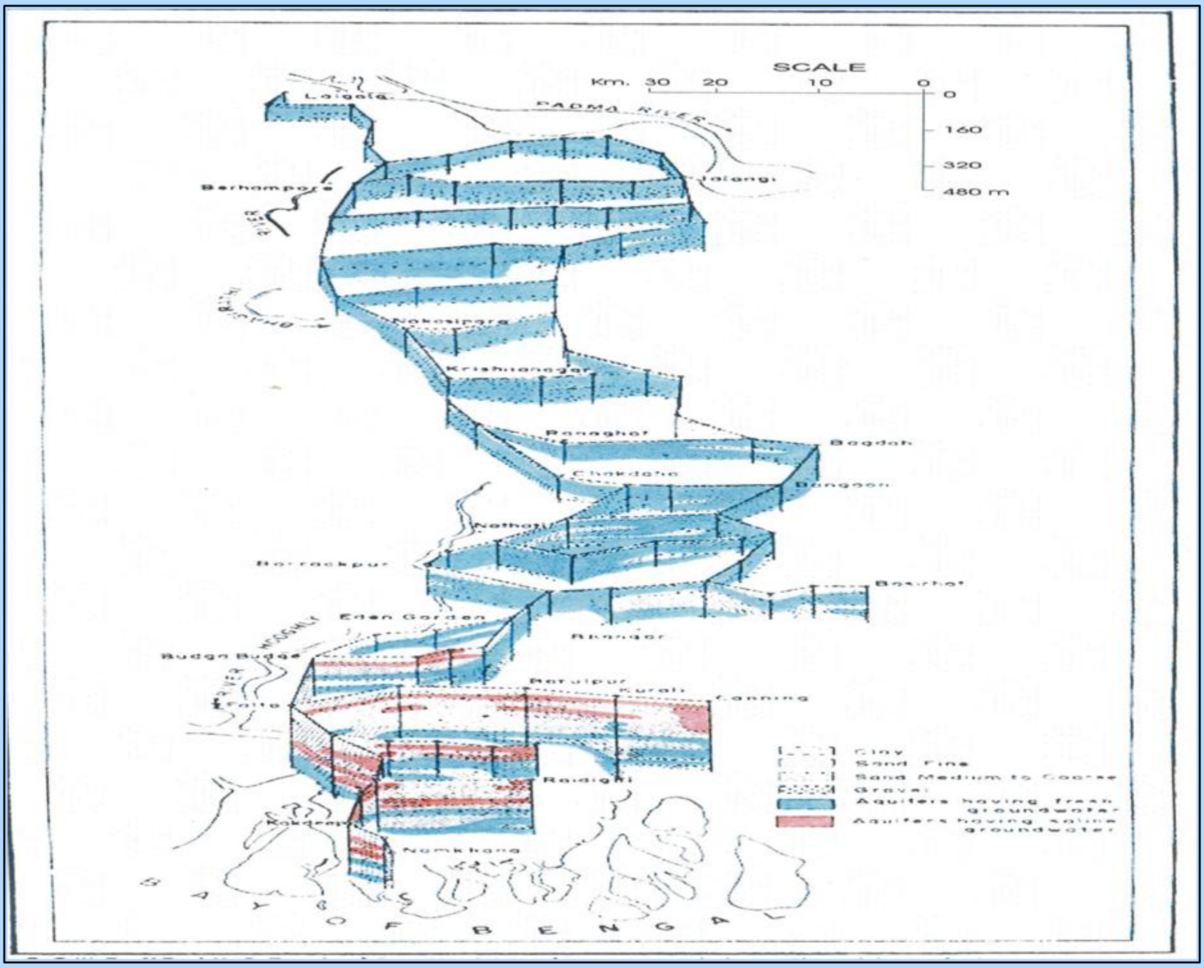


Figure 22: Fence diagrams for Yamuna, Uttar Pradesh, Bihar and West Bengal(CGWB Report,1996)

Parts of Hooghly River, West Bengal



The thickness of aquifers is recorded maximum towards north in the fore deep. The aquifer geometry inferred in Rajasthan and Madhya Pradesh clearly shows that only the unconfined aquifers are present up to the basement. In case of Haryana, Uttar Pradesh, Bihar and West Bengal, there exist at least 4-5 aquifers units down depth of 750m. The aquifer units are of unconfined, semi-confined and at places, confined in nature.

The portions in the Vindhyan range and the region in central MP are composed of Fissured formations: essentially composed of consolidated rocks and groundwater occurs in these due to secondary porosity. The secondary formations behave completely different from the primary porous formations and these formations cannot be modelled using the method adopted for the porous formations.

Recharge to the Deeper Aquifer

The sediments are predominantly arenaceous and form a good recharge zone throughout the 15-20 km wide northern foot hills of Ganga basin. The deep water table in Bhabhar zone indicate the recharge zone south of Himalayan frontal thrust fault. There always exists the recharge possibility from the Shivalik hills, situated north of the frontal fault and main boundary fault to the deeper aquifers in upper Shivaliks, middle and lower Shivaliks lying further south in the Ganga basin underlying the thick pile of alluvium through number of transverse faults. These faults are less resistant path of ground water movement horizontally as well as vertically from surface to deeper horizons during annual precipitations all along Ganga Basin.

Occurrence of ground water under artesian pressure

The flowing artesian condition is recorded at certain places and at defined depth zones in central Ganga Plain. Artesian pressure is recorded in most of the drilled wells of Ganga alluvium and they are generally of mesopiestic, myopiestic and opisthopistic nature. Sudden change in slope relief from Bhabhar to Tarai develops spring zone in Tarai belt. Three natural spring zones exist in Ganga basin viz Tarai spring zone, Sai-Gomti spring zone and Gangi, Tons, Pili, Mangai & Bhaiunsahi spring zone. Groundwater in central Ganga Plain lies under artesian pressure. The flowing artesian occurs only along conduit lines which are of close nature, and pressure confined only along these conduits. The conduit lines are lineaments and paleo channels buried under alluvium. Swelling and abrupt thinning of aquifer system at depth also creates hydrostatic pressure due to Bernoulli's effect with clay beds acting as confining layer. The alluvial plain of Ganga basin possess huge repository of ground water.

Hydrogeological Situation in Foredeep

Enormous sediments brought from the rising Himalayan mountains by the river Ganga and its tributaries are deposited in the broad depression and sub-basins over the bedrock floor of the ganga foreland basin during Upper tertiary and Quaternary period.

The sedimentation started in a narrow elongated foreland basin with the deposition of Dharamsala-Muree sediments in early Miocene period. These sediments were restricted in this narrow basin close to the Himalayan orogen. During middle Miocene to middle Pleistone the orogen ward part of the foreland basin sediments were uplifted and thrusted basin ward in discrete steps, while the basin expanded craton ward. Thus, the Shivalik sediments thickened towards foothills due to the (i) greater load of sediments, and (ii) greater concomitant sinking of the basin floor in that direction.

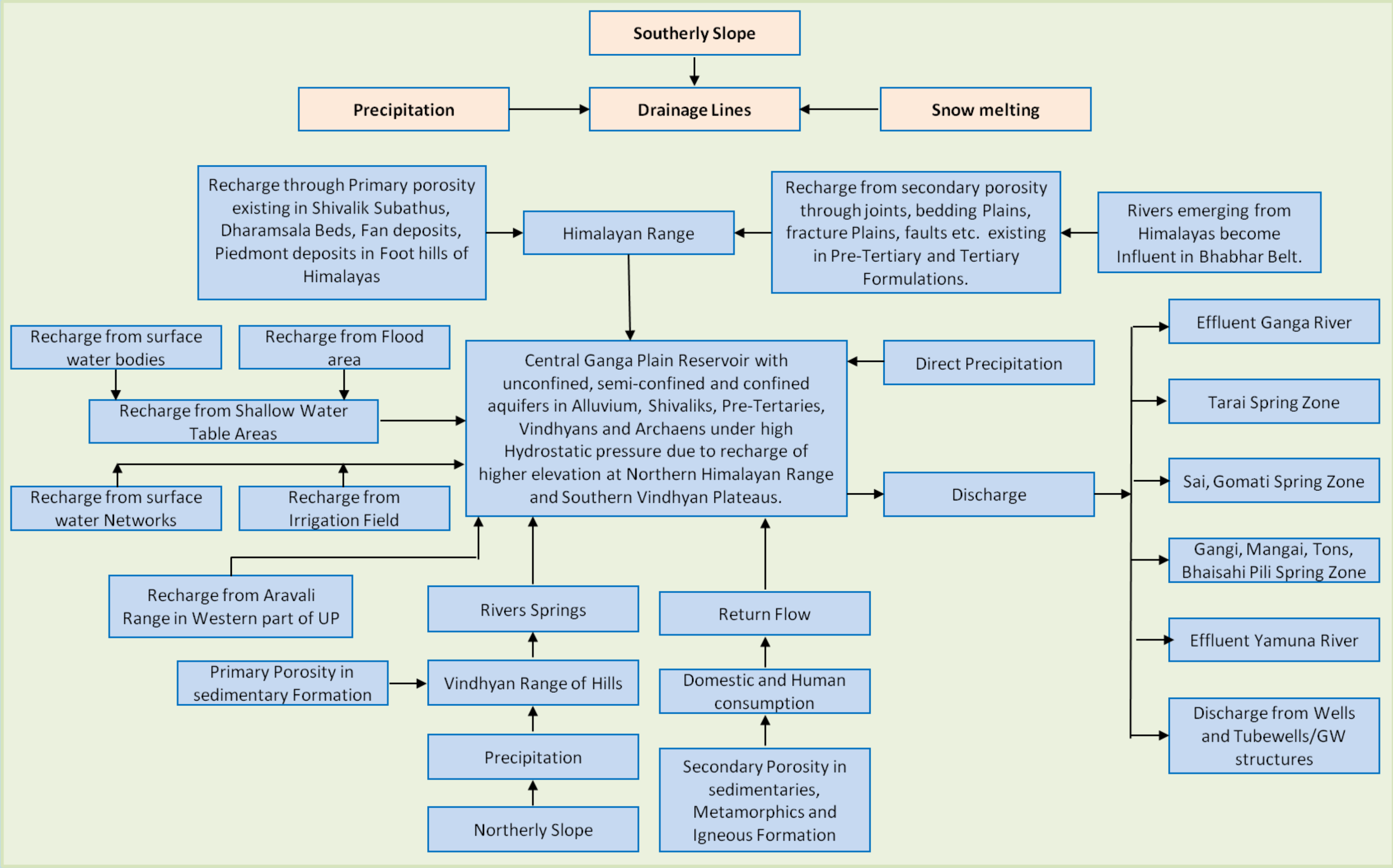
The thickness of foreland sediments shows a strong asymmetry. The younger Shivaliks shows overlapping towards south, which is an indication of the widening of the basin towards south over Bundelkhand massif. The sediments are coarse grained close to Himalayas and become finer towards the craton and show a typical coarsening upward cycle.

Geometry of Shivaliks Aquifers

14 number of deep boreholes drilled by ONGC in the Ganga basin unravelled the geometry (Depth and Thickness of each Sub-group) of Shivaliks. The prospects of suitable quality of ground water are in the Alluvium, Upper Shivaliks and upto certain parts of Middle Shivaliks only. The lower Shivaliks and lower parts of middle Shivaliks contain brackish/saline ground water. In the older formations there are no prospects of ground water development.

Flow chart showing the recharge process in the Ganga basin is depicted in Figure 23.

Figure 23: Flowchart Showing the Recharge process in the Ganga river basin



Groundwater Flow Modelling

Groundwater models are mathematical and digital tools of analyzing and predicting the behaviour of aquifer systems on local and regional scale, under varying geological environments. Models can be used in an interpretative sense to gain insight into the controlling parameters in a site-specific setting or a framework for assembling and organizing field data and formulations of ideas about system dynamics. Models are used to help in establishing locations and characteristics of aquifer boundaries and assess the quantity of water within the system and the amount of recharge to the aquifer (Anderson and Woessner, 2002)[28].

Mathematical models provide a quantitative framework for analysing data from monitoring and assess quantitatively responses of the groundwater systems subjected to external stresses. Over the last four decades there has been a continuous improvement in the development of numerical groundwater models (Mohan, 2001[29]).

Numerical modelling employs approximate methods to solve the partial differential equation (PDE), which describe the flow in porous medium. The emphasis is not given on obtaining an exact solution rather a reasonable approximate solution is preferred. A computer programme or code solves a set of algebraic equations generated by approximating the partial differential equations that forms the mathematical model. The hydraulic head is obtained from the solution of three dimensioned groundwater flow equation through MODFLOW software (McDonald and Harbaugh,1988)[30].

Finite Difference Approximation

In finite difference method (FDM), a continuous medium is replaced by a discrete set of points called nodes and various hydrogeological parameters are assigned to each of these nodes. Accordingly, difference operators defining the spatial-temporal relationships between various parameters replace the partial derivatives. A set of finite difference equation, one for each node is, thus obtained. In order to solve a finite difference equation, one has to start with the initial distribution of heads and computation of heads at the later time instants. This is an iterative process and fast converging iterative algorithms have been developed to solve the set of algebraic equation obtained through discretization of groundwater flow equation under non-equilibrium condition. The continuous modelcan be replaced with a set of discrete points arranged in a grid pattern. This pattern is more often known as finite difference grid. The general flow equation for unsteady flow in an unconfined aquifer under Dupuit assumptions [(1) flow lines are horizontal and equipotential lines are vertical and (2) the horizontal hydraulic gradient is equal to the slope of the free surface and is invariant with depth] is given by Equation 1.

$$K_x \frac{\partial^2 h}{\partial x^2} + K_y \frac{\partial^2 h}{\partial y^2} + K_z \frac{\partial^2 h}{\partial z^2} = S_s \frac{\partial h}{\partial t} - R \quad \text{.......}(1)$$

[28]Anderson M P and Woessner W W 1992 Applied groundwater modeling; Academic Press, San Diego.
[29]Mohan, S. (2001) Groundwater Water Modelling: Issues and Requirements, Modelling in Hydrogeology, (Edt. Book), Elango, L. and Jayakumar, R., Allied Publishers Limited (Mumbai).pp.3-16.
[30]McDonald M G and Harbaugh A W 1988 A modular three dimensional finite-difference groundwater flow model. USGS Open File Report 83–875. USGS, Washington,D.C

Where K_x, K_y, and $K_z$are components of the hydraulic conductivity tensor. S_S is the Specific storage and R is general sink/source term that is intrinsically positive and defines the volume of inflow to the system per unit volume of aquifer per unit of time.

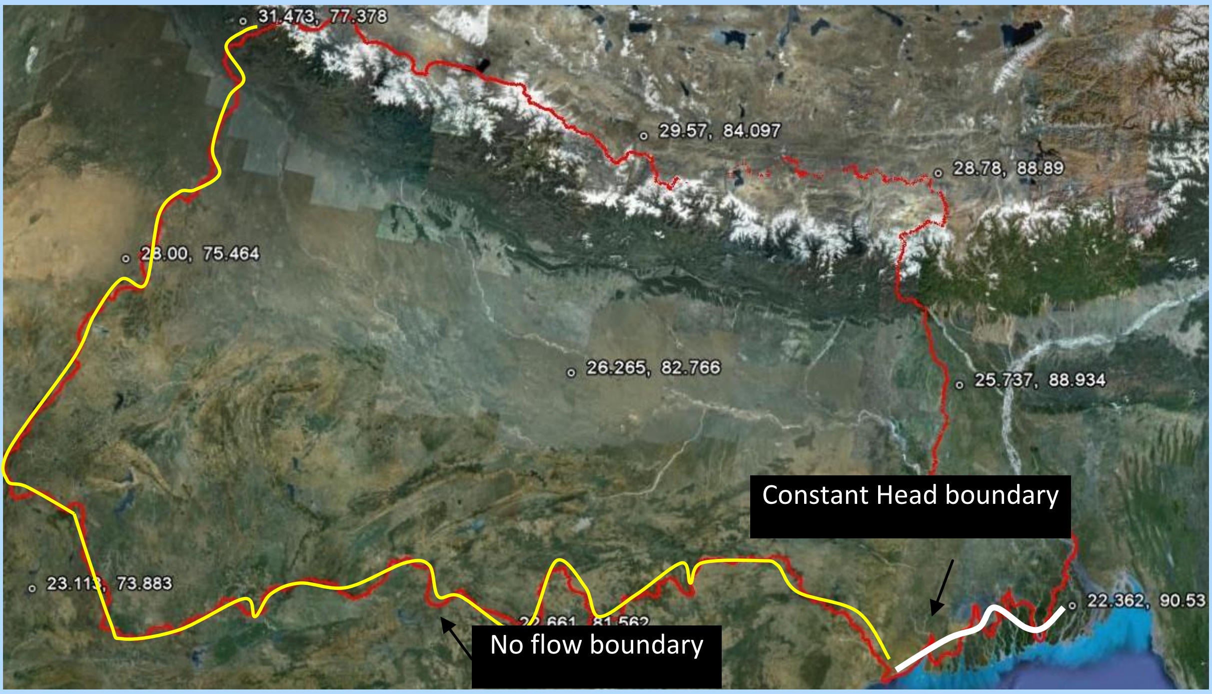
Model conceptualization and data acquisition

The purpose of building a conceptual model is to simplify the field problem and organize the associated field data so that the system can be analyzed more readily (Anderson and Woessner, 2002). The conceptualization includes synthesis and framing up of data pertaining to geology, hydrogeology, hydrology, and meteorology.

Model Area and boundary.

Figure 24 shows the model area and the no flow boundary along the southern side of the Ganga basin. The region adjoining the Bay of Bengal was taken as the constant head with the head values being the tidal heights. Similarly, the top portion of the basin is also no flow boundary. It is to be noted that the region in Figure 24 shows the areas including the mountainous regions. These regions generally do not be a part of the aquifer system and therefore it was decided to exclude this mountainous region from the modelling areas. However, since these portions will contribute to the groundwater in the central alluvium part, the recharge from this portion has to be included in the model. In order to incorporate the recharge from this area, the recharge from the SWAT hydrological model has been used as a specified flux boundary. Figure 25 shows the modelled area of the Ganga basin.

Figure 24: Groundwater Model Area and Boundary- Ganga river basin



It was also observed that the hard rock regions in the southern end of the basin have secondary porous structure and that these areas will have different dynamics than the alluvium regions. Therefore, these portions have also been cut off from the model area. The recharge from these regions was provided as the specified flux to the remaining model area. The final modified modelled region in shown in Figure 26.

Figure 25:Modified Portion of the Ganga basin used for groundwater modelling

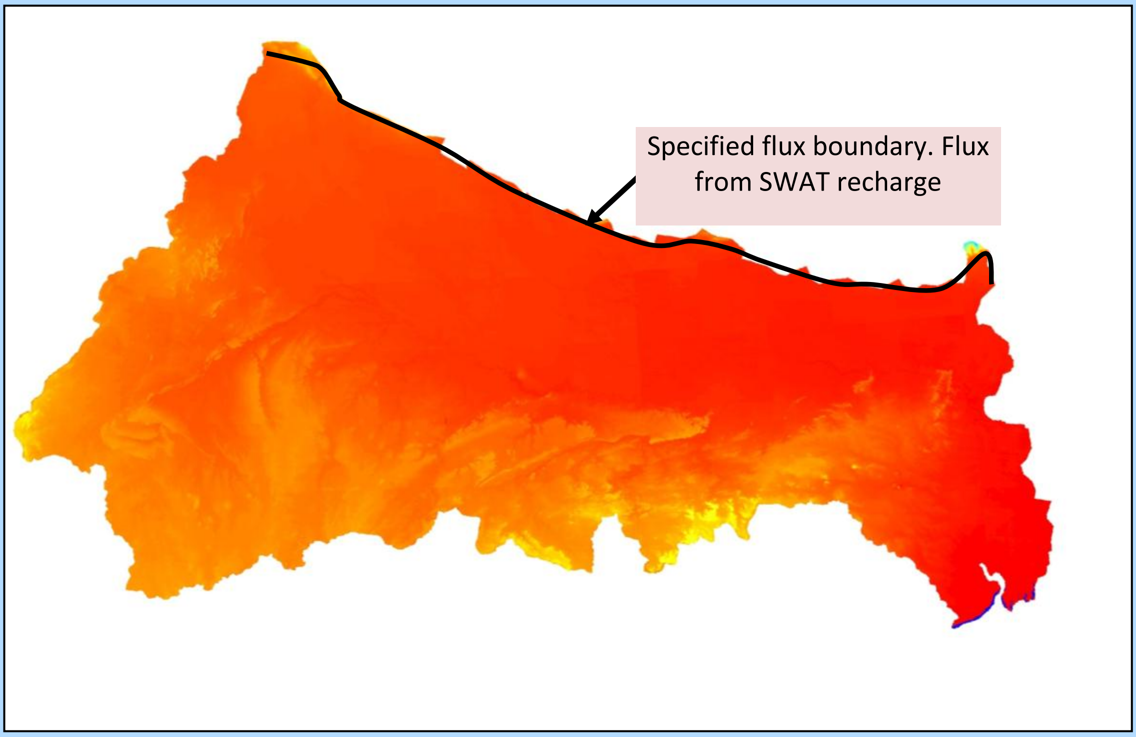
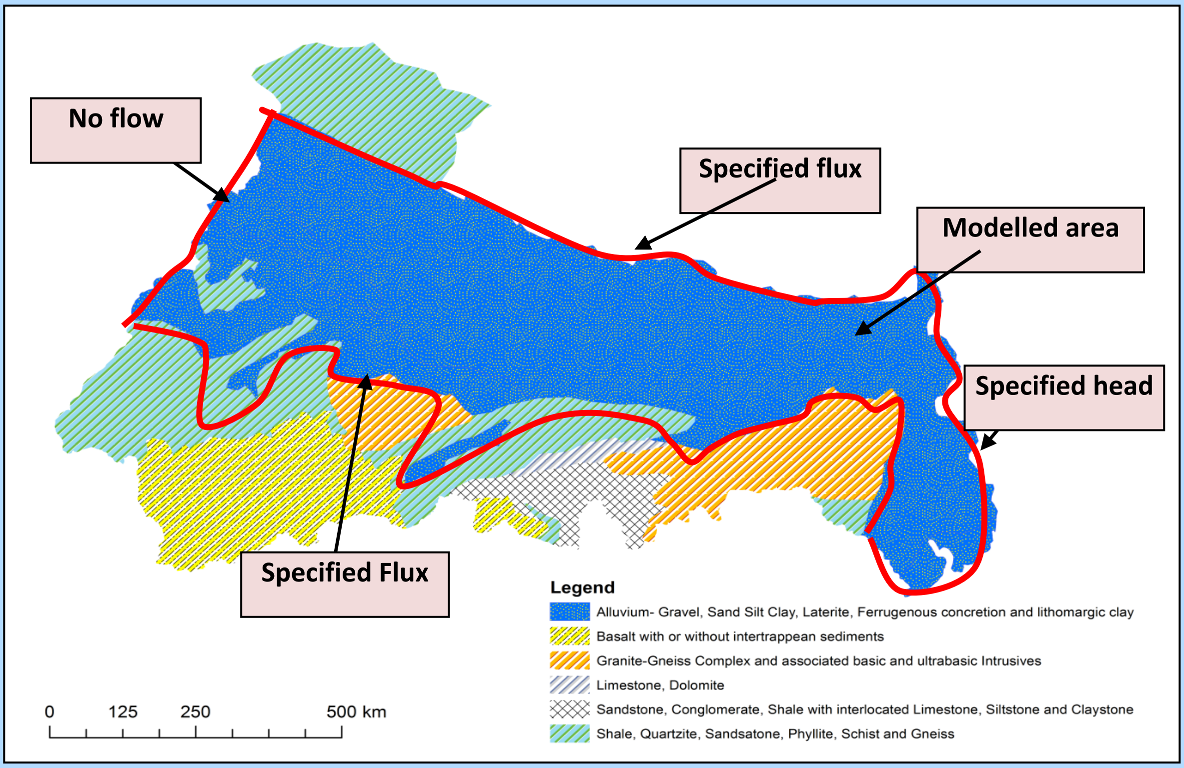


Figure 26:Final Portion of the Ganga basin used for Groundwater modelling



Aquifer Geometry

Geologic information including aquifers, cross sections and well logs were combined with information on hydrogeologic properties to define hydrostratigraphic units for the conceptual model. It was shown in previous section that the aquifer depth extends upto 750m below ground level in most places of Ganga Basin. There are some occasional clay lenses and clay layers of thickness 30-50m. Considering the areal extent of the modelled area (10 lakh sq.km) it is impossible to capture the minor variation of the aquifer structure. As a reasonable approximation, the entire aquifer stratigraphy was combined together to form a single layer unconfined aquifer of thickness of 200m. Even though this is gross approximation, considering the regional scale of modelling this would serve the purpose of modelling.

