Ganga River Basin Management Plan-2015

Volume 4:
Thematic Studies – Aviral Ganga

VOLUME 4 OF 12

Centre for Ganga River Basin Management and Studies
Indian Institute of Technology Kanpur

NATIONAL MISSION FOR CLEAN GANGA (NMCG)

NMCG is the implementation wing of National Ganga Council which was setup in October 2016 under the River Ganga Authority order 2016. Initially NMCG was registered as a society on 12th August 2011 under the Societies Registration Act 1860. It acted as implementation arm of National Ganga River Basin Authority (NGRBA) which was constituted under the provisions of the Environment (Protection) Act (EPA) 1986. NGRBA has since been dissolved with effect from the 7th October 2016, consequent to constitution of National Council for Rejuvenation, Protection and Management of River Ganga (referred to as National Ganga Council).

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ACKNOWLEDGEMENT

This document is a collective effort of a number of experts, institutions and organisations, in particular those who were instrumental in preparing the Ganga River Basin Management Plan which was submitted to the Government of India in 2015. Contributions to the photographs and images for this vision document by individuals are gratefully acknowledged.

SUGGESTED CITATION

GRBMP by cGanga and NMCG

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GANGA RIVER BASIN MANAGEMENT PLAN - 2015

Volume 4: Thematic Studies – Aviral Ganga

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Ganga river in
Himalayas mountains

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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Content

Chapter 1 - Introduction

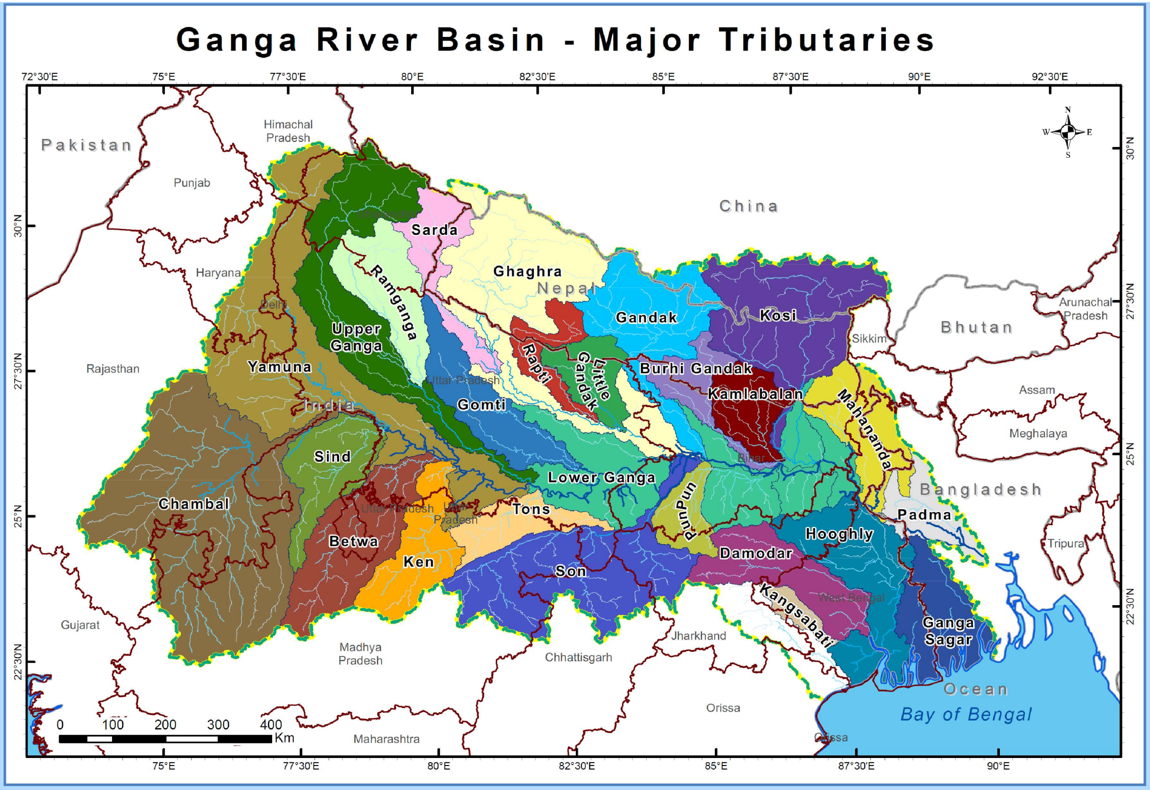
The Ganga River Basin profile

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

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[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

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[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.