Aquifer Parameters

Hydraulic conductivity (K) and storage coefficient (S) values are the two parameters which define the physical framework of an aquifer and control the movement and storage of groundwater.

The hydraulic conductivity and specific yield/specific storage, were estimated and assigned to different layers, using data derived from the reports from CGWB and the well logs given by the CGWB authorities. The hydraulic conductivity values assigned to the model ranged between 3.0 to 25.6 m/day. Figure 27shows the spatial variation of the hydraulic conductivity values as a function of the properties of the aquifer. The specific yield values were assigned based on the type of the aquifer at each location. Figure 28shows the spatial variation of the specific yield values as a function of the hydrogeologic properties of the aquifer. The specific yield values range from 0.02 to 0.16.

Figure 27:Conductivity zones of the entire Ganga Basin

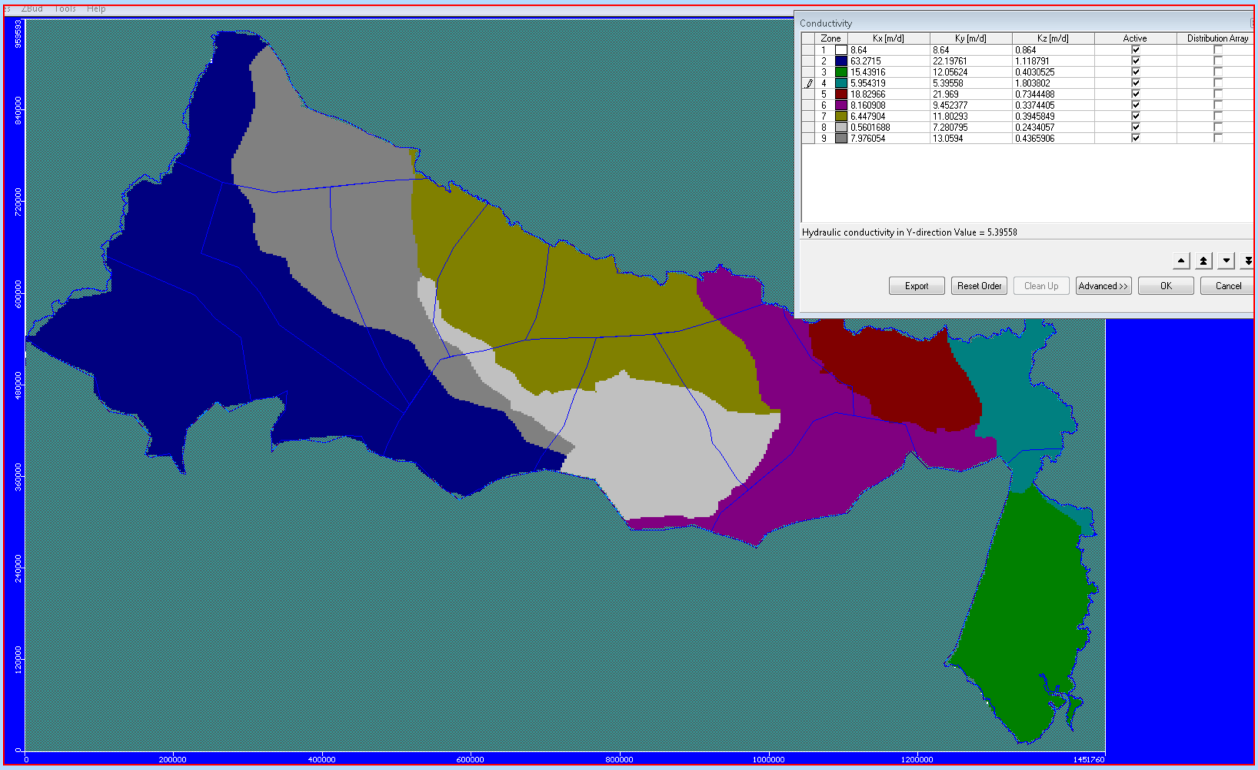
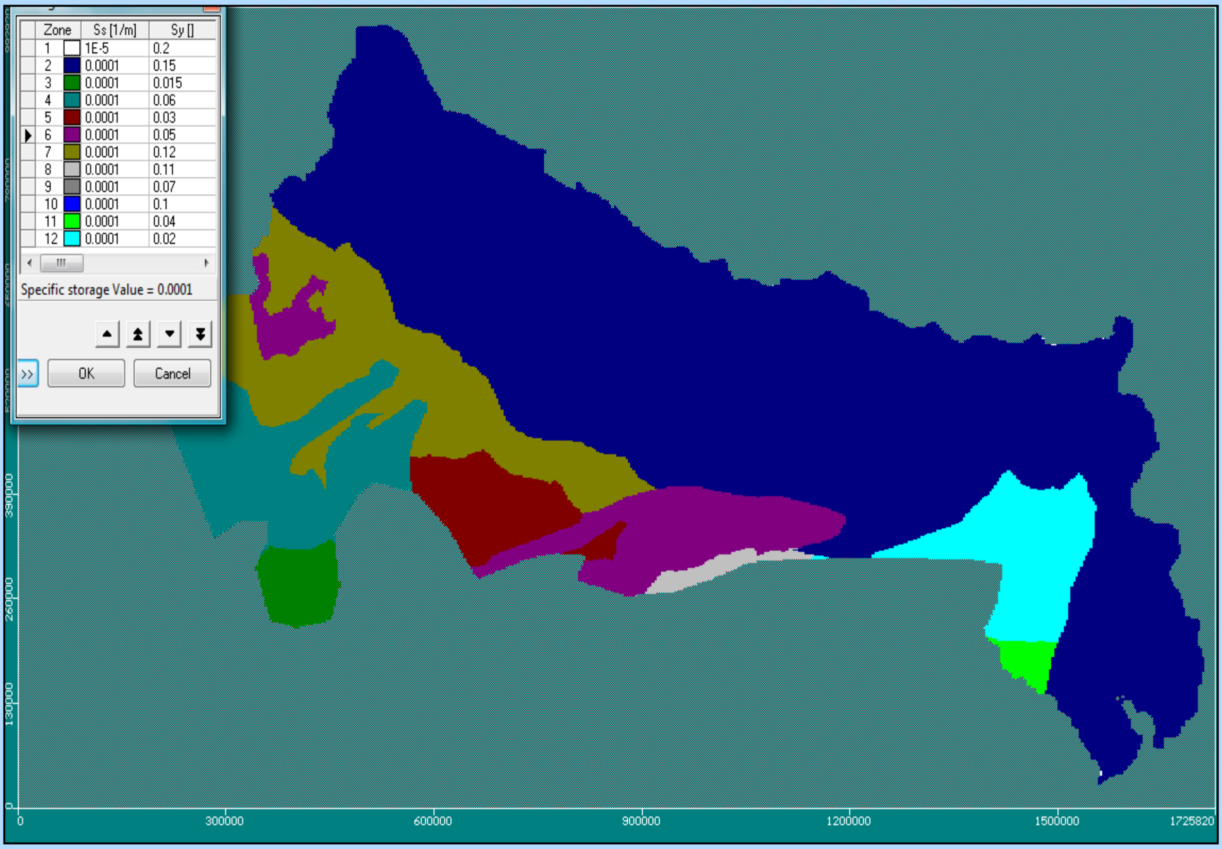


Figure 28:Specific yield values for the different zones of the entire Ganga Basin



The important aspect of the modelling is that the hard rock regions such as the Tarai regions and the fissured rock regions are cut off from the modelling regions. Thus, only the areas having aquifer which are primary porous are modelled.

Recharge

Recharge from rainfall, irrigation return water and canal seepage was taken from the model outputs of the SWAT hydrological model. Surface water model SWAT was setup for the entire Ganga Basin and the model was calibrated at monthly scale using the CWC stream discharge observations. The calibrated SWAT model in turn provided the flux that is reaching the aquifer on a monthly basis. The recharge data was provided for the entire Ganga basin that is including the Tarai and the hard rock regions. Therefore, in order to account for the water in these regions in the GW model, a specified flux boundary was provided. This would help in capturing the lateral inflows from these regions into the alluvium regions. Since, the amount of flux from the boundaries is uncertain and not measurable, this quantity has been used as some sort of calibration for the model. The recharge was provided on the monthly basis and for each of the sub basin. Since the number of sub basins was too large, some of the sub basins were combined together.

Groundwater Draft through pumping

A database of existing bore wells was obtained from Minor Irrigation census and the district wise total draft was obtained from studies carried out by CGWB (CGWB, 2004 and 2009). The aforementioned study has estimated pumping rates that vary from 1500 -2200m3/day for a total number of pumping wells in excess of 150,000. Since the Modflow does not have the capability to handle such a huge number of wells, the number of wells is reduced and the rate of pumping is increased to 40000m^3/day. Also, the pumping rates were varied temporally by having two different values of pumping for monsoon and non-monsoon seasons.

Boundary Conditions

Specified Head Boundary (River Boundary)

Every model requires an appropriate set of boundary conditions to represent the system's relationship with the surrounding area. The river boundary conditions are applied along the Ganga River and along the main tributaries. For these boundaries, river head and river bed bottom elevations were assigned from the CWC observed data. The head values were averaged over every three months starting from June. This is because the groundwater observations are taken for every three months. The river head and bed bottom elevations at the initial and final point of rivers are provided from the CWC observations and the DEM respectively. Previously reported studies have established that the river bed conductance across the entire Ganga basin varies between 150 m2/day to 30 m2/day (CWGB 1996 and Umar 2008)for its various drainage components and shown in Figure 29. However, for reasons of data availability on river water levels, the actual river network that has been considered in the present study is shown in Figure 30.

Figure 29:Major River Network in Ganga River Basin

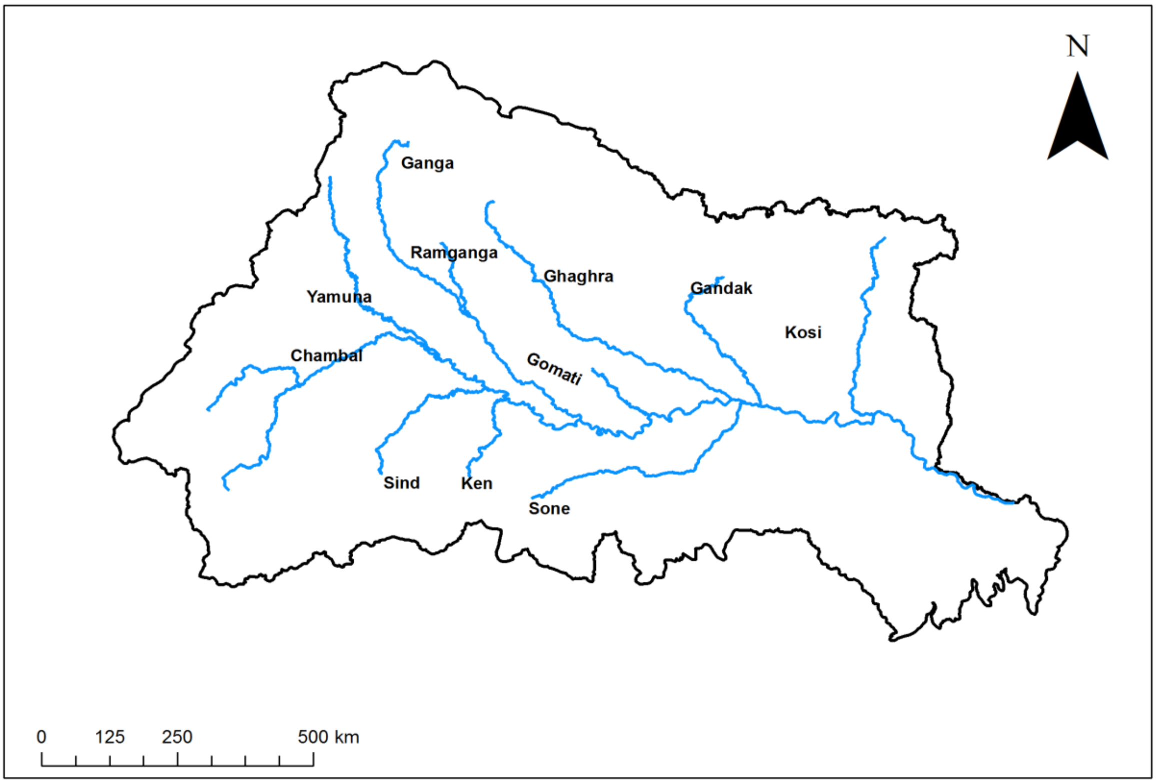
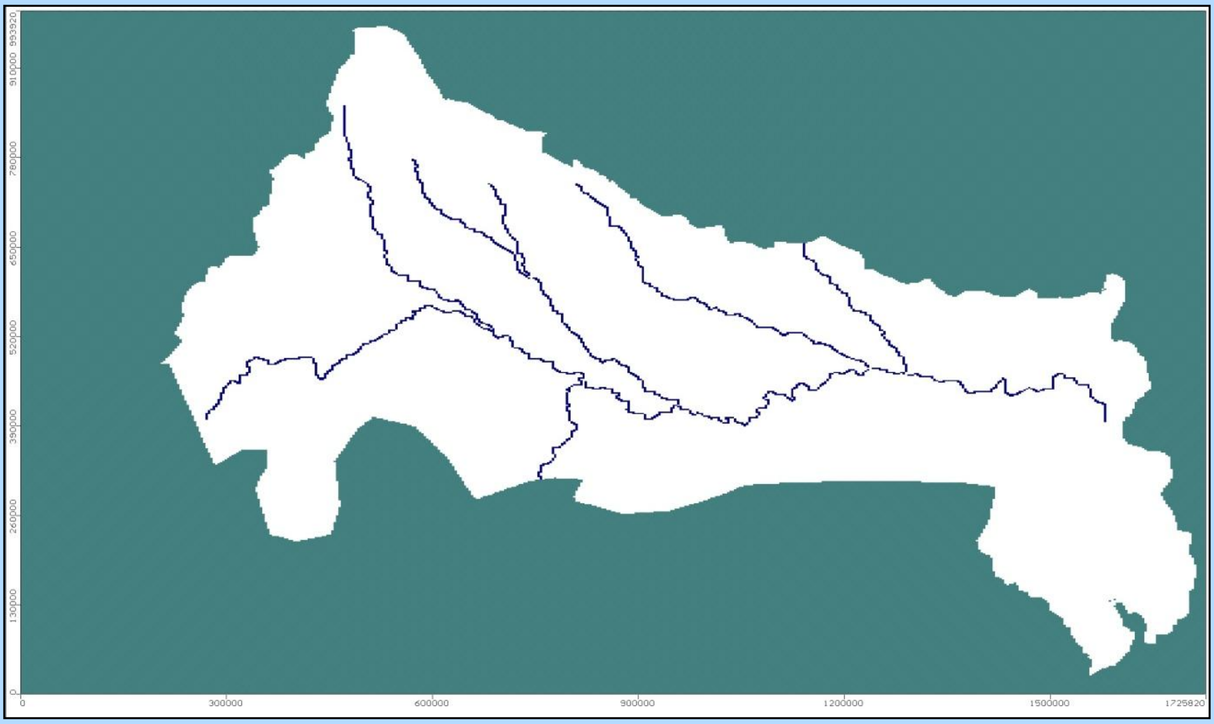


Figure 30: Incorporated River network boundary conditions in the Groundwater model



General head boundaries (GHB)

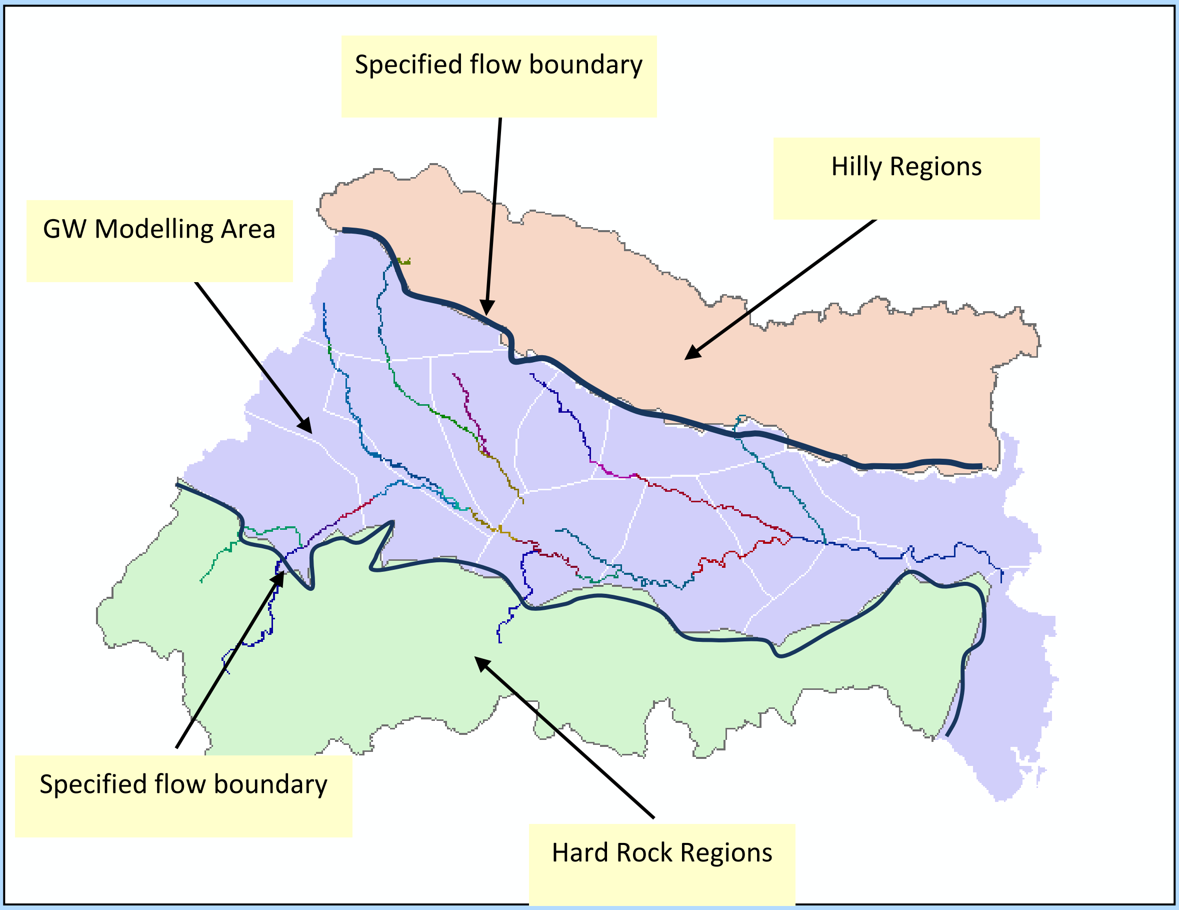
were assigned at the eastern edges (edges near the sea) of the model. Heads were assigned to the GHB with the help of historical water level data.

Also, specified head boundaries were assigned along the eastern boundary. The head values along the boundary was obtained from the observed water levels in this region.

Specified flow boundaries.

The model is developed only for the alluvium part of the Ganga basin. However, there would be contribution from the hilly regions of the basin as well as from the hard rock regions of the basin into the alluvium aquifer. In order to accommodate this flow in the study region, a specified flow boundary was considered. The specified flow boundary was put along the northern and southern end of the study region as shown in Figure 31.Since, the amount of flux from the boundaries is uncertain and not measurable, this quantity has been used as some sort of calibration for the model. The amount of flux entering the alluvium part was varied from zero to 50 % of the total recharge that is occurring in the hard rock regions.

Figure 31:Implementation of Specified flow Boundary in the MODFLOW



Conceptualization of Flow regime and Model Design

Model design and its application is the primitive step to define the nature of problem and the purpose of modelling. The step is linked with formulation of the conceptual model, which again is a prerequisite before the development of a mathematical model. The conceptual model is put into a form suitable for modelling. This step includes design of the grid, selecting time steps, setting boundary and initial conditions, preliminary selection of values for the aquifer parameters and hydrologic stresses (Umar, 2008)[31]. Following are the salient features of the model set up:

1. The aquifer model in Ganga region consists of 500 rows and 500 columns (Figure 31).
2. The model area has been gridded with a uniform grid of 2500m × 2500m Nine permeability zones were assigned to first layer of entire study area which ranges from 3.25 m/day to 26.6 m/day
3. Natural recharge from monsoon rainfall and recharge through return flows forms the main input in to the groundwater system. These values were obtained from SWAT model results. The recharge from SWAT includes the canal seepage also.
4. The pumping rates vary from 40000 -60000m3/day. There are more than 10000 pumping wells in operation.

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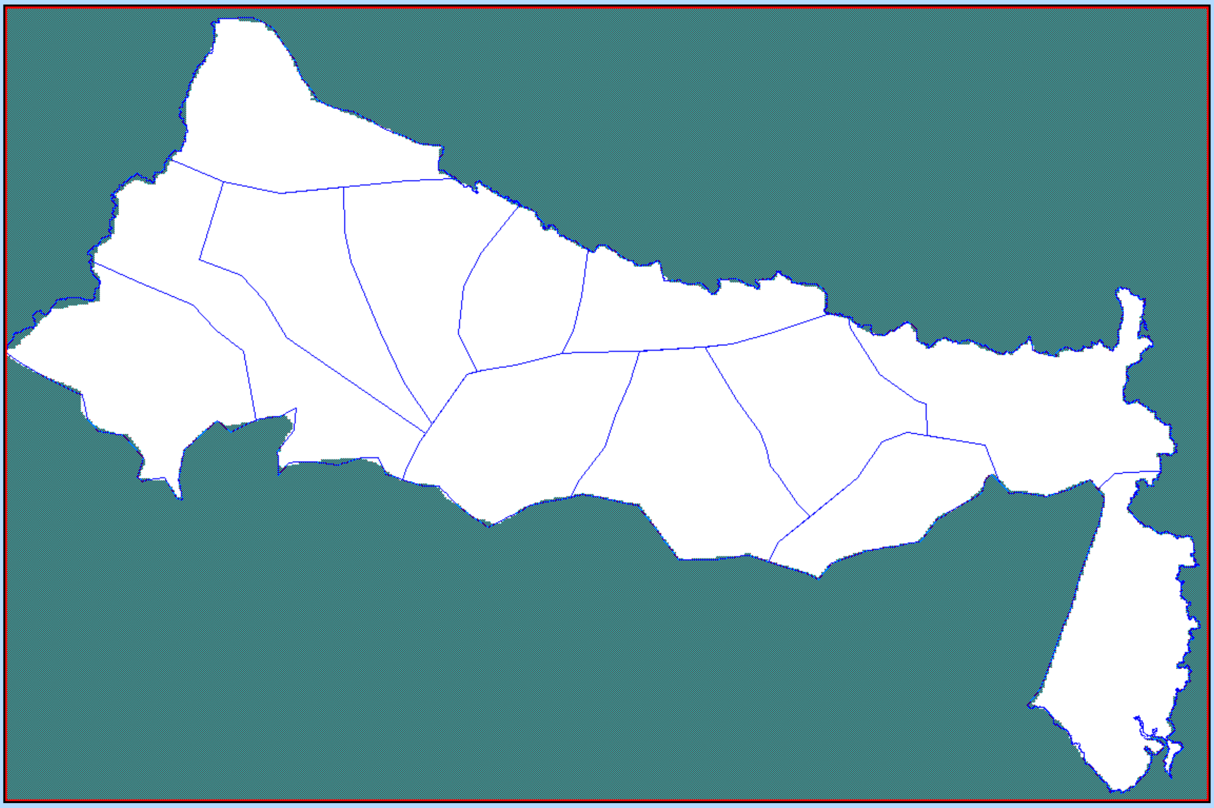
[31]Umar R 2008 Groundwater Flow Modeling and Aquifer Vulnerability Assessment studies in Yamuna–Krishni sub-basin, Muzaffarnagar District, Ministry of Water Resources, Government of India (Report)

5. The river boundary condition was applied to the river Ganga and other main tributaries. Heads are prescribed to all the boundary conditions.

Figure 32:Model region as represented in MODFLOW



MODFLOW is a versatile code to simulate groundwater flow in multilayered porous aquifer. The model simulates flow in three dimensions using a block centred finite difference approach. The groundwater flow in the aquifer may be simulated as confined, unconfined or the combination of both. MODFLOW consists of a major program and a number of sub-routines called modules. These modules are grouped in various packages viz. basic, river, recharge, block centred flow, evapotranspiration, wells, general heads boundaries, drain, strongly implicit procedure (SIP), successive over relaxation (SSOR) and preconditioned conjugate gradient (PCG) etc.

Model Calibration

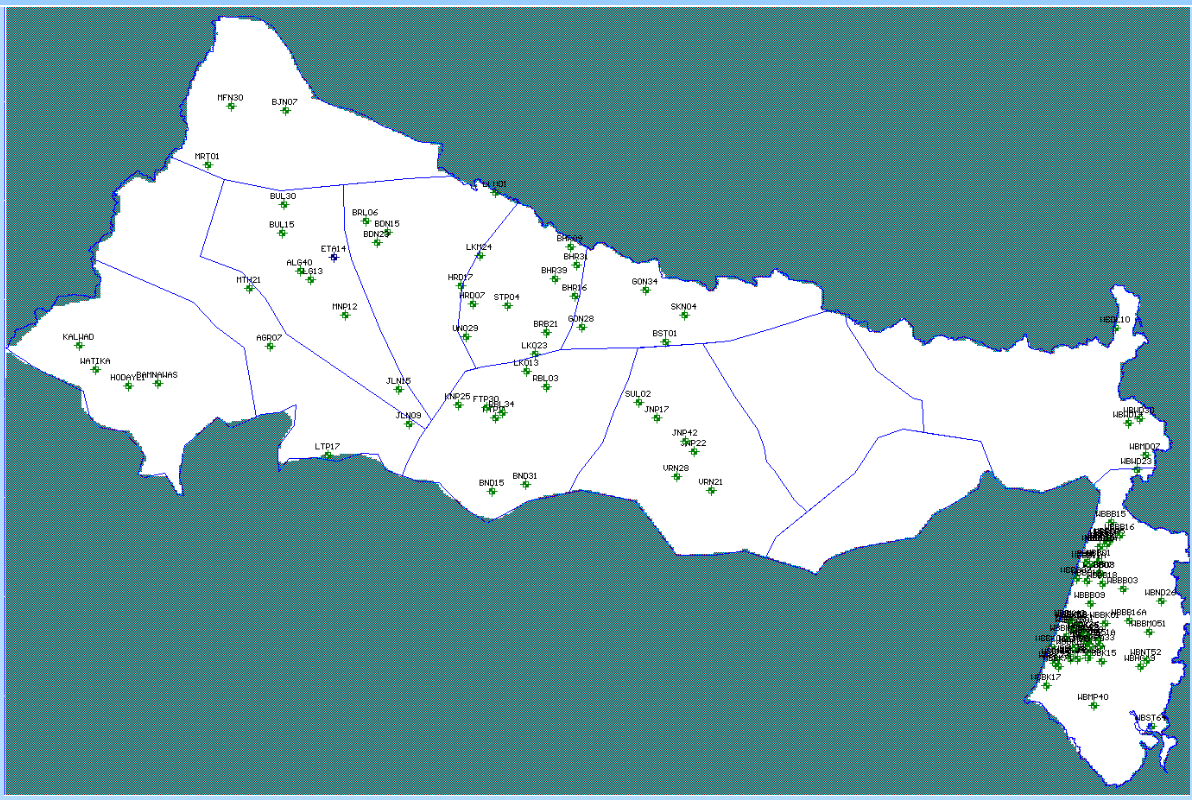
The purpose of model calibration is to establish that the model can reproduce field measured heads and flows. Calibration is carried out by trial and error adjustment of parameters.

Transient State Calibration

In practice and moreover in India where in most cases, over-exploitation is common, it is very difficult to get the aquifer in the steady state condition unless we go much beyond in time in the past which has limits on account of the data availability. Therefore in this case, the aquifer system was calibrated in transient state for a period of four years from 2000-2004. The 10-day time step for the model run was selected while the model results are presented at intervals of 45 days. For model runs, recharge values and groundwater extraction by pumps were specified at intervals of 90days. However, values corresponding to intermediate time values were obtained via a process of interpolation by Visual MODFLOW. The water level values of May 2000 were used as the initial head values for the transient state model.

For calibration, we have used the observation from the CGWB observation wells. The total number of wells used was around 100. The Figure 33 shows the location of these wells in MODFLOW window. The CGWB observes the water levels in the observation wells 4 times in a year. The observations are taken at Jan, May, Aug, and Nov of each year. These data were used to calibrate the model.

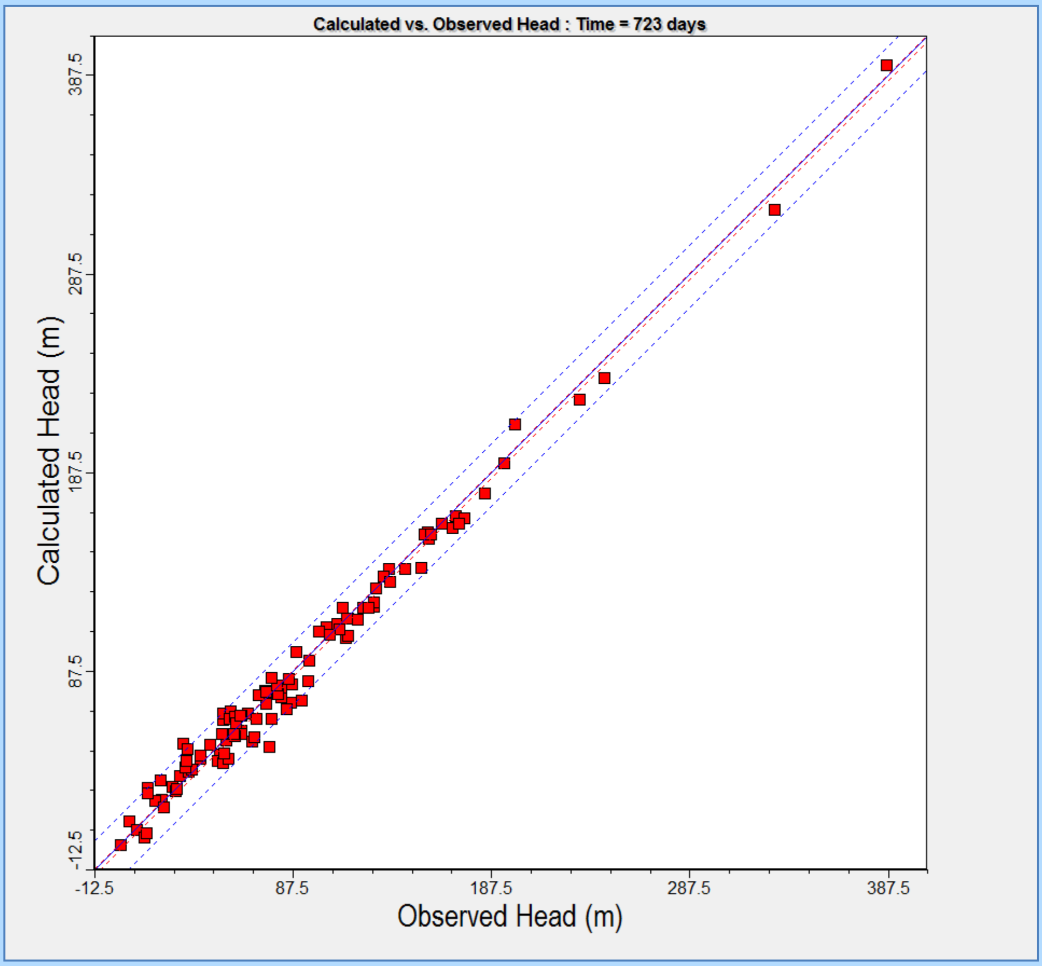
Figure 33:Location of the observation wells



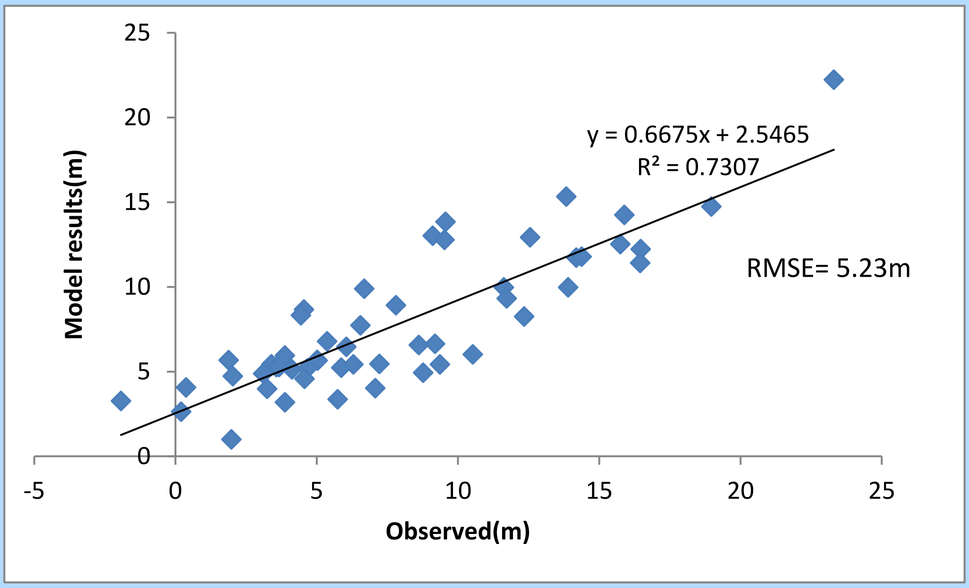
PEST (Parameter Estimation by Sequential Testing) Run

The model was auto calibrated using the PEST module in the MODFLOW. In this exercise, the hydraulic conductivities were calibrated to get a better match between the observed water levels and the simulated water levels. The hydraulic conductivities of all the sub basins were made as the target variables and minimizing the root mean square error between the observed and simulated water levels was made as the objective function. The PEST module was run for nearly 24 hours. The model results from the PEST run were comparatively better with reference to the manually calibrated model. Figure 34 shows the scatter plot between the observed and the simulated values for respective time step.

Figure 34:Simulated versus observed heads at the end of 723 days since May 2000 (a) datum as mean sea level (b) datum as local ground level



(a)



(b)

It can be seen that model water levels during the given stress period (the period used by MODFLOW for making calculations, it can include a number of time steps within it) matched with the observed water levels during that period to a satisfactory level. The dotted lines show the 95% confidence limits. Figure 35 shows the histogram of the residual. It can be seen that the model residual are near normal. Also, Figure 36 shows the plot of the time series of the model results and the observation for three randomly selected wells. It can be seen that the model is able to closely capture the real observations and the trend in the water levels.

However, it can be seen at some locations simulated water levels are higher or lower than the observed. This can be attributed to two possible reasons.

- In the absence of terrain data from SOI, international source of terrain data in the form of SRTM DEM (Digital Information Model) has been used. Errors in DEM get propagated into the water levels and thereby create errors in the water level values.
- It is also possible that the model parameters in these regions can be further refinedby getting observed value of hydraulic conductance and river bed conductance to get better match between modelled and observed values.

Figure 35:Calibration residual Histogram

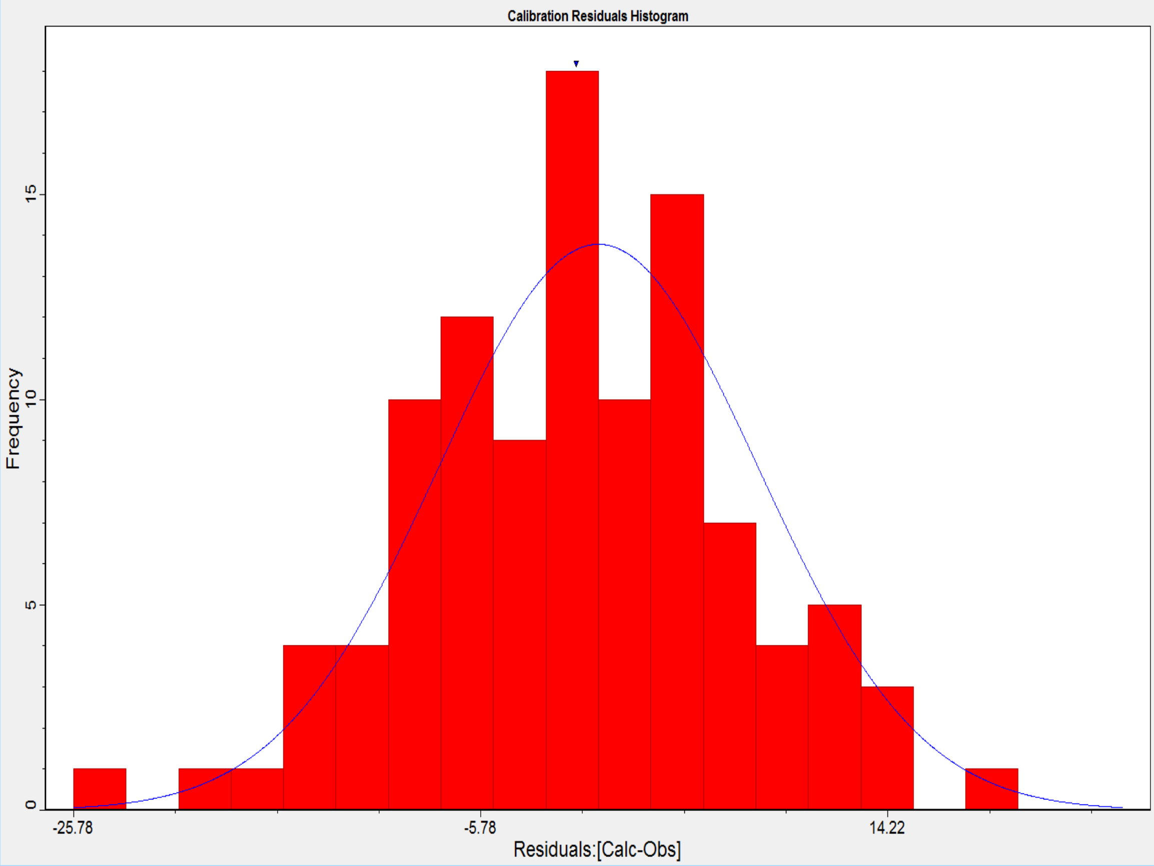


Figure 36:Time series plot of the Model results and observations for three observation wells

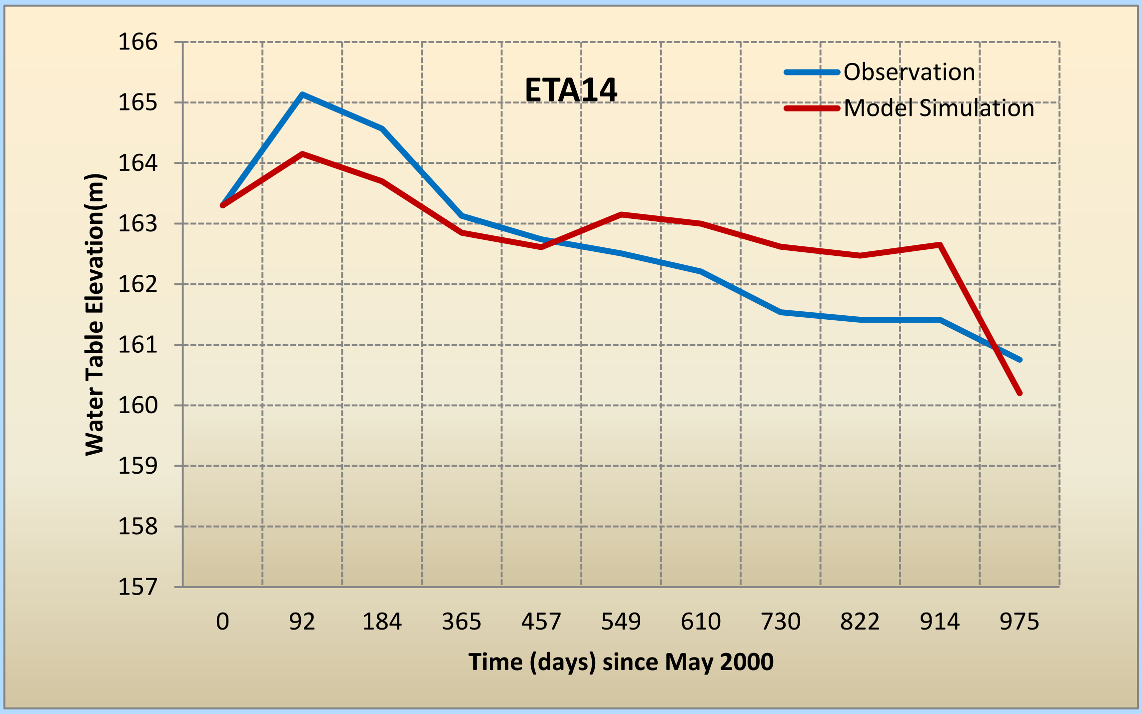
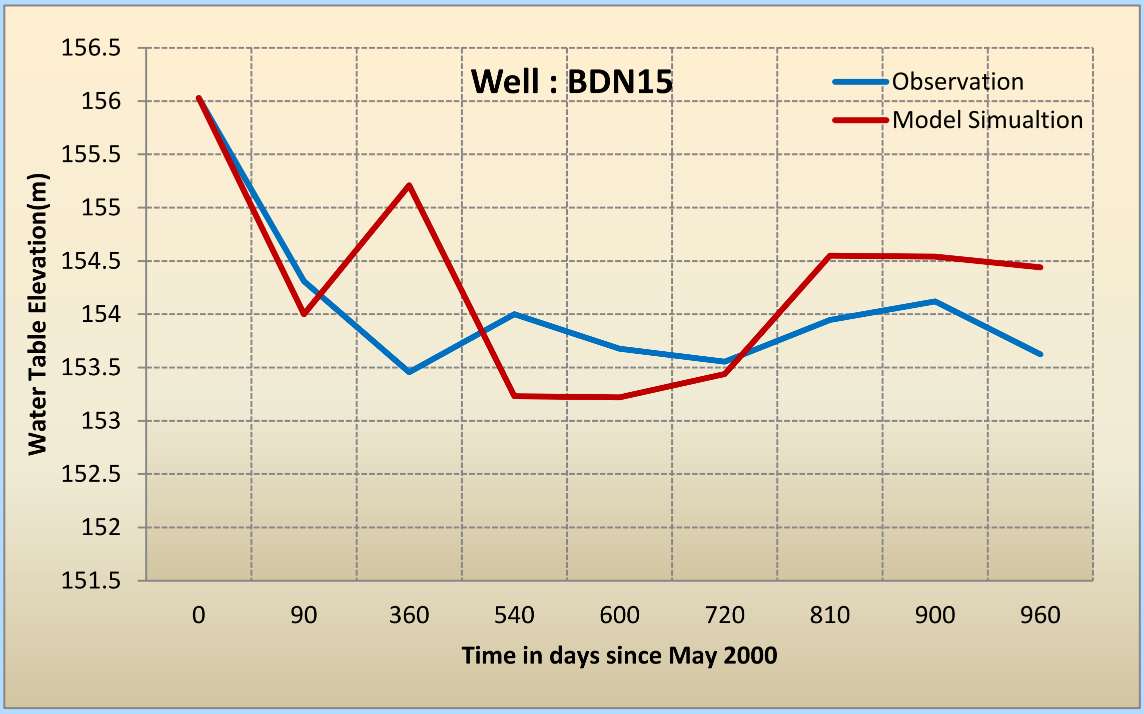


Figure 36:Time series plot of the Model results and observations for three observation wells



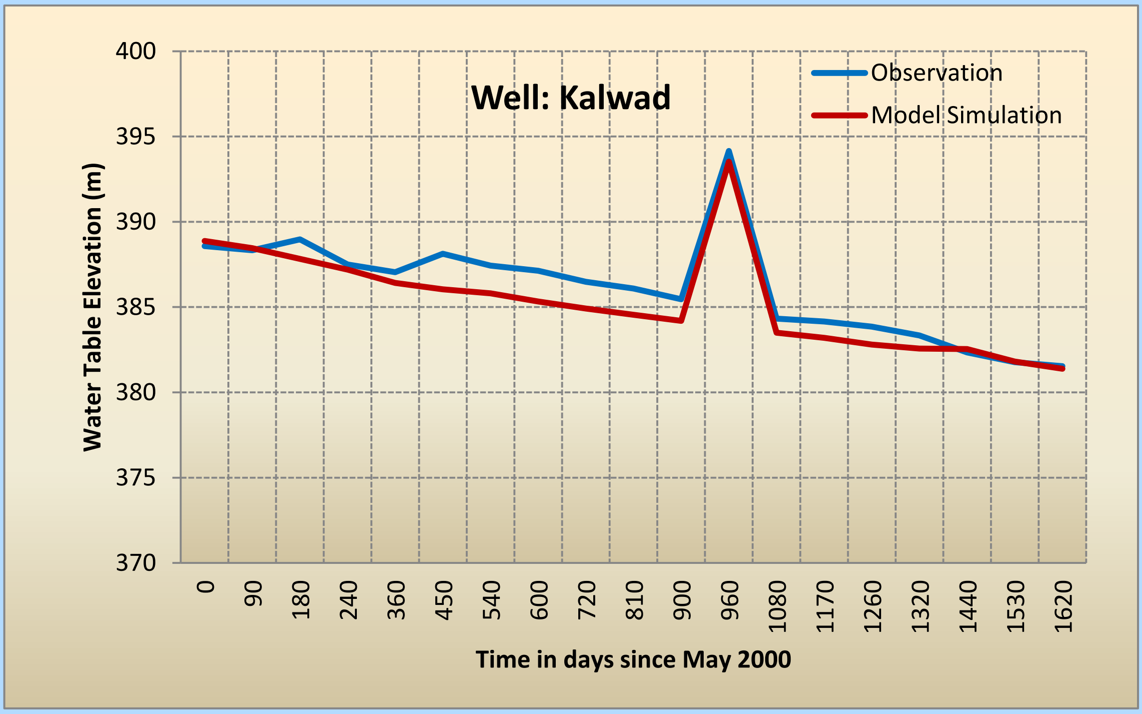


Figure 37 shows the contour plot of the water levels obtained from the model. The contour and the directions of the water flow was verified using the water level contour map produced by CGWB. It was observed that the flow pattern and direction obtained from the model was matching with the observed one. Figure 38 shows the contour plot of groundwater table levels below ground surface for the time 1200days from the start of the simulation (May 2000). It can be seen that the water levels at some places(shown in green patches) have gone below 10m from the ground surface. The model results in terms of observed and simulated water levels at different times for the validation wellsare shown inTable 2. The RMSE and other error statistics for different periods of model runtime are tabulated in Table 2.