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

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

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[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]

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[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]

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[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

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[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

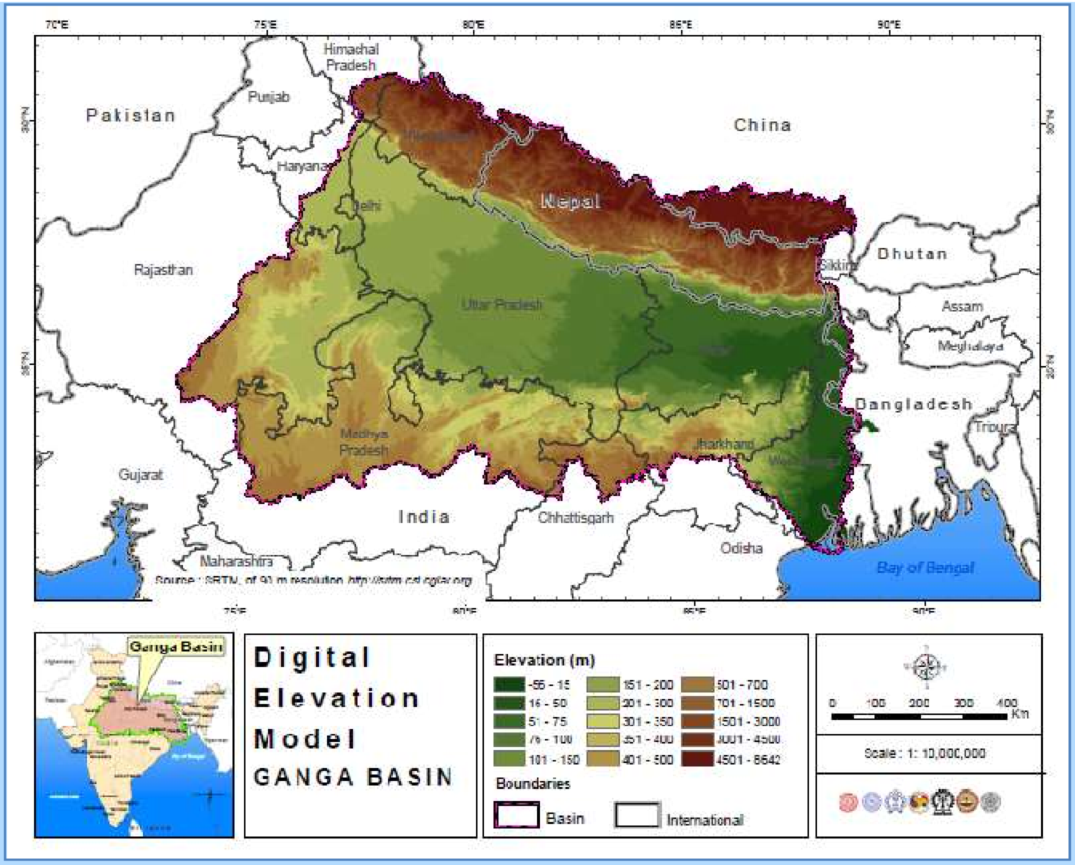
[15] Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith, 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, Transactions of the ASABE, Vol. 50(3): 885–900 2007

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



Source : SRTM, of 90 m resolution http://srtm.csi.cgiar.org

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[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