RMSE values are calculated with the observed values and calculated values from the Mean sea level (MSL). The correlation is the R^2 value as calculated using observed and calculated values from MSL. The average annual variation in the Ganga basin is in the range of 0-10 (m bgl), hence the model results justify the ground reality.

Table 2: Statistics on growth of errors at various stages of model runtime (the results are wrt the msl datum)

Length of model runtime (days)	RMSE (m)	Correlation	Max Residual	Min Residual	Standard Error(m)
600	6.90	0.990	-14.5	0.079	0.689
1312	7.50	0.987	+18.5	0.052	0.722
1718	6.45	0.990	-12.4	0.032	0.654
2010	8.40	0.984	-16.7	0.070	0.800

Figure 37:Contour plot of the water levels(msl) obtained from the model using PEST

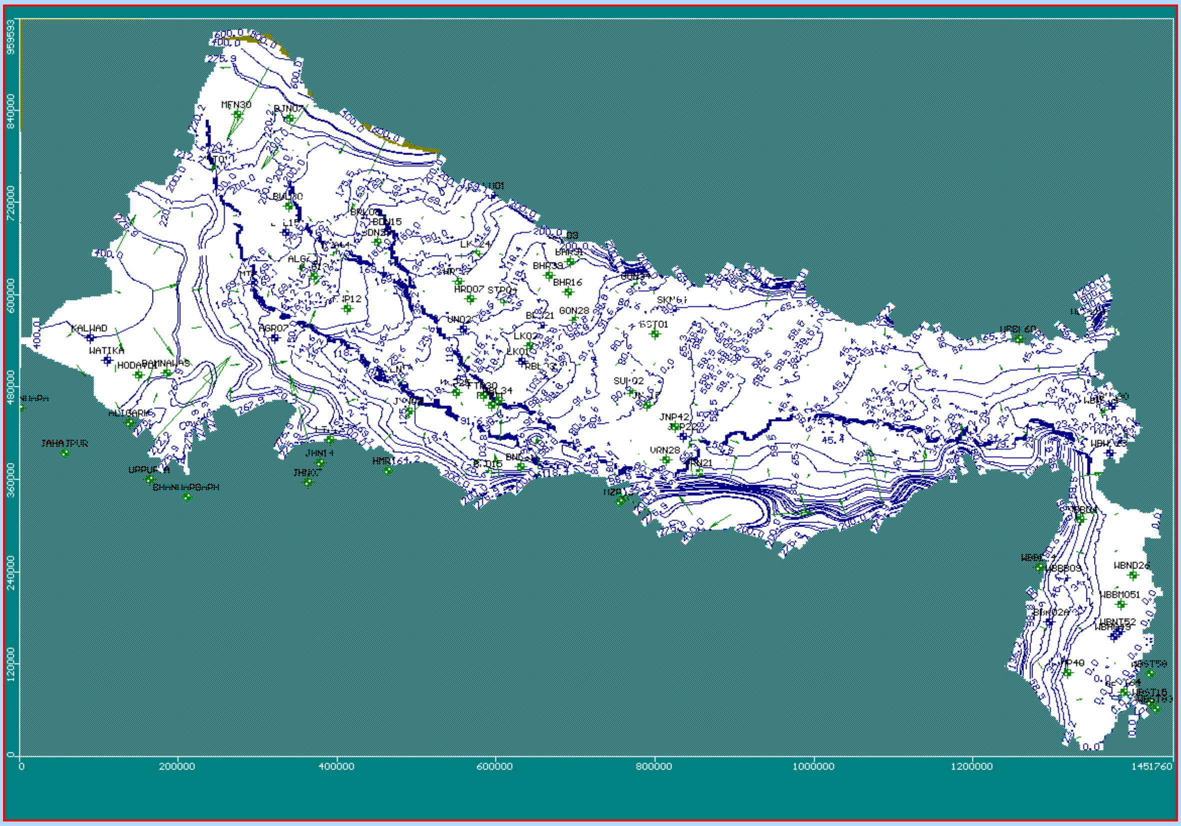


Figure 38:Depth to water Table in Ganga basin (Pre monsoon and Post monsoon average)

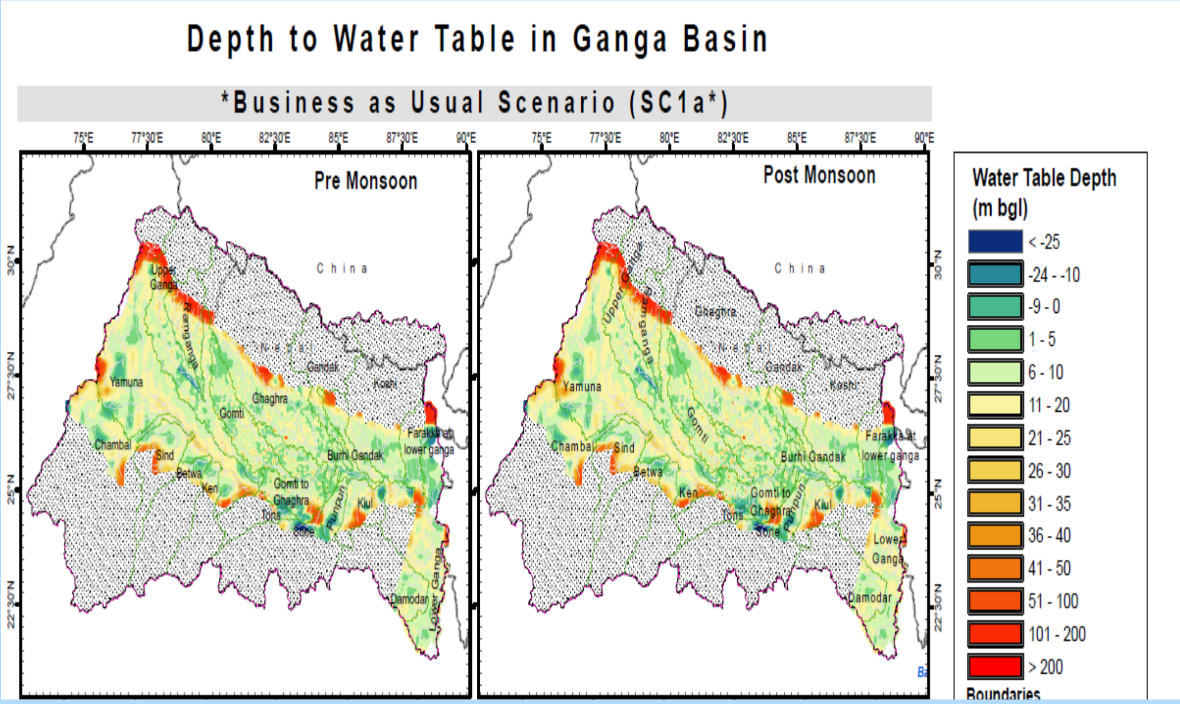
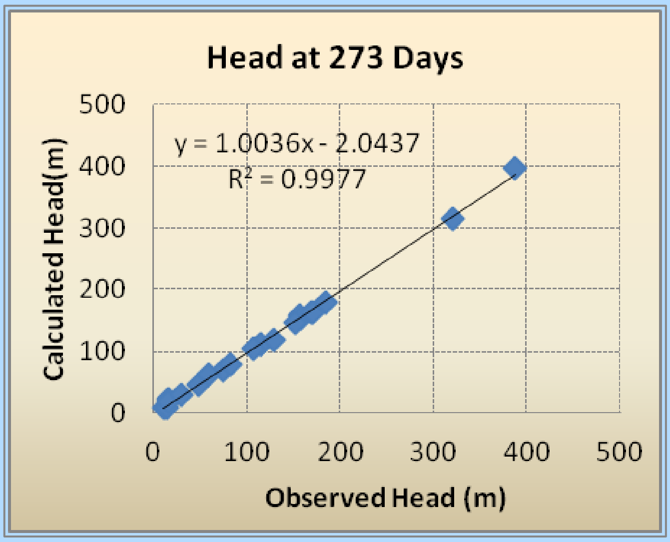


Figure 39:Scatter plot between the simulated water levels using auto calibration and observed water levels.



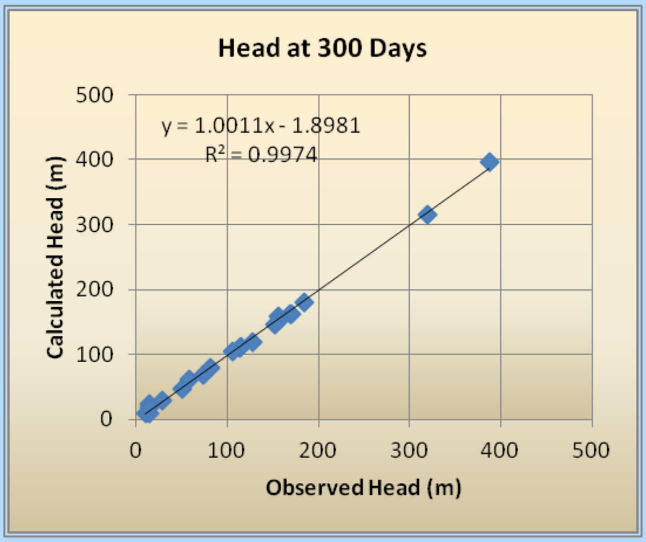
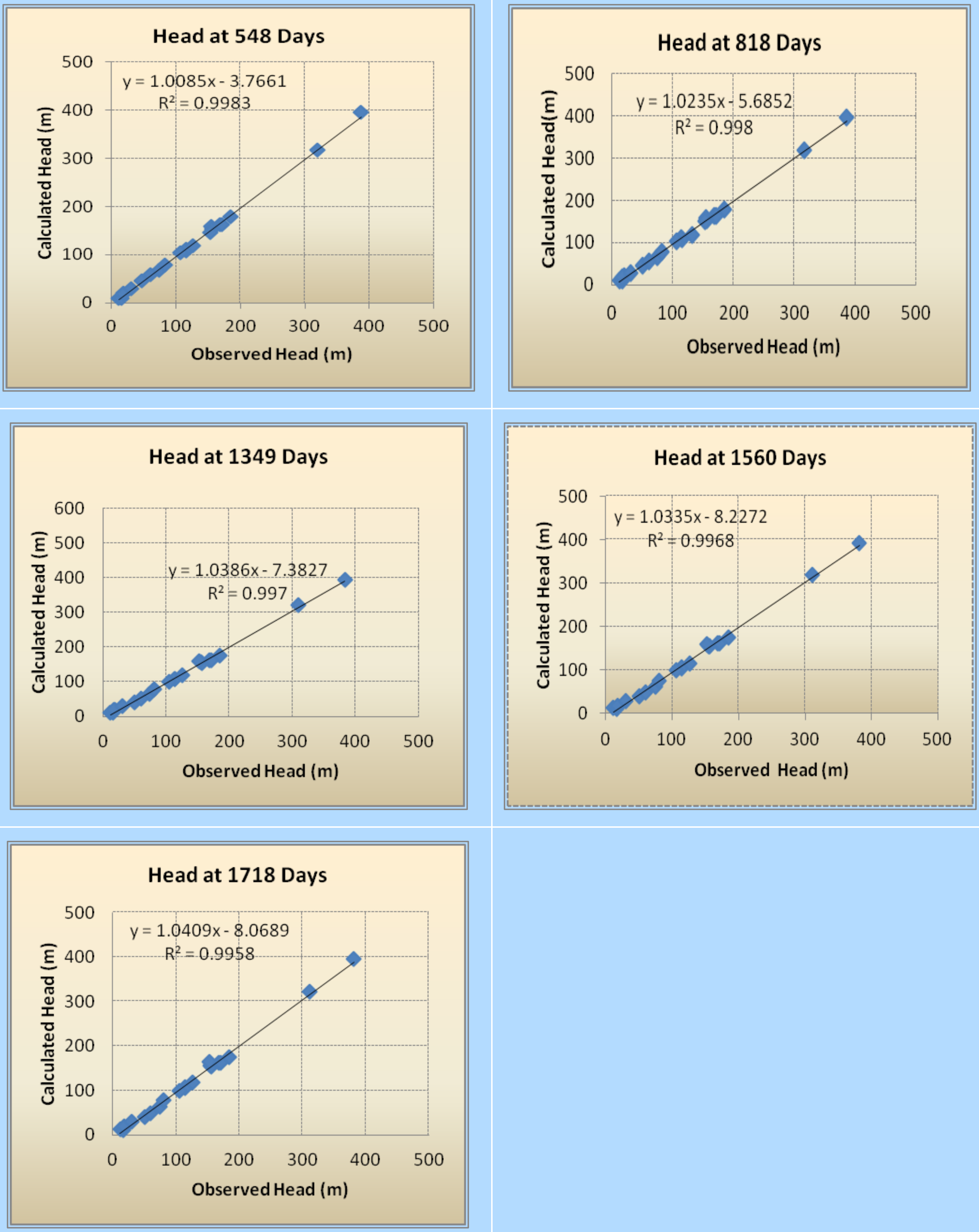


Figure 39:Scatter plot between the simulated water levels using auto calibration and observed water levels.



Discussions of Results

The groundwater simulation of the Ganga basin is a very useful step towards formulation of the Ganga river basin management plan. The groundwater model shall enhance the understanding of the system and shall help make decisions accordingly. The various components of the results range from the River-water balance to the Aquifer-Stream Interaction for various zones. Following paragraphs analyse the various components of the model results.

Mass Balance

Once the groundwater model of the Ganga basin is in place, it can be used for extracting a range of information that provides an insight into the dynamics of the groundwater at any selected instance. For example,Figure 40 depicts the mass balance of the modelled region for a given stress period- 365 days from the start of the simulation (May 2000). Similar results were also obtained for the other stress periods. Here, the blue colour bars indicate the mass that goes into the system and the red indicates the one that is being taken out of the system. It can be seen that during this stress period, the extraction is 5 times more than the recharge that is taking place during this period.

$(\text{Storage})_{in}$ + $(\text{Constant Head})_{in}$ + $(\text{River Leakage})_{in}$ + $(\text{Recharge})_{in}$ = $(\text{Storage})_{out}$ + $(\text{Constant Head})_{out}$ + $(\text{Wells})_{out}$ + $(\text{River Leakage})_{out}$

where,

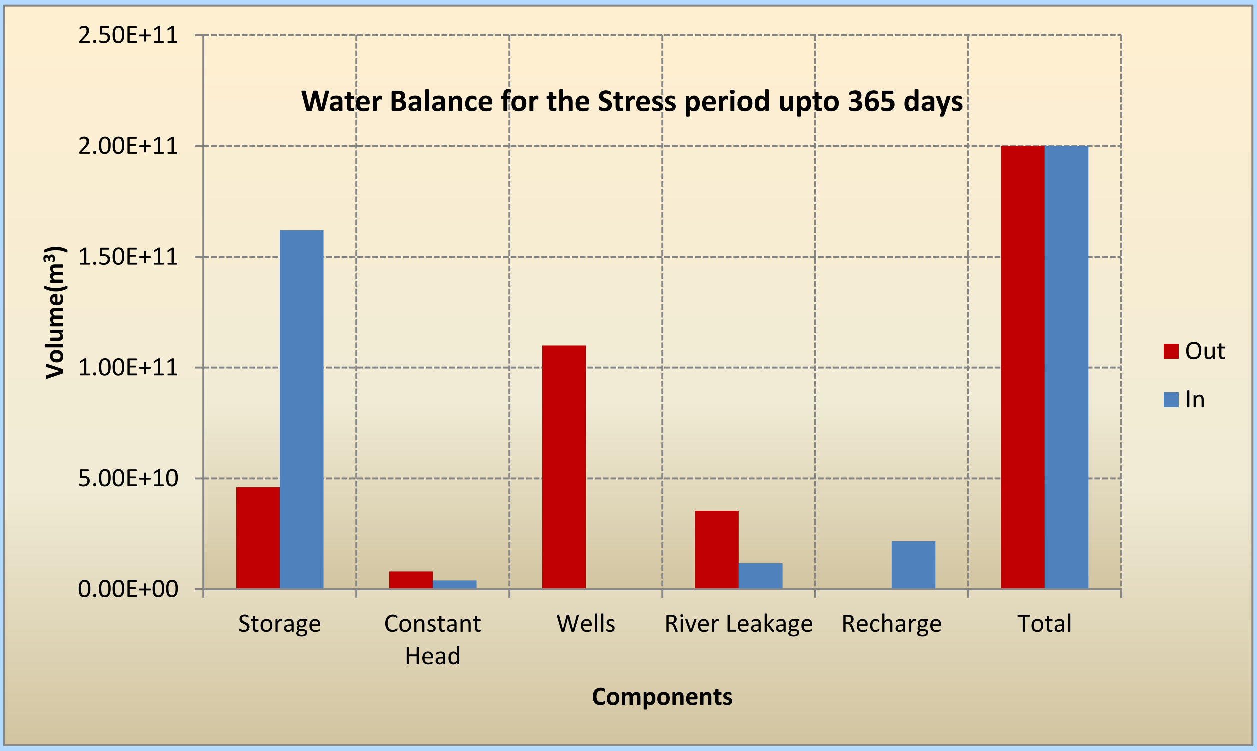
Storage is the amount of water going as storage in the ground water

Constant Head is the boundary condition for such places where required

River Leakage is the leakage from and to the ground water from the river boundaries created in the model

Recharge is the boundary condition for recharging the system zone wise.

Figure 40:Mass balance for the entire study region



Conclusions and Recommendations

The MODFLOW model has been successfully run and calibrated for present conditions in transient mode. The model results are found to be satisfactory and are matching the observed water levels. The model is stable and is converging during the transient run, this means that for different time steps the convergence is established. Overall, the model is working satisfactorily; therefore it can now be used for scenario generation and future projections and for developing suitable policies and management practises for sustainable development of groundwater in this basin.

Chapter 4

Water Demand- Stylised Scenario Simulation

Chapter 4- Water Demand- Stylised Scenario Simulation

Having set up the model and validating it to the extent possible in the wake of the limited data availability of the water utilizations, various scenarios were contemplated to evaluate the implications of the future demands and development as well as ways and means to restore the hydrological health of the Ganga basin. In all three main scenarios have been contemplated (Scenario 1 to 4) for implementation. The first scenario (Scenario 1) is geared to capture the present baseline (being the scenario obtained at the end of the calibration/validation process in the previous sections). This scenario is essential to understand the present status of the Ganga system so as to evaluate its sustainability in the future. Table 3gives a brief outline of the scenarios.

Table 3: Scenarios used in the study

<table>
<tr><th>Scenario</th><th>Years Representing</th><th>Major Water Infrastructure</th><th>Operation</th><th>Diversions</th></tr>
<tr><td>Current Baseline - Business as Usual Scenario 1</td><td>1969-2005</td><td>Existing</td><td>Current</td><td>Existing diversion estimates</td></tr>
<tr><td>Virgin Condition – Pre-development Scenario 2</td><td>Hypothetical – created by switching off all projects</td><td>None</td><td>None</td><td>None</td></tr>
<tr><td>Implementation of Planned Projects Scenario 3</td><td>2020-30</td><td>Mahakali, Kosi, Chisapani (Nepal), and India</td><td></td><td></td></tr>
<tr><td>Business as Usual with increased Irrigation Efficiency Scenario 4</td><td>1969-2005</td><td>Existing</td><td>Current</td><td>Existing diversion estimates</td></tr>
<tr><td rowspan="2">Major Water Infrastructure</td><td colspan="4">Baseline: out of 206 dams/reservoirs available 104 structures were implemented as major structures with available data on the area, capacity and starting year of operation, diversions: major canal diversions as irrigation water use was implemented</td></tr>
<tr><td colspan="4">Future: Planned projects in India and Nepal (Mahakali, Kosi, Chisapani) implemented</td></tr>
<tr><td>Operation</td><td colspan="4">Baseline: Current management/operation practices, irrigation through existing crop water demand. Note: 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</td></tr>
</table>

Description of the Scenarios

Scenario 1 – Current Baseline

It was essential to generate a good understanding of the surface and groundwater behaviour in the Ganga basin. For the purpose the selected models namely, the SWAT hydrological model and the

MODFLOW groundwater model were used to map the Ganga basin and were followed with calibration and validation procedure as described and Chapters 2 and 3 respectively. Thus, both the validated SWAT and MODFLOW models have been used for developing other scenarios in a reliable manner and the results of the same are discussed in the subsequent sections.

Scenario 2 - Virgin condition

The Virgin scenario is required to get an estimate of the hydrological condition prior to the water resources development as prevalent presently in the basin. This scenario has been developed for both surface and groundwater. The virgin condition shall also serve as the guiding condition for the assessment of environmental flows in various stretches of the basin and the implication of the water resources development thereof.

In order to get an estimate of the virgin surface water hydrological condition of the Ganga basin, the calibrated SWAT model was used after switching off all the projects and reservoirs that are existing in the basin and are being used for distributing water for irrigation and various other purposes. Accordingly, all the irrigation management practices were also changed in the Virgin Scenario. All the irrigation practices are assumed to be absent in case of virgin condition.