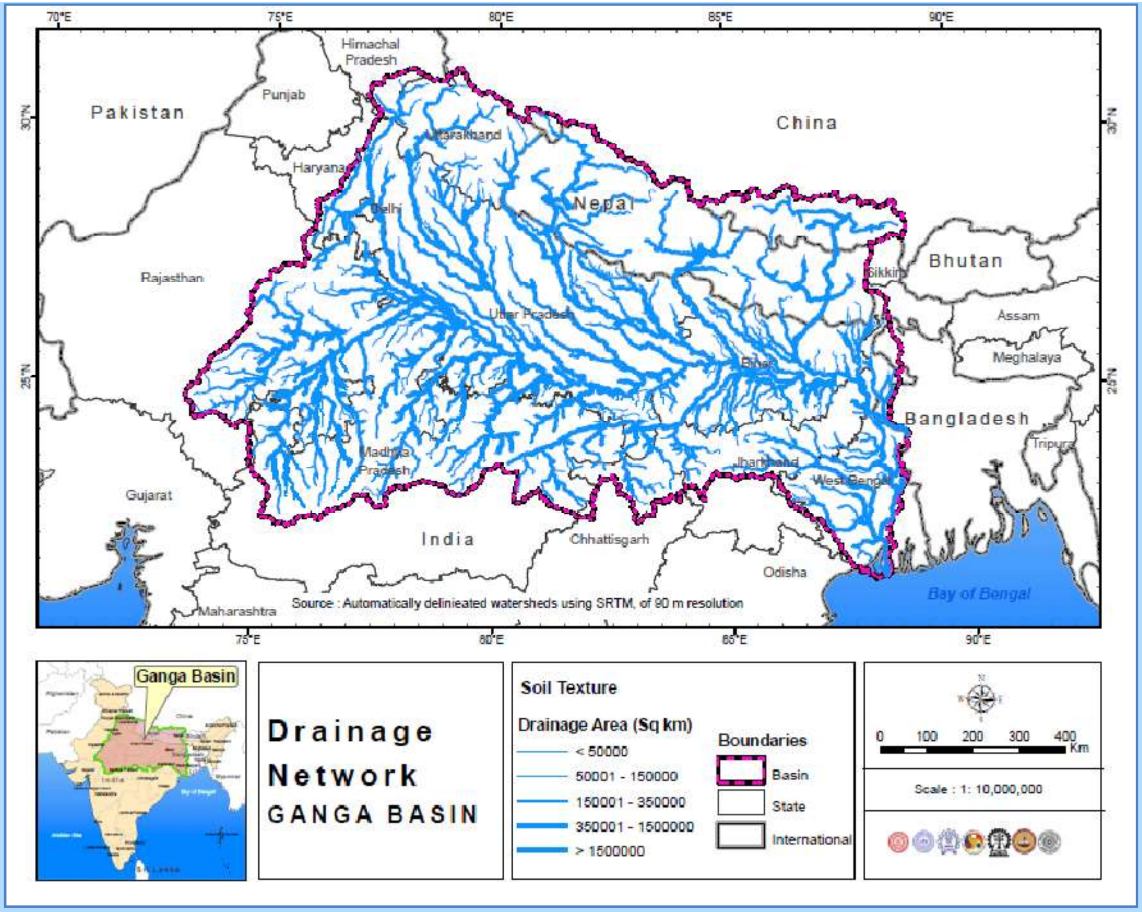
Table 1: Elevation Summary – Ganga Basin

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

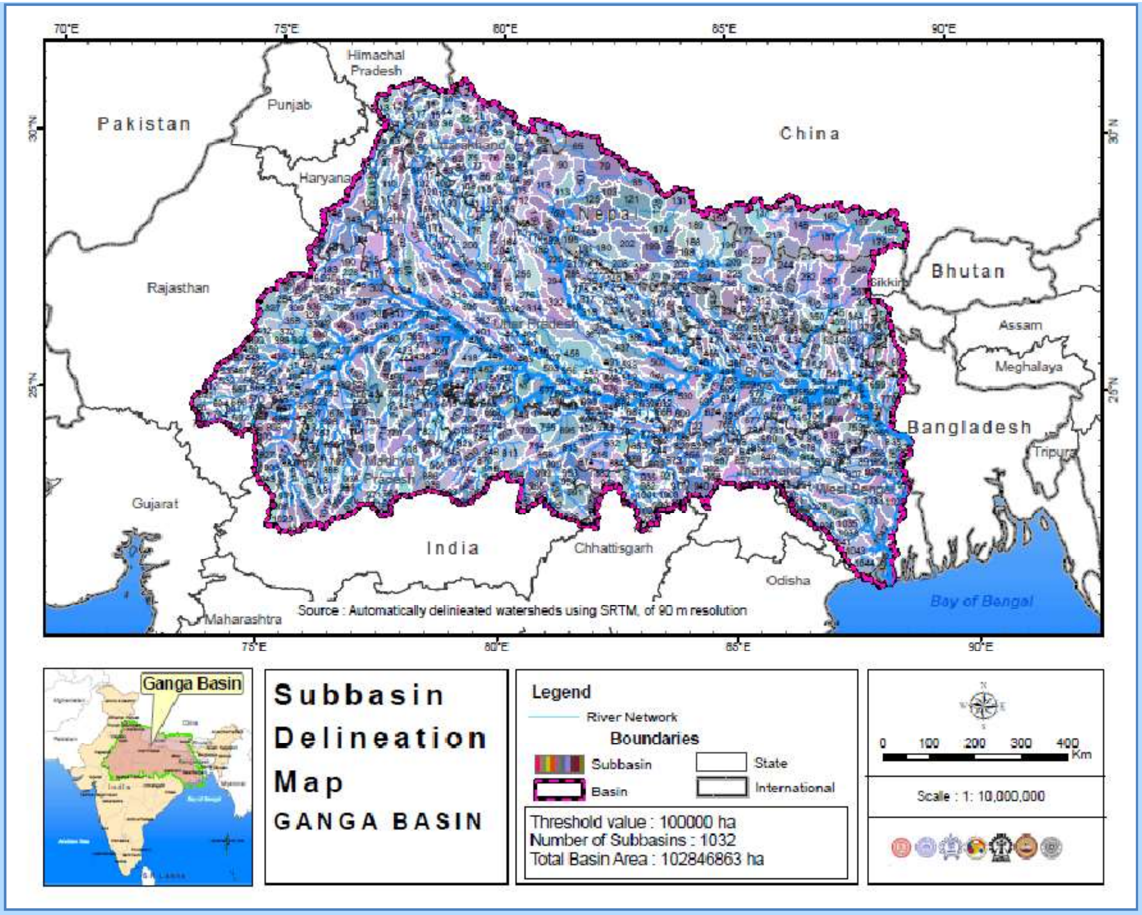


Source : Automatically delinieated watersheds using SRTM, of 90 m resolution

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

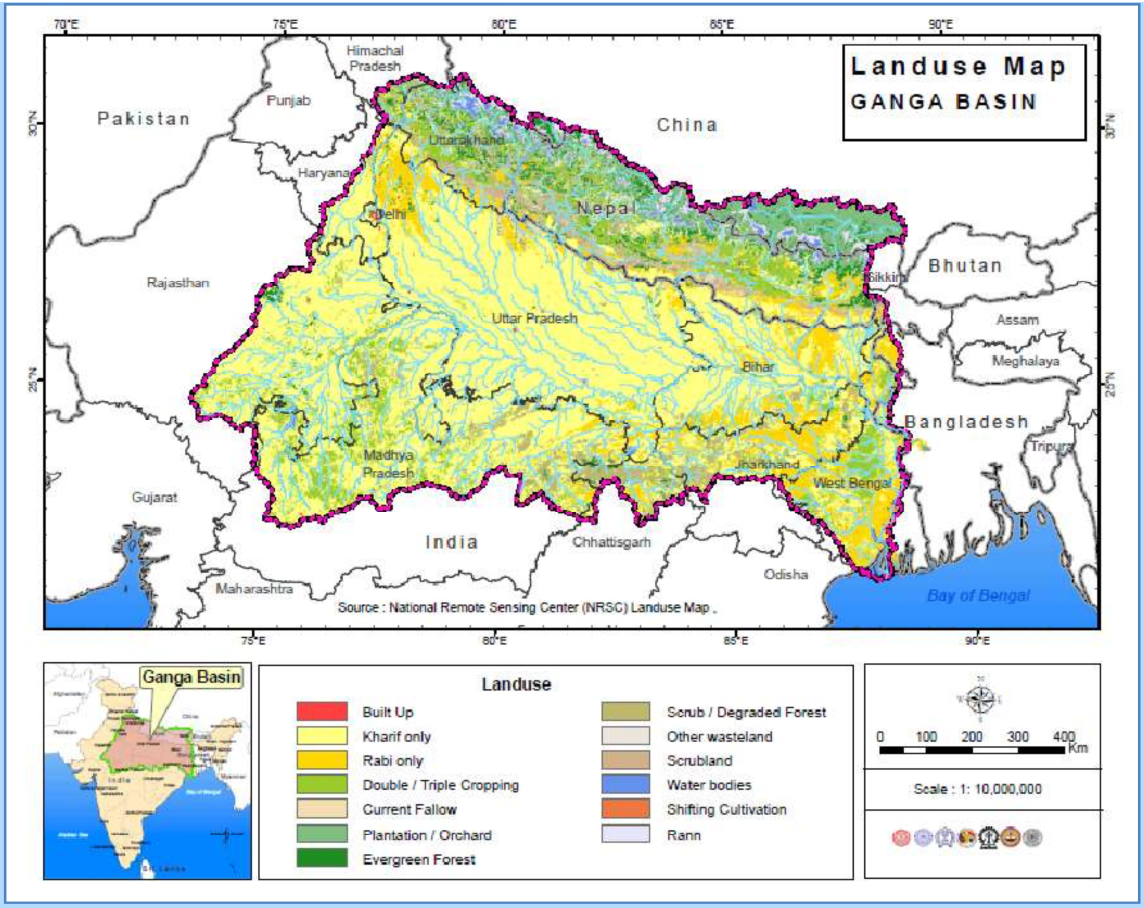