In the case of the MOFLOW model, the virgin conditions were obtained assuming that there is no pumping from the groundwater. Through this analysis using the results from the virgin flows it can be evaluated as to how much extent to which the basin has been exploited because of anthropogenic groundwater abstraction. More importantly, this study will reveal the stretches that were originally effluent (gaining) stretches and how these stretches have been converted to influent (loosing) due to over exploitation of groundwater resources in some areas of the basin. Another important fact which is of interest to us is to know as to which of the stretches where losing stretches even under virgin conditions.

Scenario- 3 - Implementation of Planned Projects (Future Scenario)

In this scenario, the effect of the future projects on the overall hydrologic health of the system is evaluated. This is implemented by adding the future planned projects in SWAT model. In the absence of the detailed information on the future project details, such as command areas and utilization policies appropriate assumptions have been incorporated wherever required.

Scenario -4 - Business as Usual with increased Irrigation Efficiency condition

Under this scenario, the main objective is to unearth the effect of increase in the Irrigation efficiency while demand, rainfall, developments remain same as per the Present Scenario. Also, this scenario can be used to see the effect of the advancement of irrigation practices on the surface runoff.

Attributing impact of increased Irrigation Efficiency condition

The advantage of purported increase in irrigation efficiency can be thought to have circumvented the demand on surface or groundwater. The increase in irrigation efficiency implemented in SWAT model is synonymous with reduction in water usage of about 33% of the actual water utilization under the present condition. This reduction in water usage concomitant to the increase in efficiency of irrigation may be attributed to surface water usage and/or ground water extraction. The following two sub-scenarios are, hence, generated:

a) Reducing pumping by 20% of the actual pumping rates: In this case, the assumption is that the attribution of reduction in water usage is given to surface water and ground water. Assuming that 13% (of the 33%) is the reduction attributable to surface water usage, the ground water pumping reduction is remaining 20% (of the 33%) of the gain on account of enhanced efficiency while implementing MODFLOW ground water model.
b) Reducing pumping by 33% of the actual pumping rates: This scenario assumes that the whole benefit of enhanced irrigation efficiency has been attributed to reduction in pumping of ground water. Hence, the full reduction of 33% of the actual pumping rates is implemented for ground water simulation in MODFLOW.

Model Results

The model results for the various scenarios are compiled and discussed on a sub-basin scale to make more sense out of the results for the recommendation towards the River Basin Management Plan. The following section describes the scenarios for each of the sub-basins.

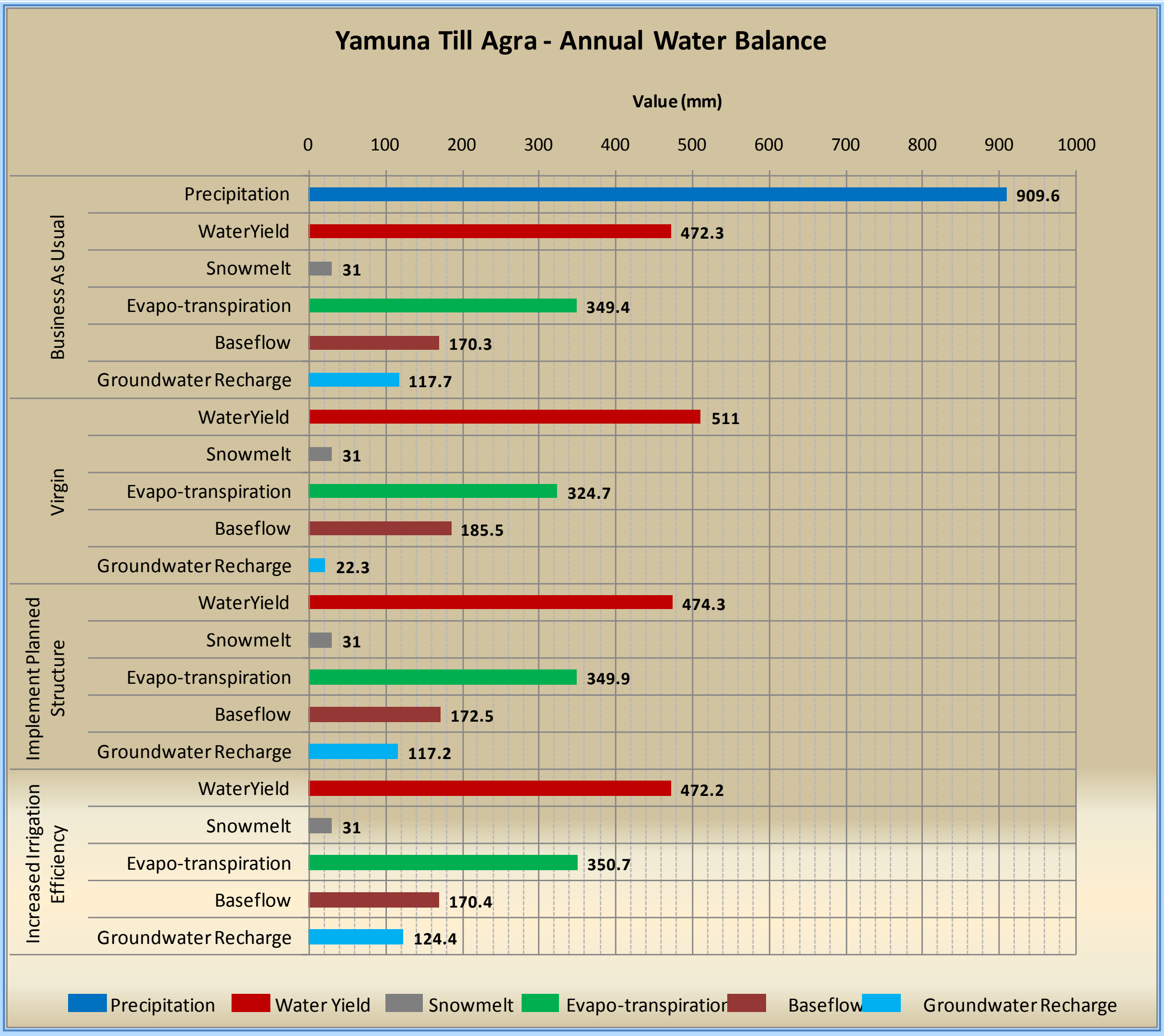
The Scenario 2, generated a very important output for pre-development (Virgin) conditions. It may be observed that in comparison with the virgin condition, there is a considerable deviation in the present status of the system. Except for the head water regions such as Kosi, Yamuna and Ram Ganga basin, for all other basins there is a considerable reduction in the dependable flows in the FDC. The FDC for all the basins are shown as Appendix to this document.

Yamuna Sub-basin

It can be observed from the water balance plots for different scenarios that there is considerable drift from the virgin to the present status in terms of the Groundwater recharge. The recharge into groundwater is on account of the increased area under irrigation when compared to the virgin conditions. However, the base flow contribution to the river from the aquifer has reduced from a value of 185.5mm to 170.3mm on an average basis. This may be attributed to the fact that even though there is a considerable recharge that is happening in the sub-basin, but the extraction rate is so high that water levels gets reduced and thereby the base flow contribution to the river is reduced. The Yamuna basin being headwater region, most percent of it is still virgin from the water yield point of view. It can be observed that there is only 7.5% change in the water yield when compared to the virgin conditions.

Similarly in the case of scenarios of future development and increased efficiency also, there is a 10% decrease of water yield and a drastic increase of ground water recharge. It is to be noted that the groundwater recharge under the increased efficiency scenario is much more than that of the present status. This can be attributed to the way the scenario has been implemented. Although the increase in efficiency has been implemented at the crop water use level, but the irrigation amount applied is the same as business as usual that has resulted in the surplus water that is obtained from the increased efficiency to add to the groundwater rather into the water yield.

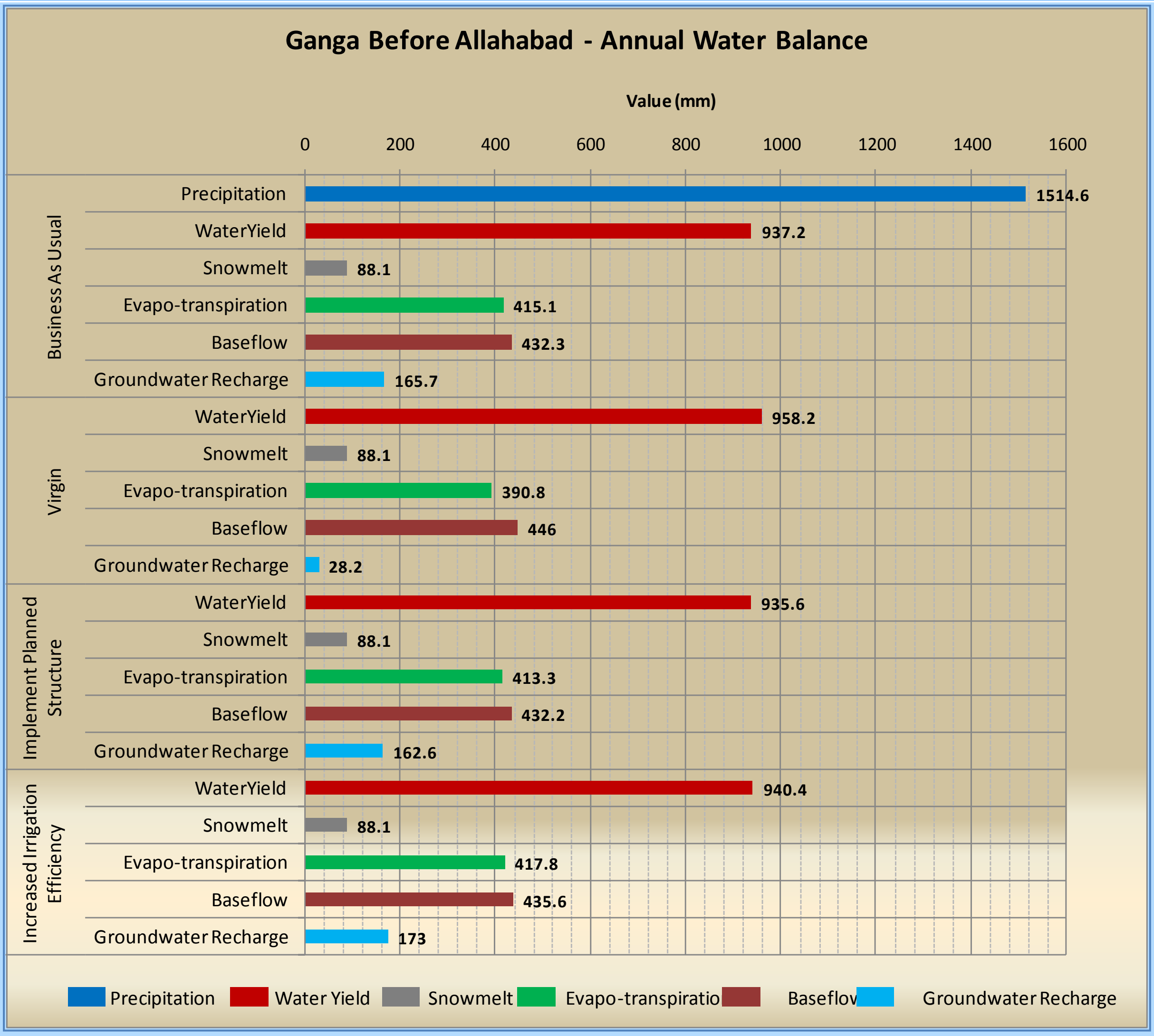
Figure 41: Annual Water Balance for Yamuna Basin Till Agra



Ganga basin before Allahabad.

The average annual water balance for the Ganga basin till Allahabad for all the scenarios show a similar behavior as seen in the case of Yamuna basin. There is a small decrease (2%)in the water yield when compared to the virgin conditions. Also, there is no considerable change in the baseflow component. It may be said that the system is under control and can sustain future water resources development as is shown from the results of the future scenario in which the planned structures are implemented.

Figure 42: Annual Water Balance for Ganga Basin Till Allahabad

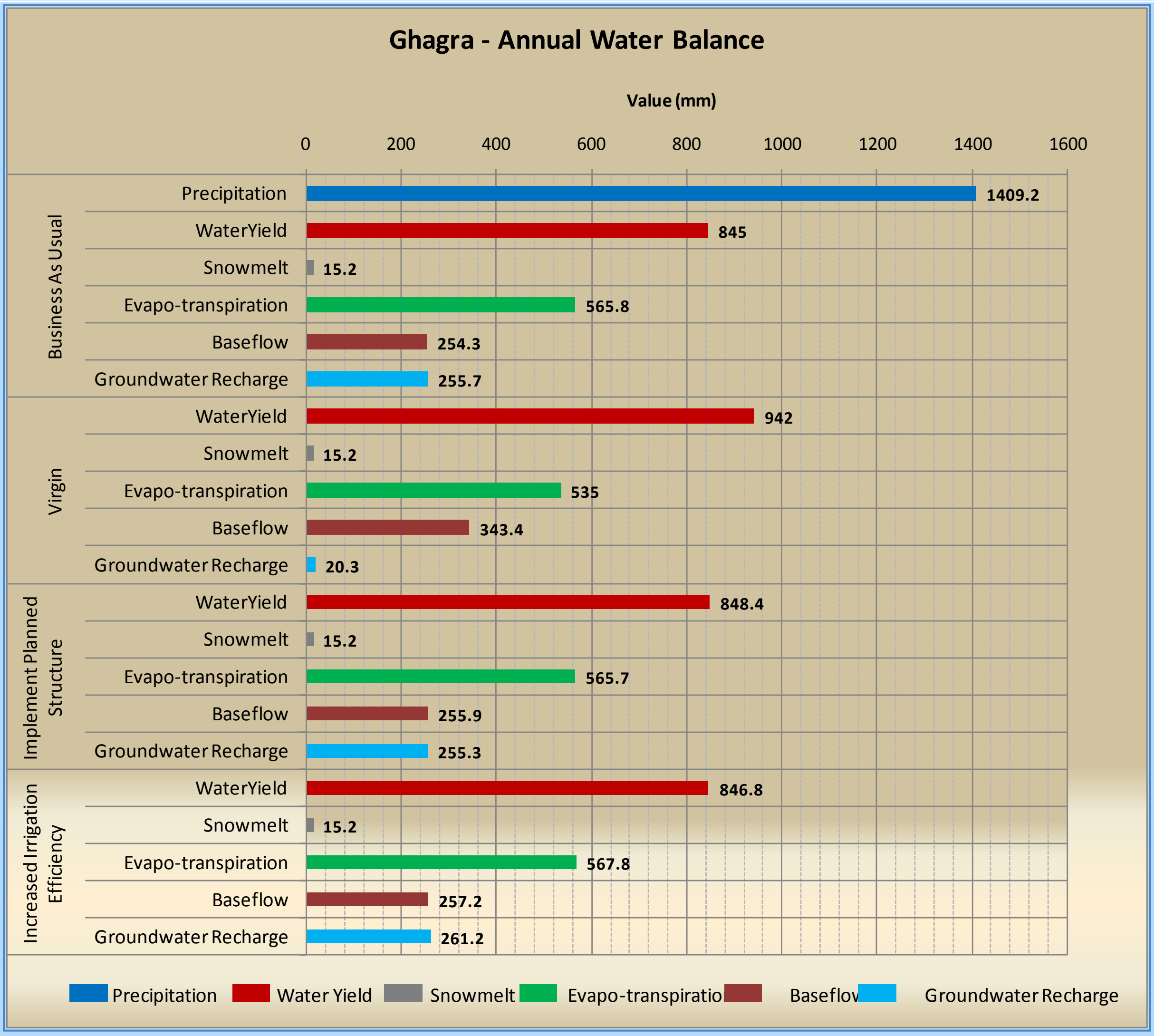


Ghaghra Basin

The scene in the Ghaghra basin is slightly different from the Yamuna and Ram Ganga basins. Here, the water yield has decreased by 10% in comparison with the virgin conditions. And also, there is a huge increase in the groundwater recharge. These above facts show that there is considerable area under irrigation (irrigation projects) which has lead to the decrease in the water yield and increase in the groundwater recharge.

Similar kind of observation was seen in the other basins also. Overall it can be said that the condition at present is very much deviated from the virgin condition and it will become more worse with future developments in the basin.

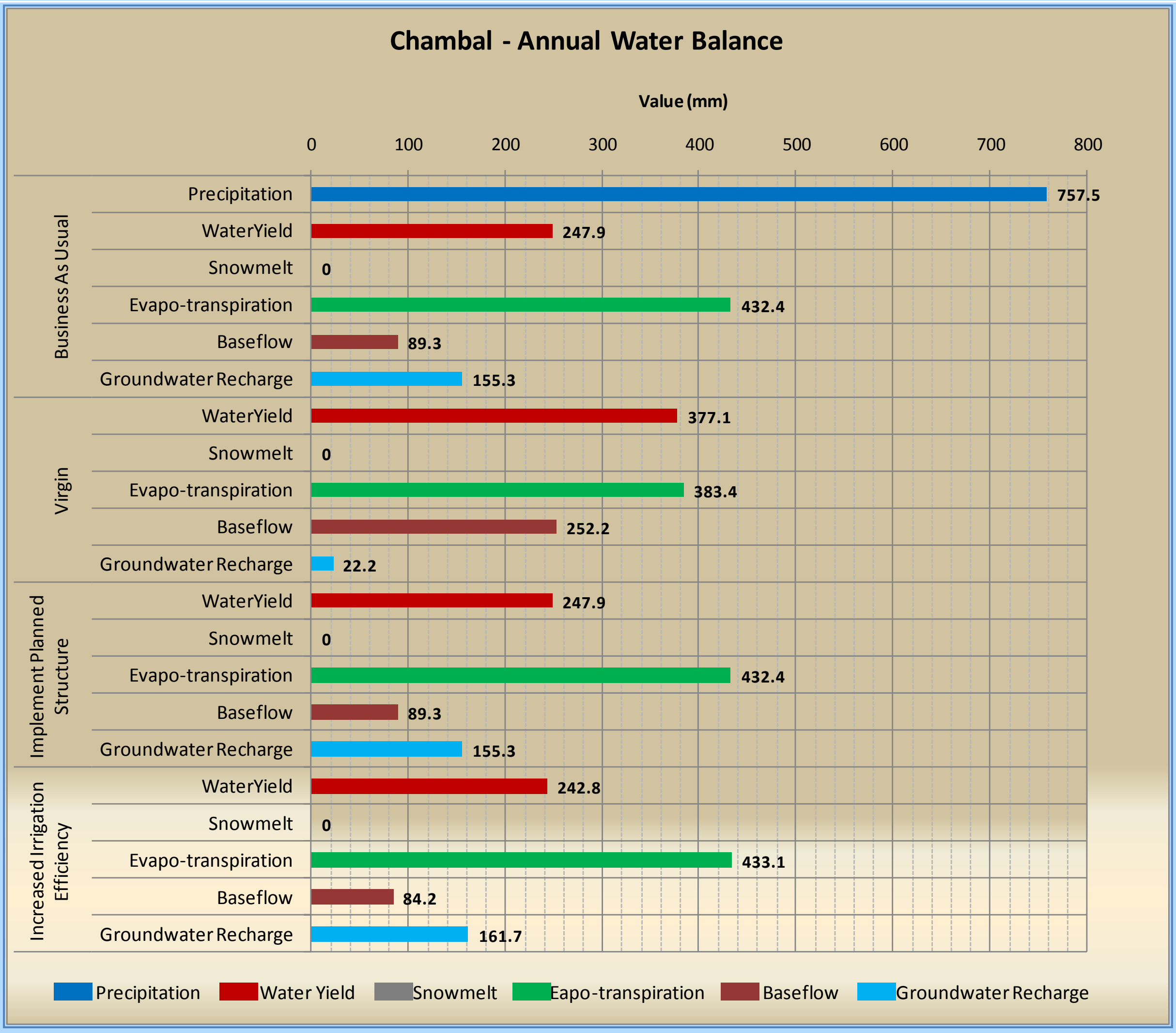
Figure 43: Annual Water Balance for Ghagra Basin



Chambal Basin

The scenario in the Chambal basin is slightly different from Ghaghra basin. Here, the water yield has decreased by whooping 34% in comparison with the virgin conditions. And also, there is a huge increase in the groundwater recharge. These above facts show that there is considerable area under irrigation (irrigation projects) which has lead to the decrease in the water yield and increase the groundwater recharge. Also, there is a considerable increase in the evapotranspiration in comparison with the virgin conditions. This can be attributed to the increase in the area under irrigation. In the future scenarios, there is no change in the water balance because there are no projects coming up in the recent years. However, in the increased efficiency scenario there is an increase in the groundwater recharge due to the fact that the excess water saved through efficiency is fed to the aquifer.

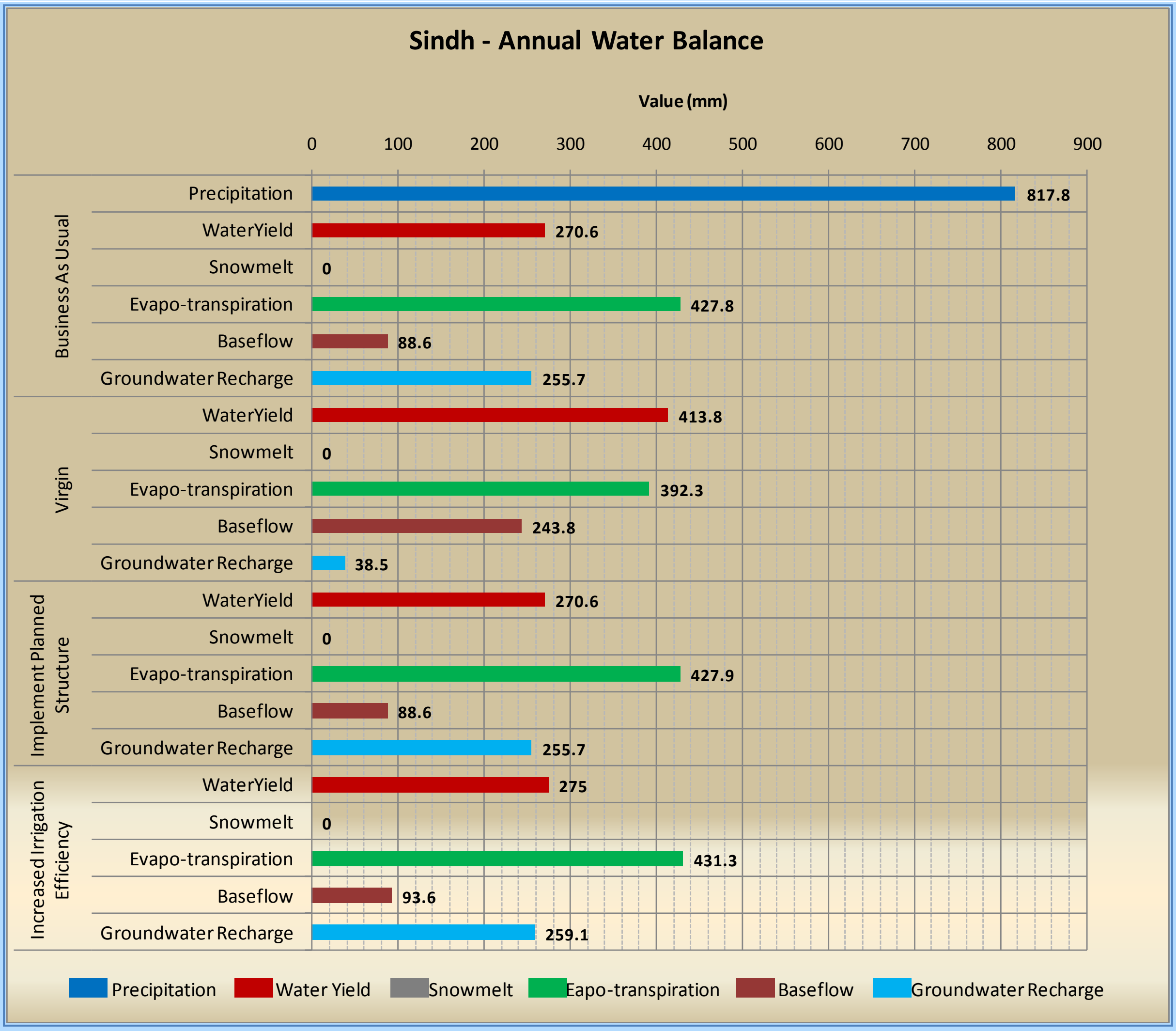
Figure 44: Annual Water Balance for Chambal Basin



Sindh Basin

In this basin, the water yield has decreased by 34% in comparison with the virgin conditions. And also, there is a huge increase in the groundwater recharge. These above facts show that there is considerable area under irrigation (irrigation projects) which has lead to the decrease in the water yield and increase in the groundwater recharge. Also, there is a considerable increase in the evapotranspiration in comparison with the virgin conditions. This can be attributed to the increase in the area under irrigation. In the future scenarios, there is no change in the water balance because there are no projects coming up in the recent years. However, in the increased efficiency scenario there is an increase in the groundwater recharge due to the fact that the excess water saved through efficiency is fed to the aquifer.