Source : Automatically delinieated watersheds using SRTM, of 90 m resolution

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



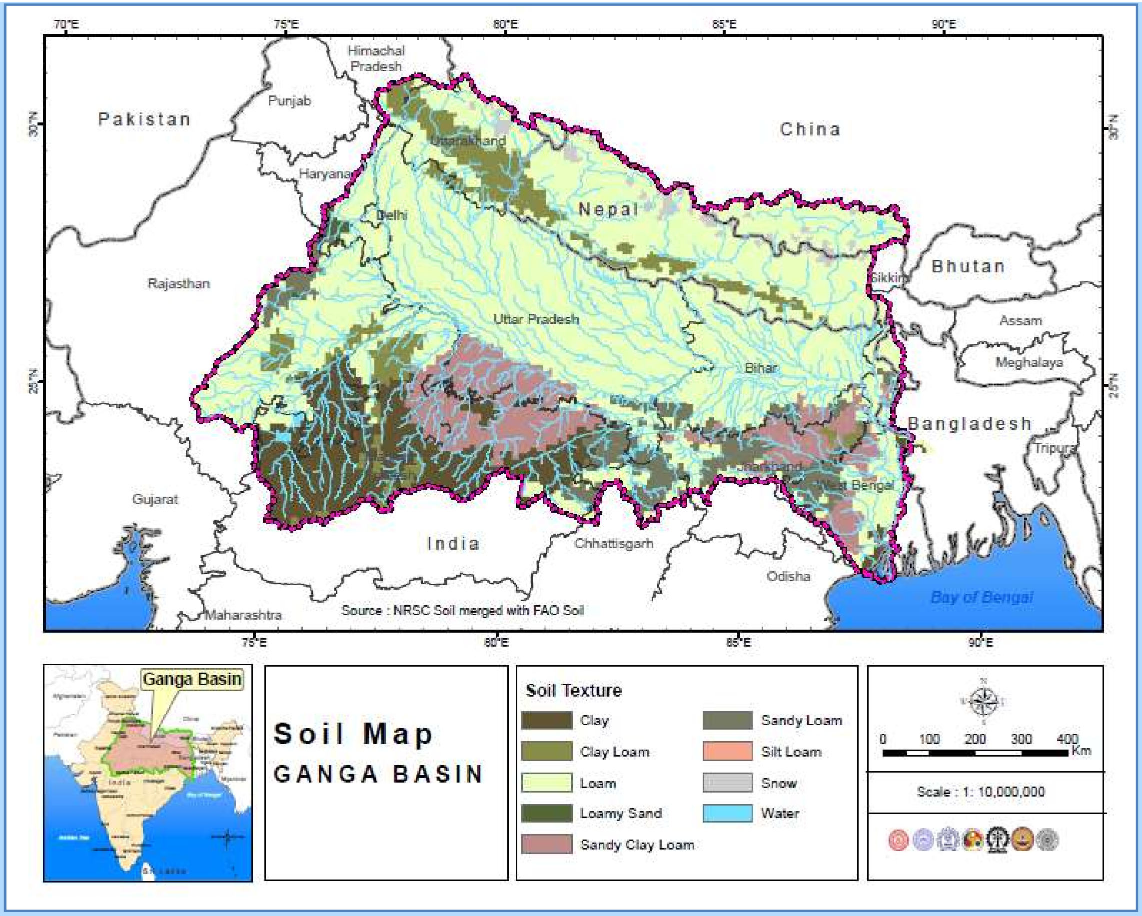
Source : National Remote Sensing Center (NRSC) Landuse Map

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

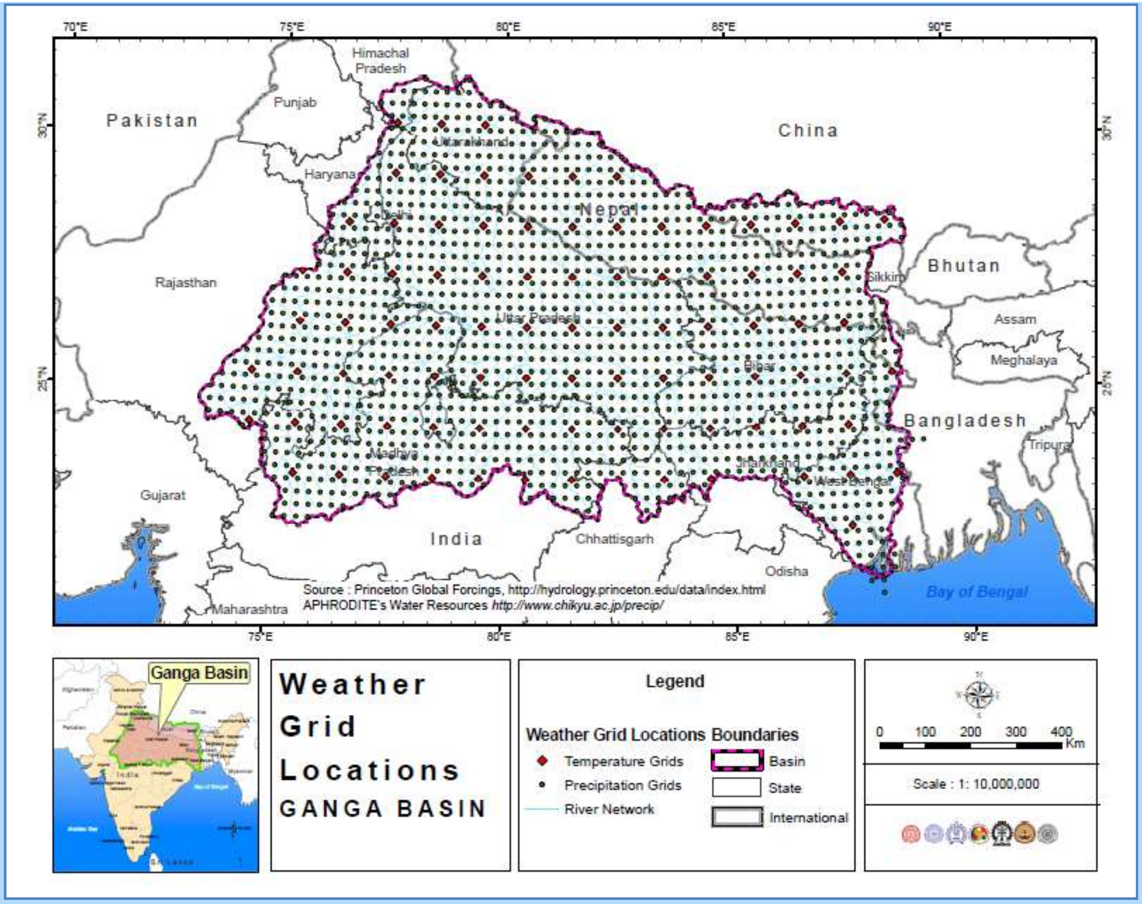


The soil is predominantly loamy.However; sandy clay loam and sandy loam are also prevalent. There are about 41 soil sub types within the loamy soil.

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.

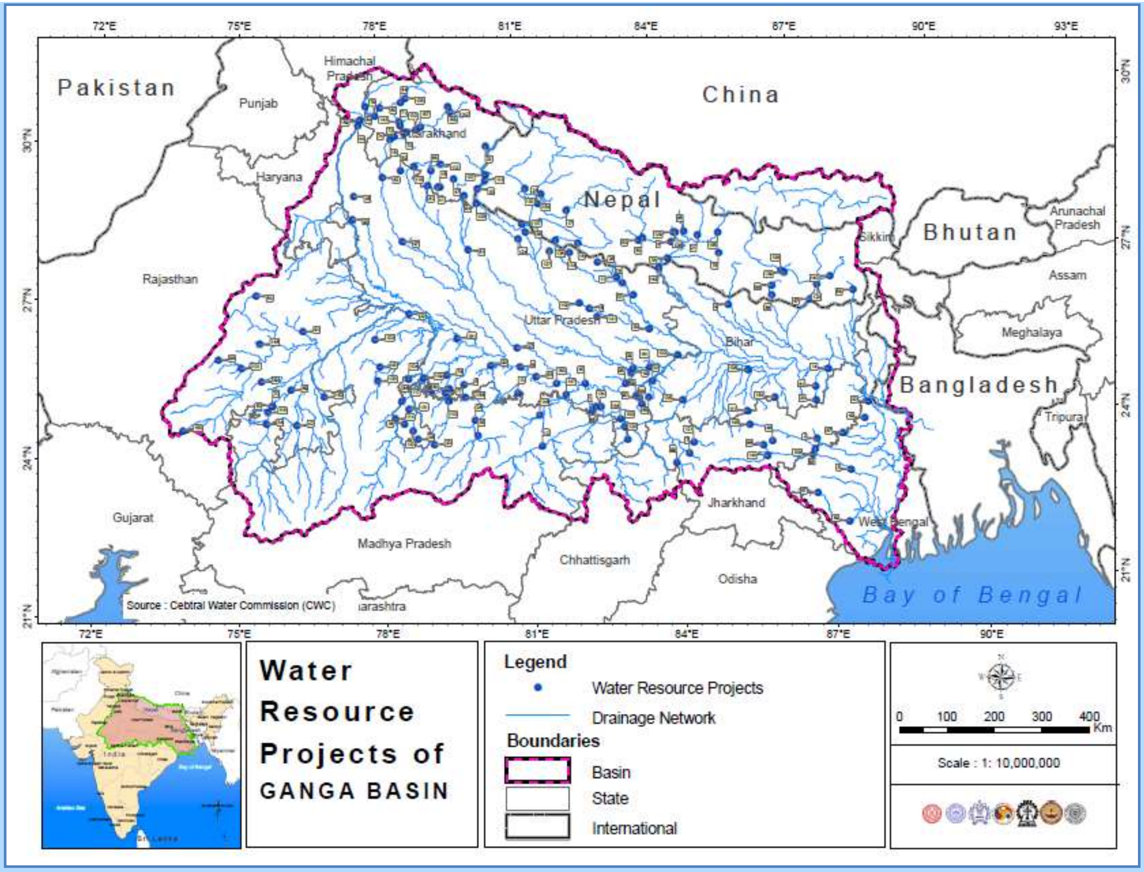
Figure 8: IMD Gridded Rainfall and Temperature grid locations for the Ganga river basin