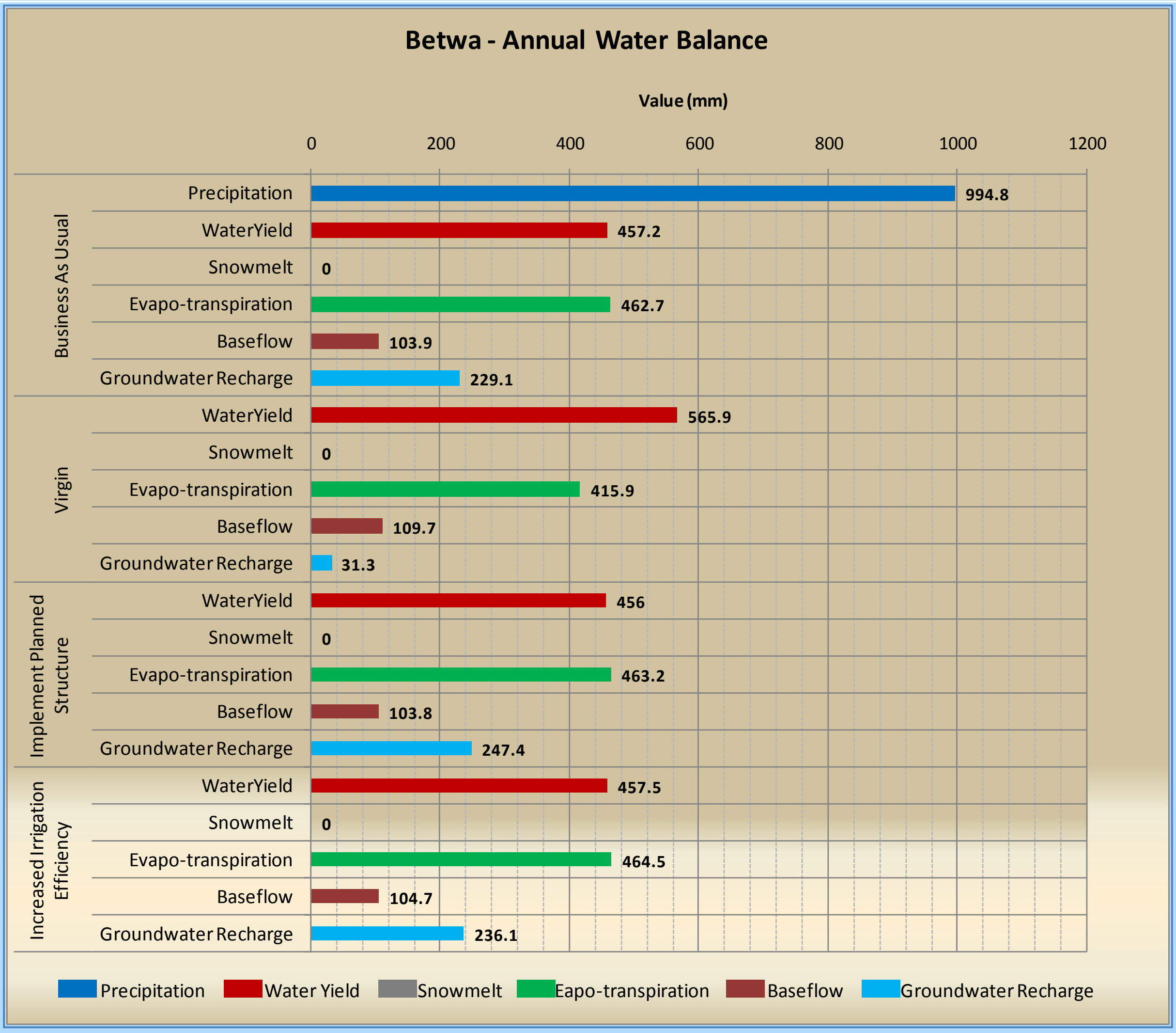
Figure 45: Annual Water Balance for Sindh Basin



Betwa Basin

The scenario in the Betwa basin is slightly different from the other basins, here, the water yield has decreased by 19% in comparison with the virgin conditions. And also, there is a huge increase in the groundwater recharge. These above facts show that there is considerable area under irrigation (irrigation projects) which has lead to the decrease in the water yield and increase in the groundwater recharge. Also, there is a considerable increase (11%) in the evapotranspiration in comparison with the virgin conditions. This can be attributed to the increase in the area under irrigation. In the future scenarios, there is no change in the water balance because there are no new projects coming up in the recent years. However, in the increased efficiency scenario there is an increase in the groundwater recharge due to the fact that the excess water saved through efficiency is fed to the aquifer.

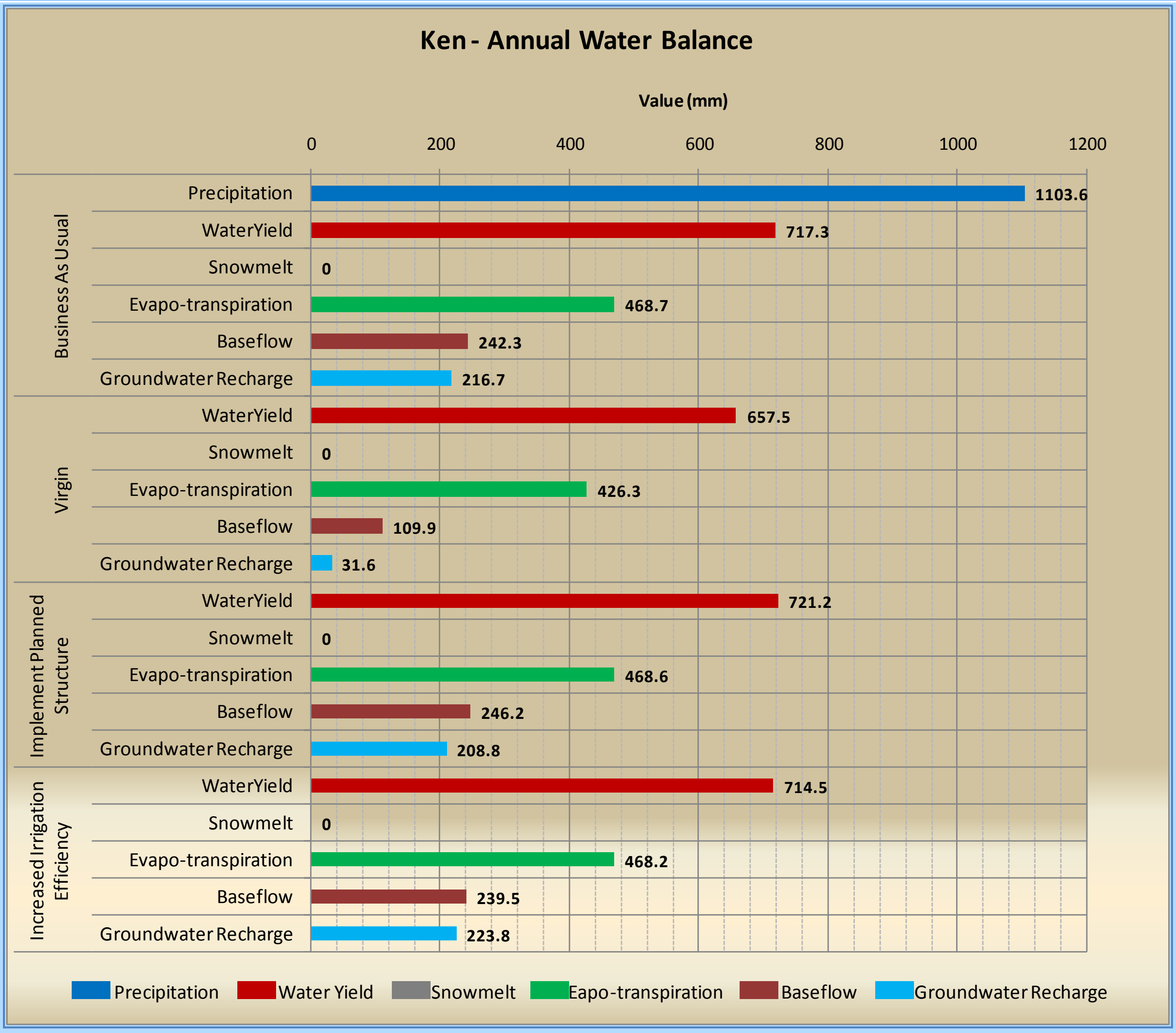
Figure 46: Annual Water Balance for Betwa Basin



Ken Basin

The scenario in the Ken basin is slightly different from the other basins, here, the water yield has increased by 15% in comparison with the virgin conditions. And also, there is a huge increase in the groundwater recharge. These above facts show that there is considerable area under irrigation (irrigation projects) which has lead to the decrease in the water yield and increase in the groundwater recharge. Also, there is a considerable increase in the evapotranspiration in comparison with the virgin conditions. This can be attributed to the increase in the area under irrigation. However, in the increased efficiency scenario there is an increase in the groundwater recharge due to the fact that the excess water saved through efficiency is fed to the aquifer.

Figure 47: Annual Water Balance for Ken Basin



Gandak and Kosi Basin

The scenario in the Gandak and Kosi basins is slightly different from the other basins, here, the water yield has decreased by 34% in comparison with the virgin conditions. And also, there is a huge increase in the groundwater recharge. These is considerable area that has been brought under irrigation (irrigation projects) which has lead to the decrease in the water yield and increase the groundwater recharge. However, it is to be noted that the baseflow in rivers have considerably reduced in comparison with the virgin conditions because of the reduction in the net recharge of aquifer and over extraction from aquifer for irrigation. In the future scenarios, there is no change in the water balance because there are no new projects coming up in the recent years. However, in the increased efficiency scenario the there is a increase in the groundwater recharge due to the fact that the excess water saved through efficiency is fed to the aquifer.

Figure 48: Annual Water Balance for Gandak Basin

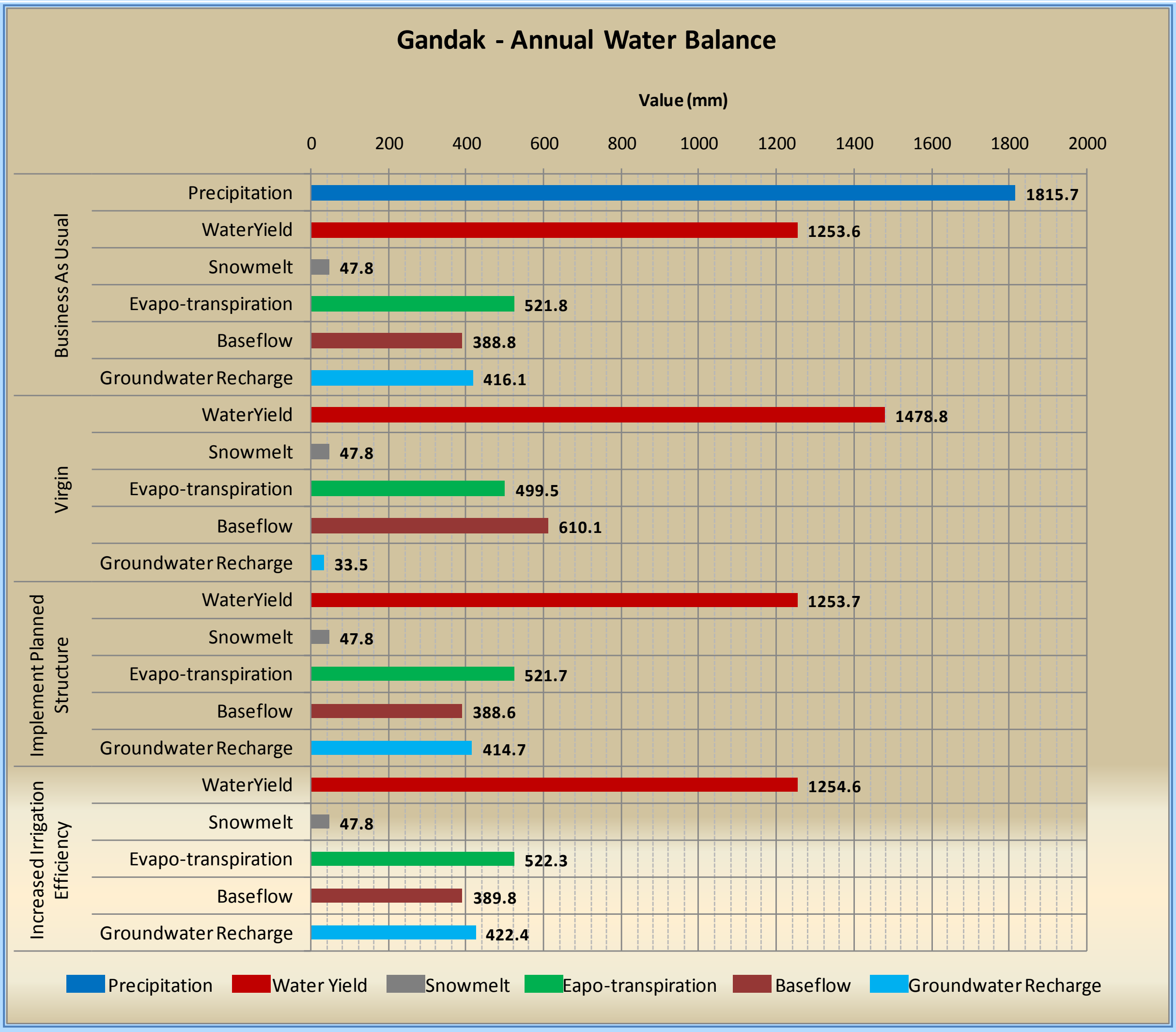
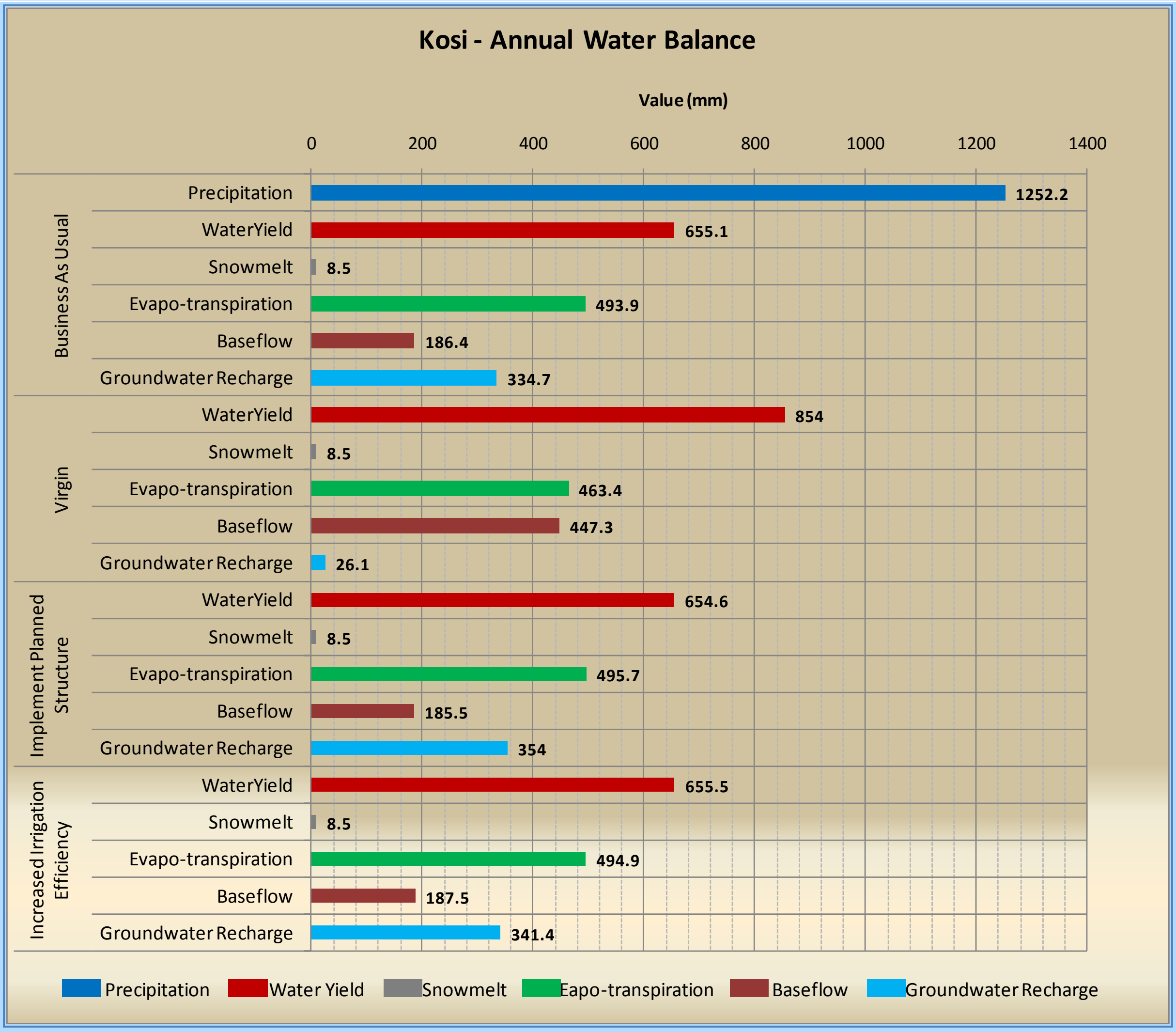


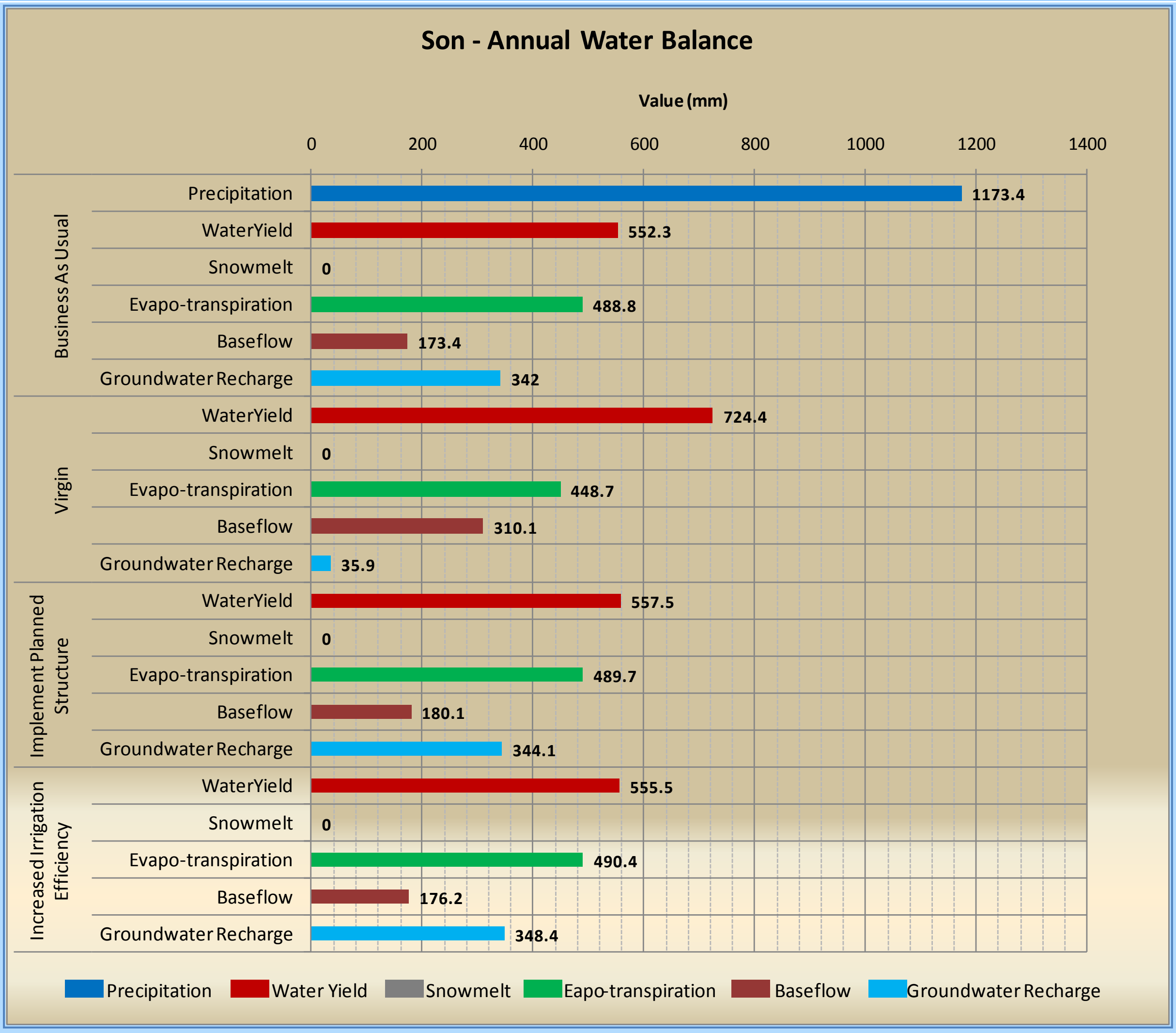
Figure 49: Annual Water Balance for Kosi Basin



Son Basin

The scenario in the Son basin is similar to Kosi basin, here also, the water yield has decreased by 23% in comparison with the virgin conditions. And also, there is a huge increase in the groundwater recharge.