Source : Princeton Global Forcings, http://hydrology.princeton.edu/data/index.html
APHRODITE's Water Resources *http://www.chikyu.ac.jp/precip/*

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°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

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[20] www.india-wris.nrsc.gov.in/

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

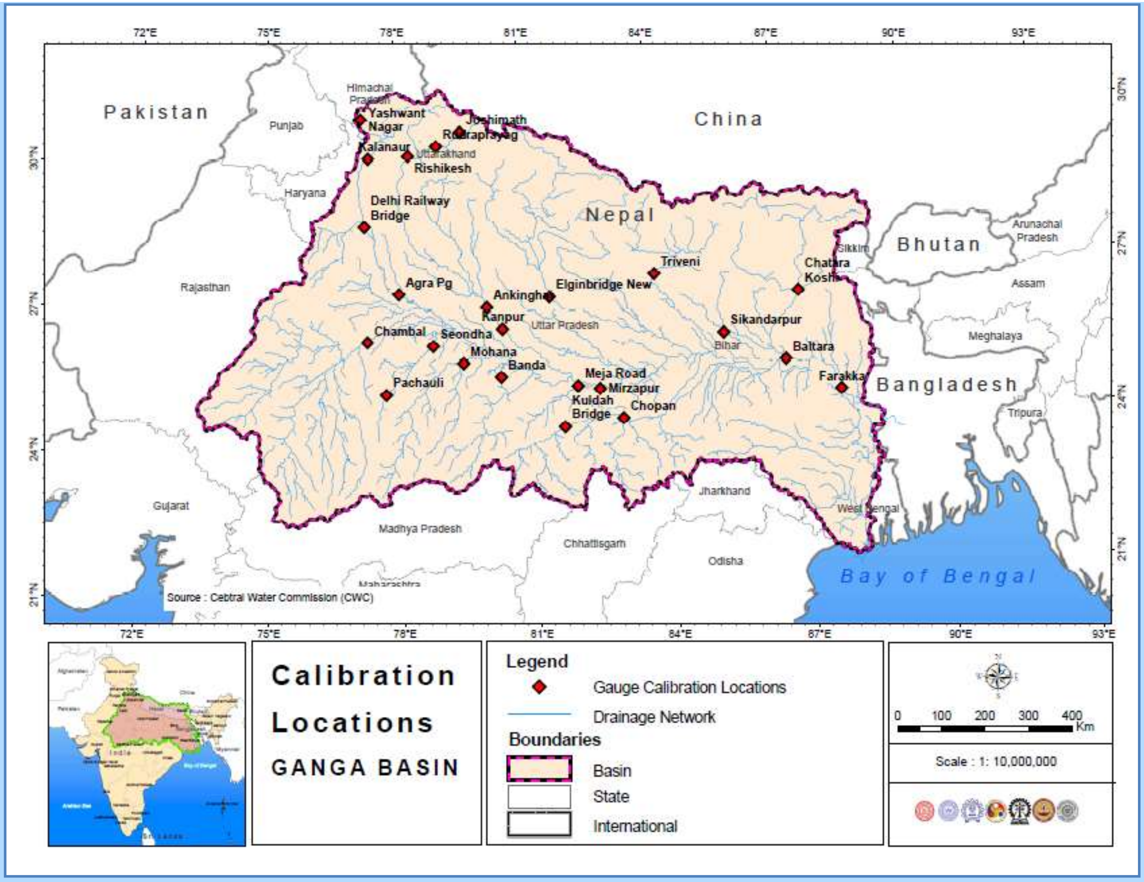
[22] http://www.icrisat.org/vdsa/vdsa-mesodoc.htm

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

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[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.