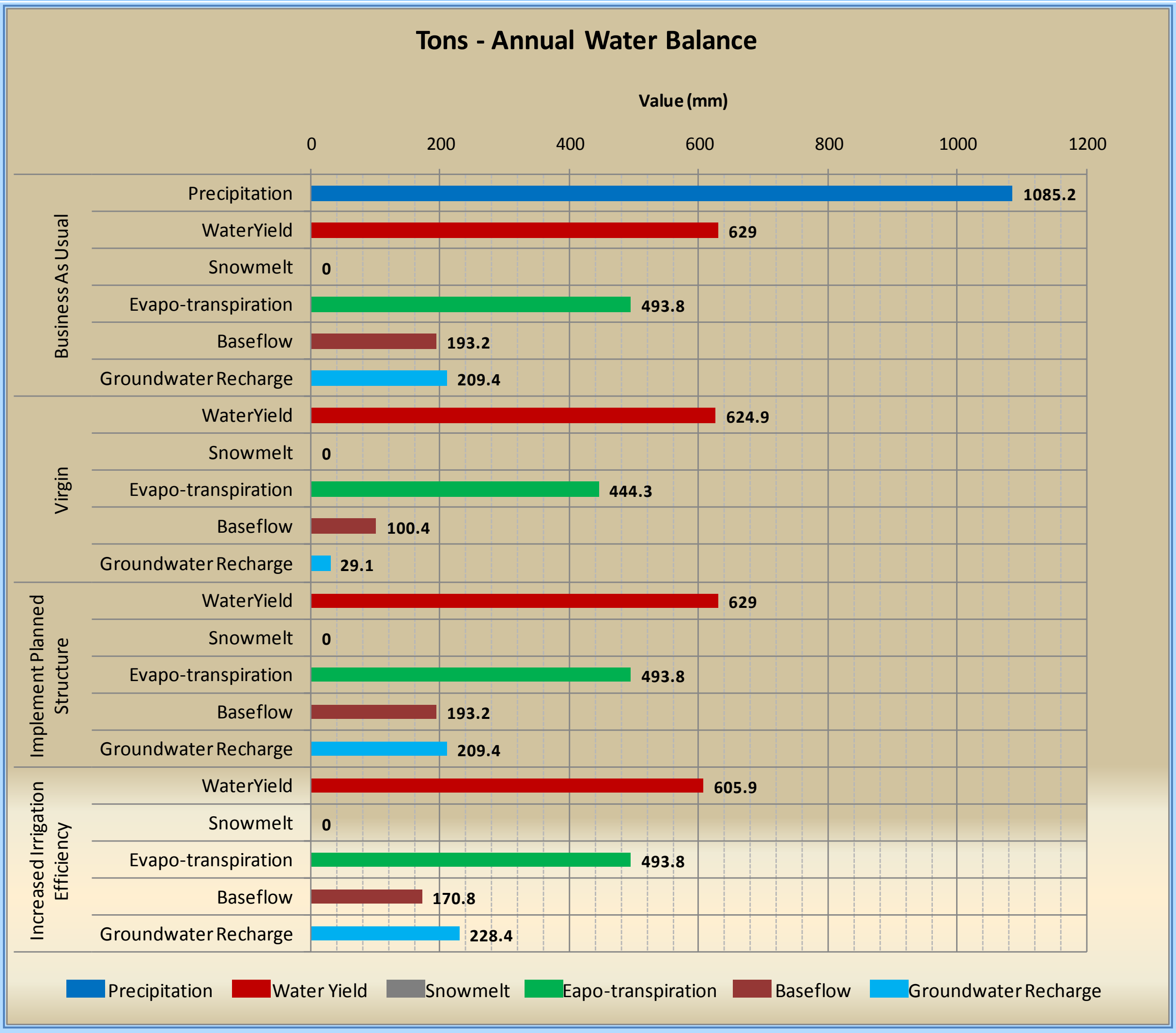
Figure 50: Annual Water Balance for Son Basin



Ton Basin

The scenario in the Ton basin behave similar to Yamuna. Here, water yield has not changed much in comparison with the virgin conditions. And also, there is a huge increase in the groundwater recharge.

Figure 51: Annual Water Balance for Tons Basin



Ground water Results

The model results for the various scenarios in the groundwater system are captured in the form i) resultant groundwater tables and ii) river-aquifer interaction.

Figure 52 shows the depth to water tables for the virgin and the present (BAU) scenarios. It can be seen that the depth to water table was around 1-5 m in most of the regions basin during the virgin conditions. However, due to over exploitation, the water levels have gone down to a depth range 11-20m during the present scenario. It is to be noted that the red patches in the plots are the mountainous regions and in these regions, therefore, these areas are depicted as dry cells. On the whole it can be seen that there is a marked difference between the virgin and the present scenarios. In other words, through this scenario, it has become possible to have an assessment of the groundwater status during the pre-development time and this status shall also be the target status for revival of the hydrological health of the basin.

Figure 52: Plot showing the Depth to Water Table for Present and Virgin Scenarios

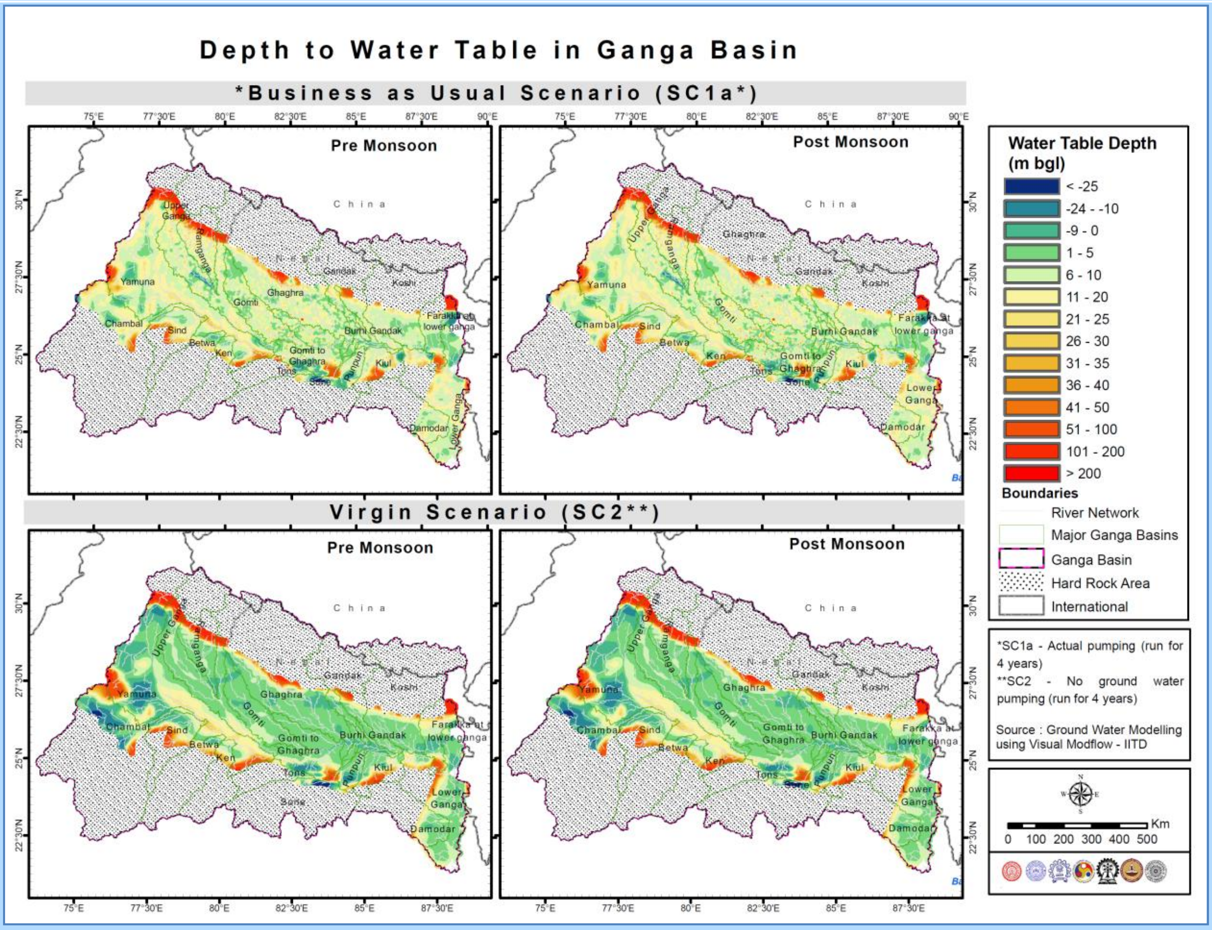
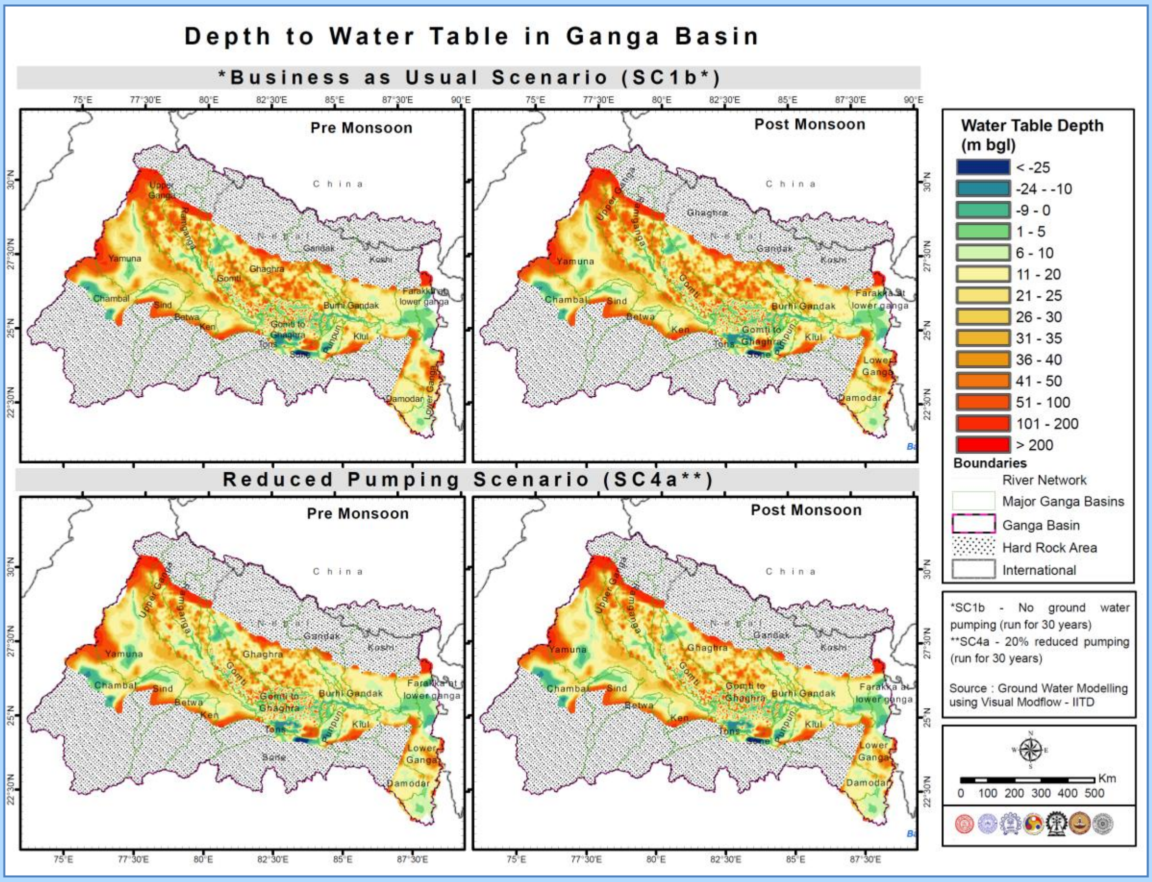
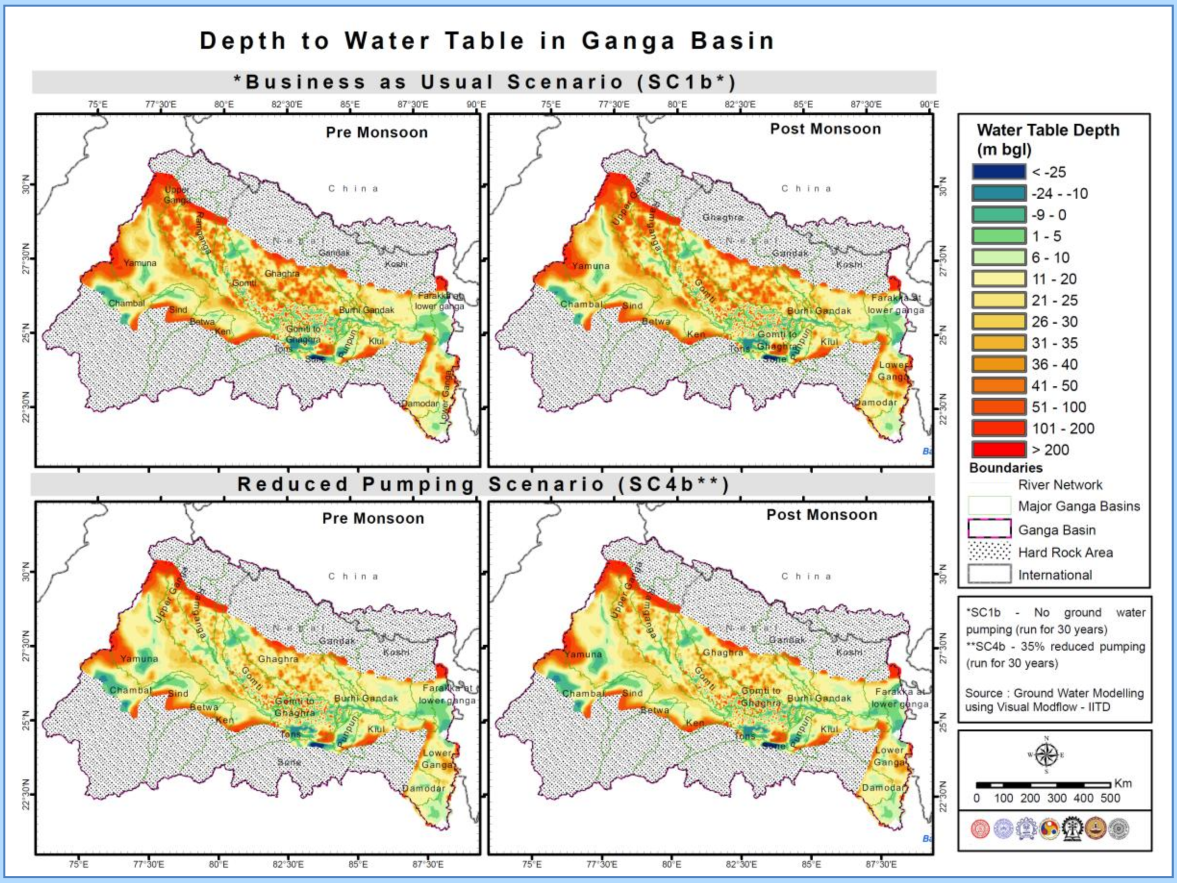


Figure 53 shows results from the scenarios where a comparison has been made between the present scenario and the scenarios where reduction in pumping due to increase efficiency has been made. It can be observed with the improved efficiency in irrigation, there is some reduction in pumping and thereby the system is recovering towards its original state.

Figure 53: Plot showing the Depth to Water Table for different scenarios





The effect of the scenarios over the groundwater was also studied with respect to the river aquifer interaction. Figure 54 shows the pictorial representation of the flux between the aquifer and the river for different stretches along the River Ganga. The results are presented as long-term pre-monsoon and post-monsoon averages. It can be seen that the during the Virgin conditions where there is no pumping, all the stretches are gaining stretches (effluent) except for the one between Chapra and Varanasi. This might be attributed to the topographical nature of this stretch. However, with the over exploitation of the groundwater under the present conditions, most of the river stretches have become either loosing or are gaining much lesser amount of water from the groundwater. For example, some of the stretches under the virgin condition that were blue have become orange or red indicating the over exploitation of aquifer in these areas. It has also been noted that there is a seasonal behavior in the influent / effluent nature of the river stretches. Since, the range of the flux is high, this seasonal difference is not being captured in the figures.

Figure 54: Plot showing the Surface GW interaction for Present and Virgin

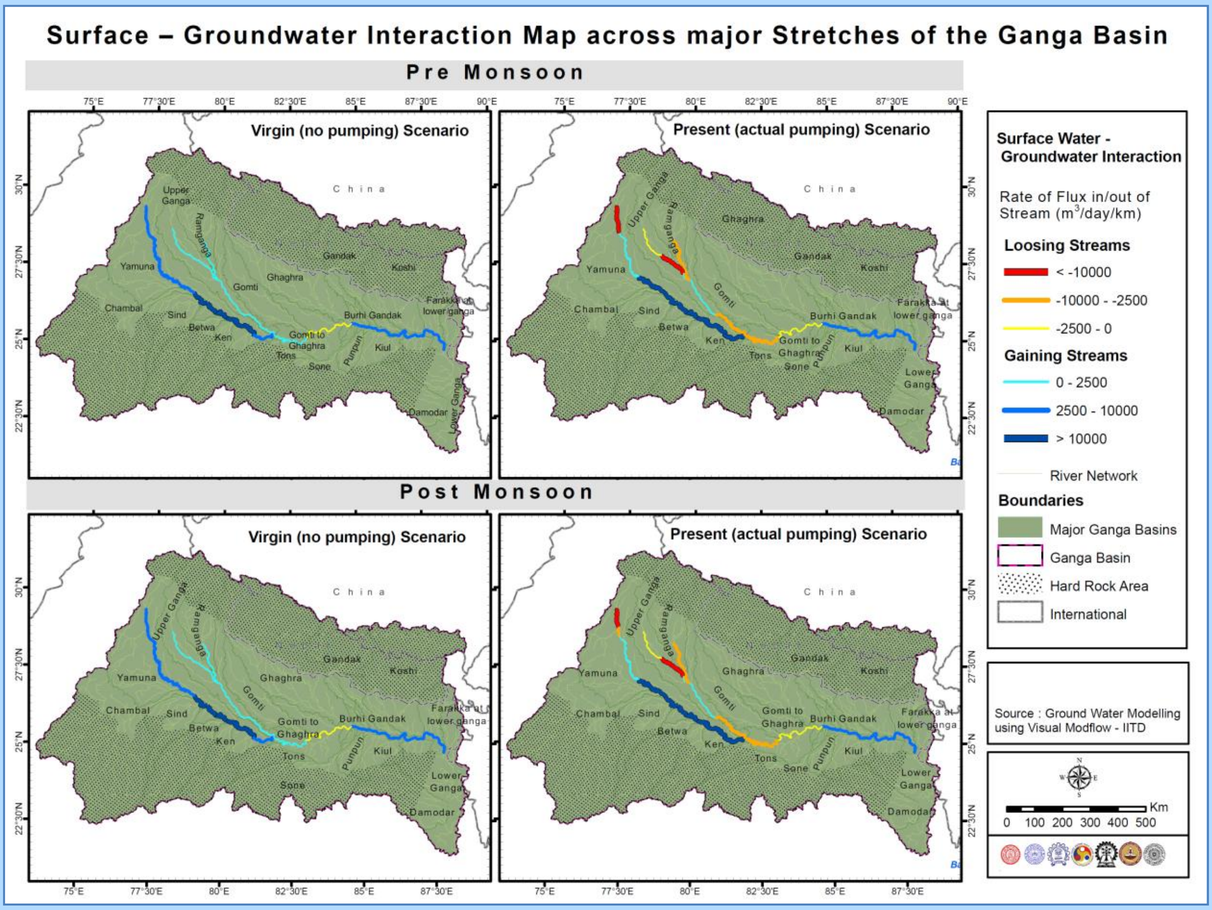
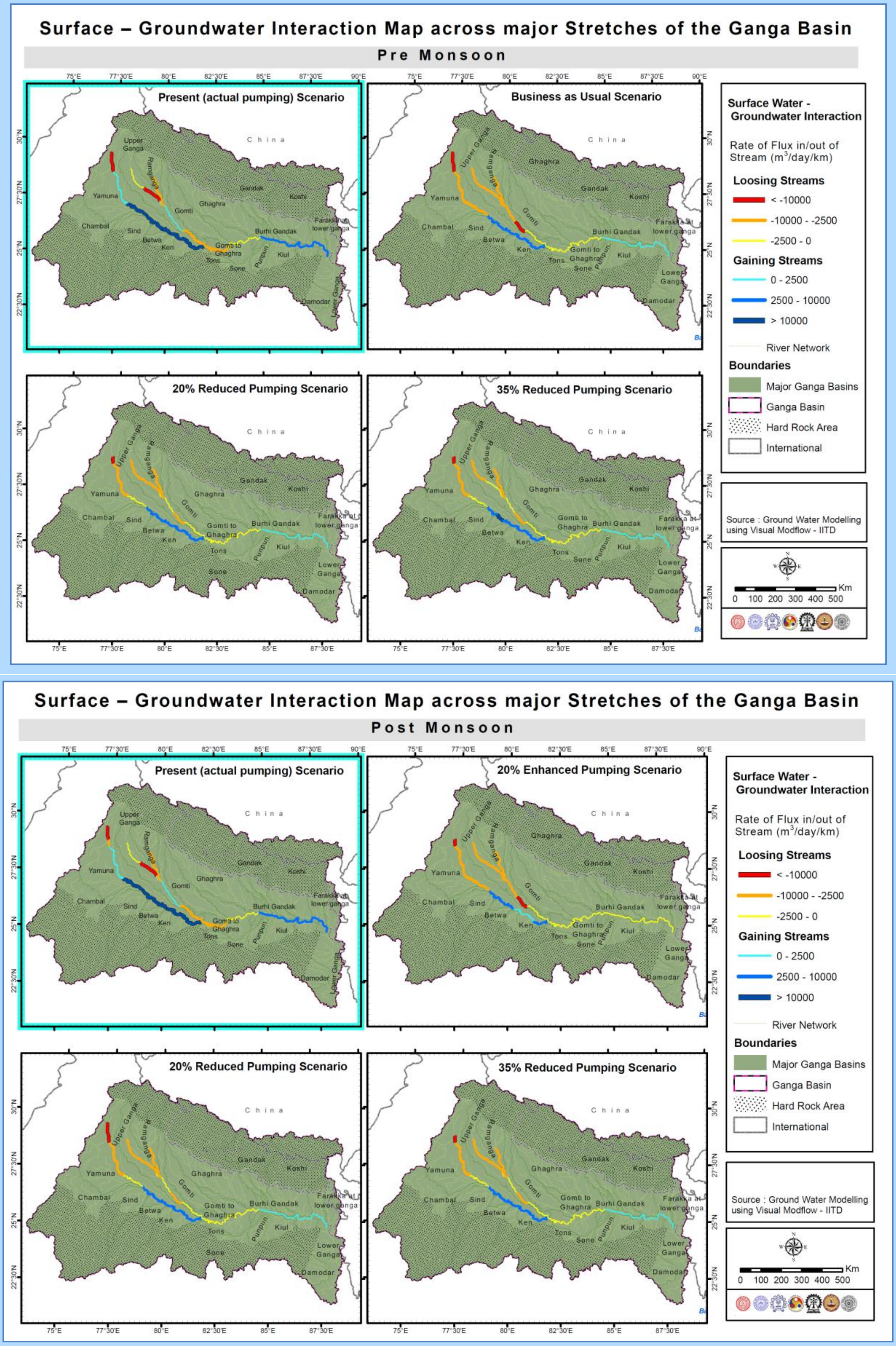


Figure 55 presents the comparison of the present scenario with the different future scenarios. It can be observed that the conditions are becoming worse with the increased pumping and more number of stretches are becoming loosing stretches (see the topmost plot on the right hand side). However, with the increased efficiency of irrigation (Scenario 4), the pumping or the stress over the groundwater is reduced and thereby some of the stretches are again becoming gaining stretches.

Figure 55: Plot showing the Surface GW interaction for different scenarios-Pre Monsoon



Recommendations

For the overall objective of obtaining aviral Ganga it is very essential to restore the hydrologic health of the basin not only w.r.t. the surface water but also w.r.t. the ground water. The comprehensive analysis using hydrological and groundwater model has given us a desired insight into the present functioning of the river basin which would have been otherwise impossible to achieve. At the outset, one thing which has been an obvious outcome of the analysis is that there has been unabated over exploitation of the surface and ground water resources in many parts of the basin. Most of this can be attributed towards irresponsible and unscientific water resources management.

A set of feasible scenarios were formulated and implemented to evaluate the impacts of choosing those scenarios. Although, with the modelling framework established it shall be possible to generate many more scenarios as and when we feel the need for such scenarios, the following recommendations are based only on the limited number of scenarios that have been run.

1. Agriculture being the biggest user of water in the basin, its imperative that the water use efficiency should be reasonably good to match the international achievable levels (a 35% enhancement has been considered). This shall result in a huge saving of water that can be used to revive the hydrological health of the system by reducing the demand on the surface and ground water.

   It is important to understand the interaction between surface water and ground water to ensure a proper regulation of ground water use. The hydrological health of the river basin, which in turn dictates a large number of environmental functions, is intertwined with the ground water usage. For example, if we keep on abstracting the ground water to an extent that the water table falls much below the river water level then a time comes that the river stretch starts losing water to the adjoining ground water aquifer and may render the stretch to be dry. This is entirely opposite to the previous situation where the higher ground water table was feeding to the stretch to provide the base flow during the lean flow season.

   It is recommended that the present system of identifying the ground water mining to declare the grey and red zones should be updated by incorporating the presently demonstrated modelling approach because there can be situations where a lot of ground water is being mined but is not declared a grey or red zone as the water is coming from the adjoining stream and thus, there is no appreciable ground water fluctuation observed, which is the basis of the present situation of declaring the area to be a grey or red zone.

   The ground water abstraction policy should hence, be dictated by the volume of water abstracted from the ground but can also be having a broad based monitoring of the ground water fluctuation as an additional basis.

2. It has been observed that the proposed future developments are going to increase the stress further of the already stressed system. Therefore, it is important that the above mentioned measures are put in place before we execute any of the additional development projects on the system.

3. One other option that can be useful is to induce the recharge during the monsoon period by rejuvenating the existing water bodies and also by artificially inducing the ground water recharge, through reverse pumping close to the major river systems, during the monsoon period. This scenario has not yet been generated, but can be put together once we get a clarity on the quality of water in the various rivers and the strategy to be used to take care of the quality issues.

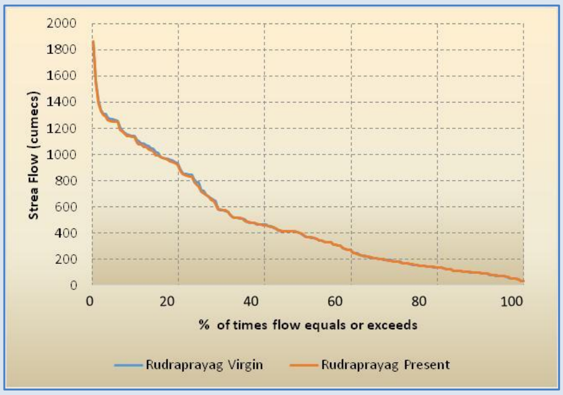
4. The framework developed is also ready to handle the "Nirmal" aspects of the river by modelling the point and non-point sources of pollution of surface and ground water. The attempt could not be made due to the paucity of required data on the source and quantum of the point sourcedomestic pollution load. A detailed spatio temporal data on fertilizer and pesticide use is alsorequired to model the non-point source pollution.

Appendix

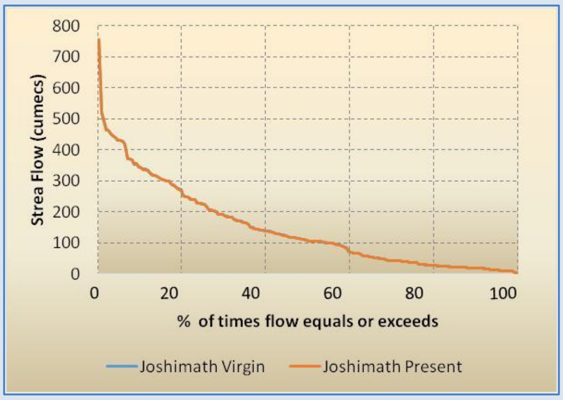
Appendix A: Flow Duration Curve at selected Locations for the Ganga river basin

Flow Duration Curve at selected Locations for the Ganga river basin

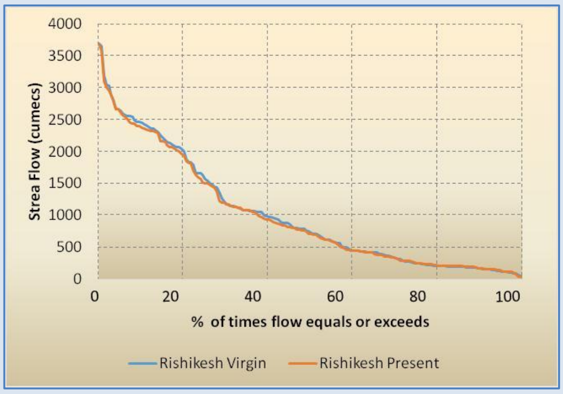
Rudraprayag on Alaknanda (Ganga/Alaknanda)



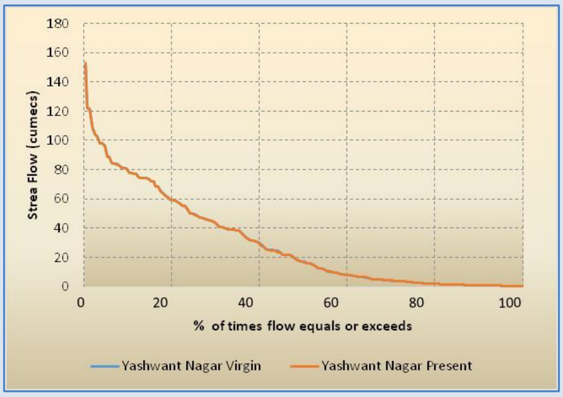
Joshimath on Alaknanda (Ganga/Alaknanda) river



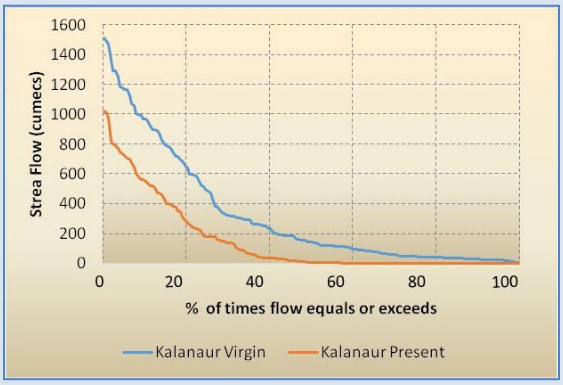
Rishikesh on Ganga river



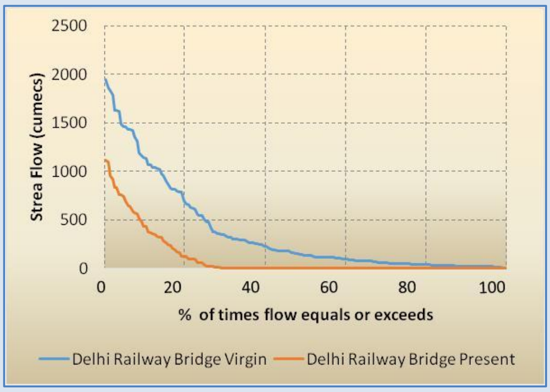
Yashwant Nagar on Giri (Yamuna/Giri) river



Kalanaur on Yamuna (Ganga/Yamuna)river

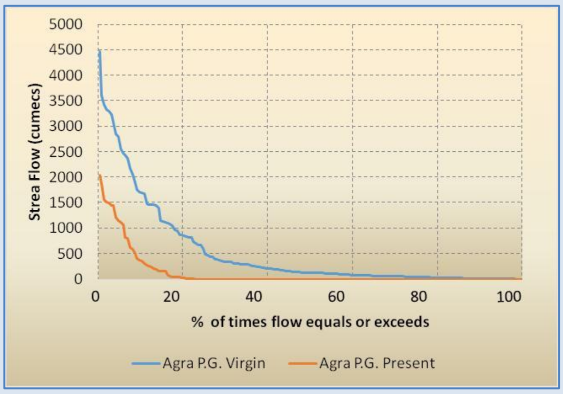


Delhi Rly Bridge on Yamuna (Ganga/Yamuna)

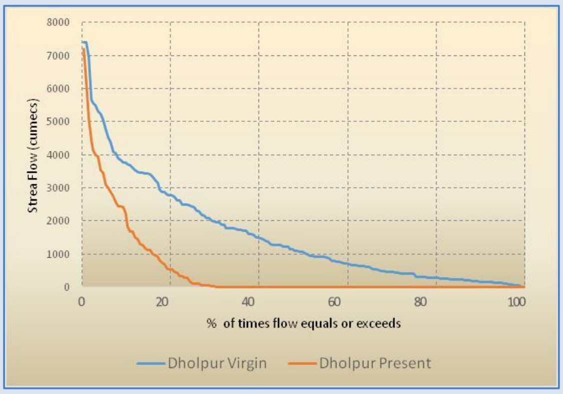


Flow Duration Curve at selected Locations for the Ganga river basin

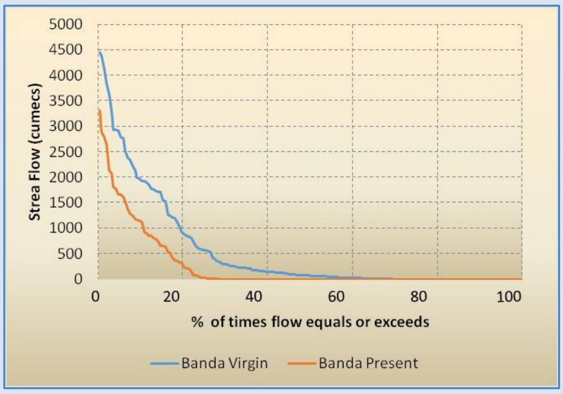
Agra P.G. on Yamuna (Ganga/Yamuna) river



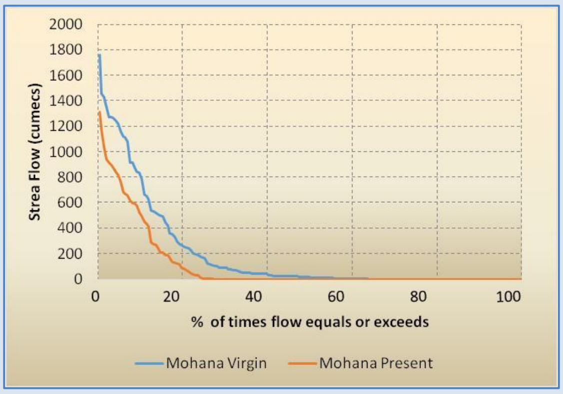
Dholpur on Chambal (Yamuna/Chambal)



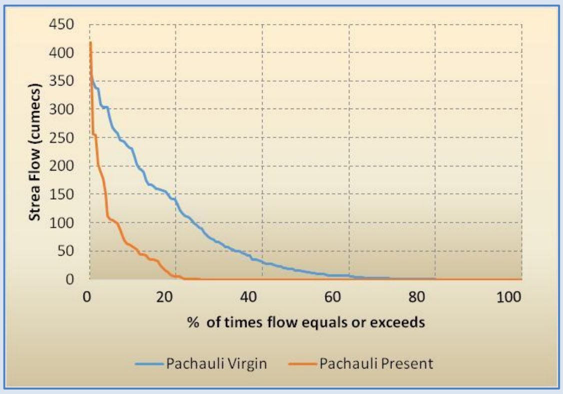
Banda on Ken (Ganga/Yamuna/Ken) river



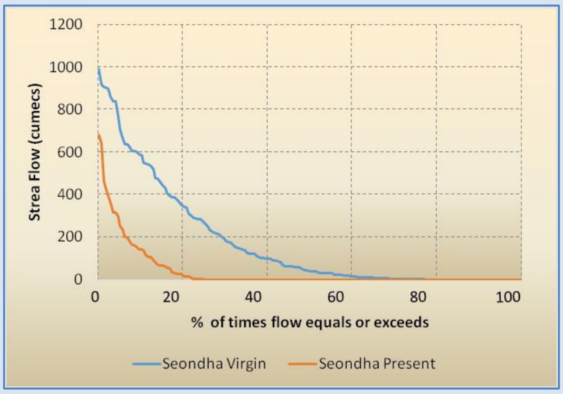
Mohana on Betwa (Ganga/Yamuna/Betwa)



Pachauli on Sind (Ganga/Yamuna/Sind) river

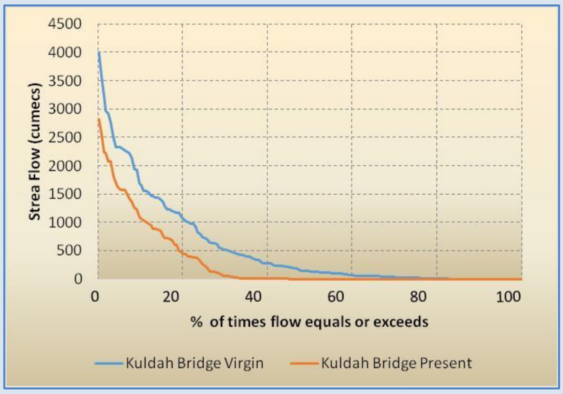


Seondha on Sone (Ganga/Yamuna/Sind) river

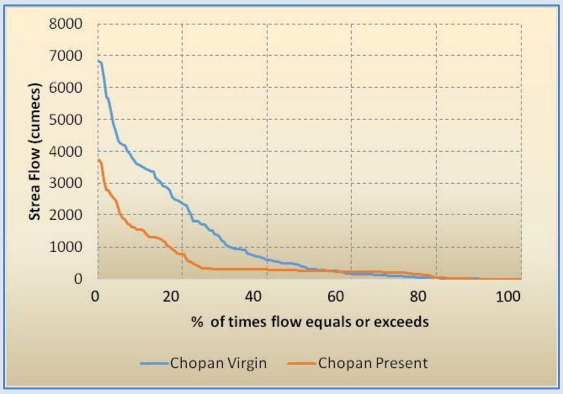


Flow Duration Curve at selected Locations for the Ganga river basin

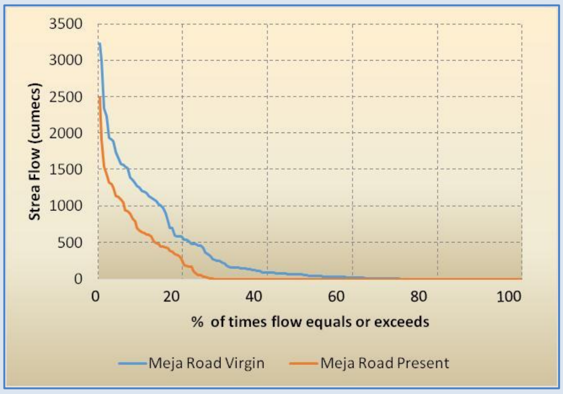
Kuldahbridge on Sind (Ganga/Sone) river



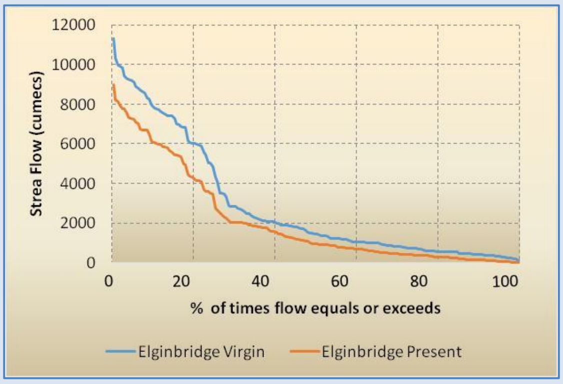
Chopan on Sind (Ganga/Sone) river



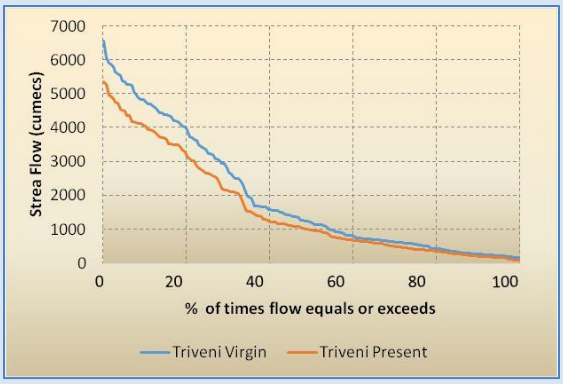
Meja Road on Tons (Ganga/Tons) river



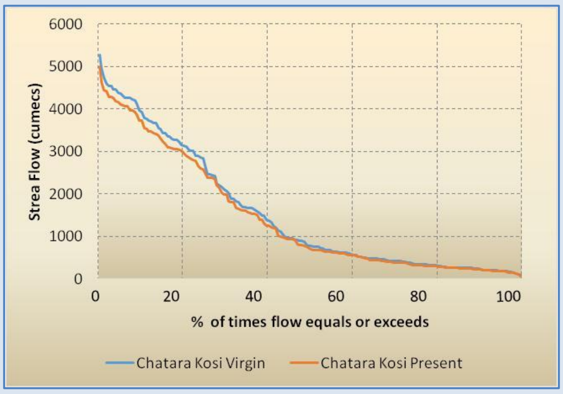
Elginbridge on Ghagra (Ganga/Ghagra) river



Tribeni on Gandak (Ganga/Gandak) river

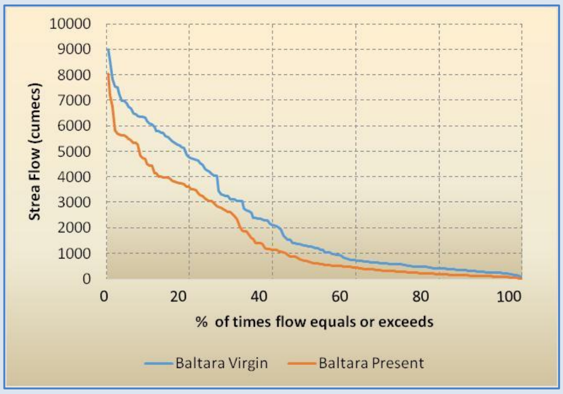


Chatara Kosi on Kosi (Ganga/Kosi) river

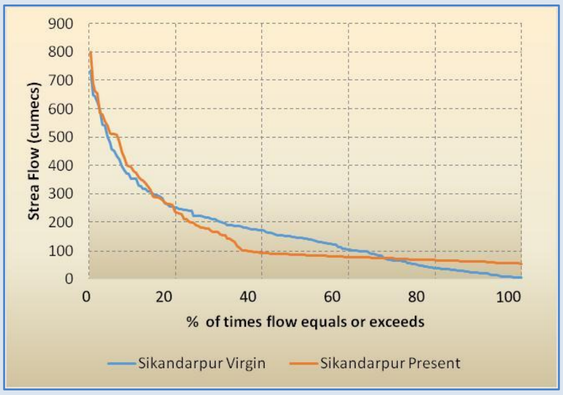


Flow Duration Curve at selected Locations for the Ganga river basin

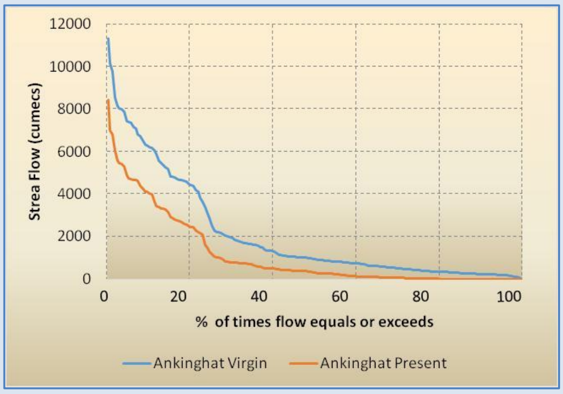
Baltara on Kosi (Ganga/Kosi) river



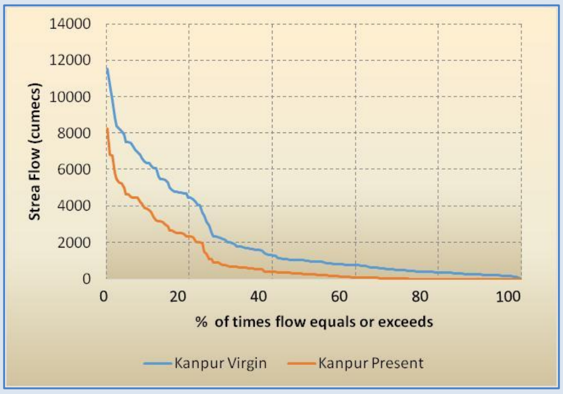
Sikanderpur on Burhi Gandak (Ganga/BurhiG)



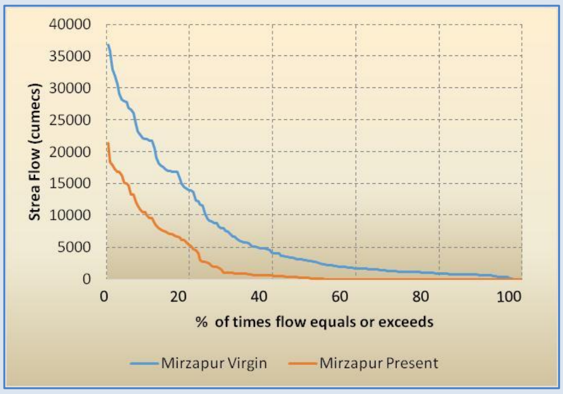
Ankinghat on Ganga river



Kanpur on Ganga river



Mirzapur on Ganga river



Farakka on Ganga river