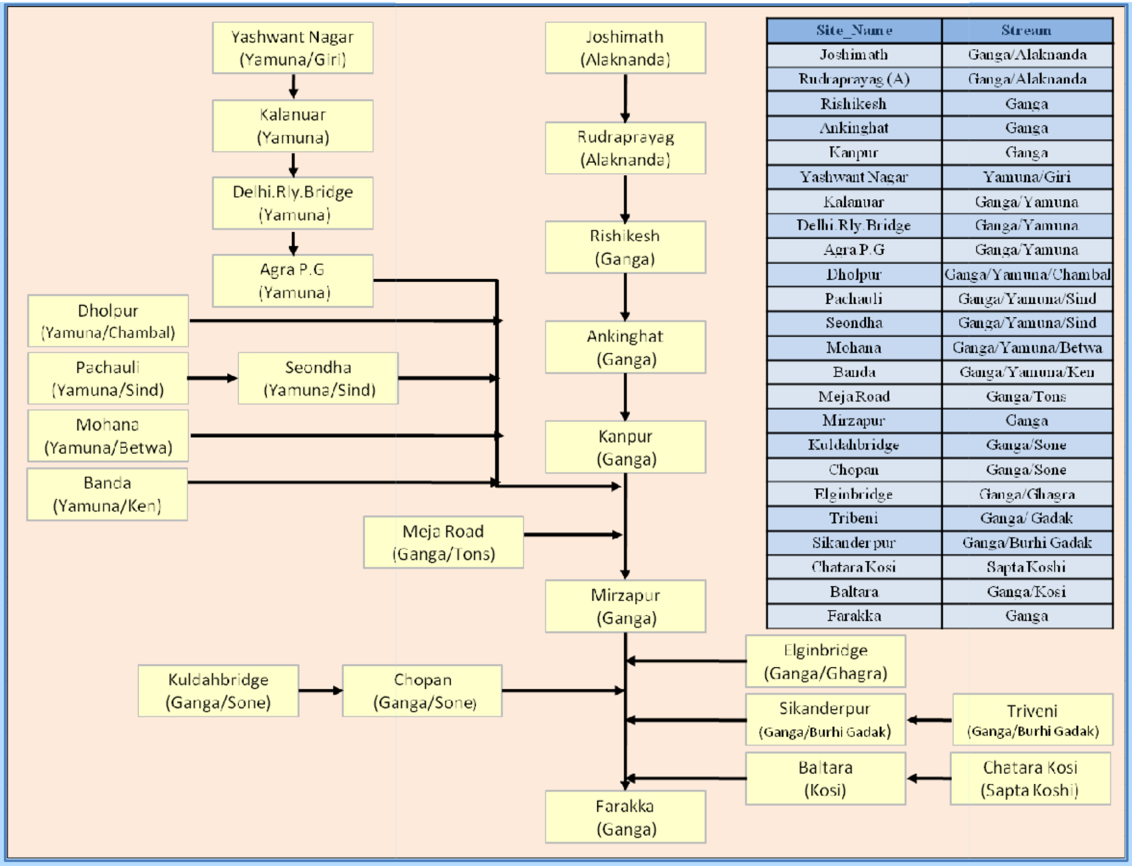
[24] Central Water Commission, MoWR

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



Site_Name	Stream
Joshimath	Ganga/Alaknanda
Rudraprayag (A)	Ganga/Alaknanda
Rishikesh	Ganga
Ankinghat	Ganga
Kanpur	Ganga
Yashwant Nagar	Yamuna/Giri
Kalanuar	Ganga/Yamuna
Delhi Rly Bridge	Ganga/Yamuna
Agra P.G	Ganga/Yamuna
Dholpur	Ganga/Yamuna/Chambal
Pachauli	Ganga/Yamuna/Sind
Seondha	Ganga/Yamuna/Sind
Mohana	Ganga/Yamuna/Betwa
Banda	Ganga/Yamuna/Ken
Meja Road	Ganga/Tons
Mirzapur	Ganga
Kuldahbridge	Ganga/Sone
Chopan	Ganga/Sone
Elginbridge	Ganga/Ghagra
Tribeni	Ganga/ Gadak
Sikanderpur	Ganga/Burhi Gadak
Chatara Kosi	Sapta Koshi
Baltara	Ganga/Kosi
Farakka	Ganga

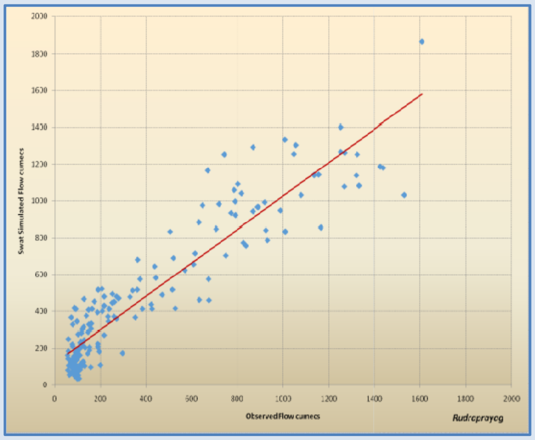
Figure 12 shows the 24 locations where model performance has been validatedon the major tributaries of the Ganga river. Time series plots of observed and simulated have not been provided because the data is classified. Therefore, only scattered plots for the observed vs. simulated monthly discharge have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

Figure 12: SWAT Calibration Locations for the Ganga river basin

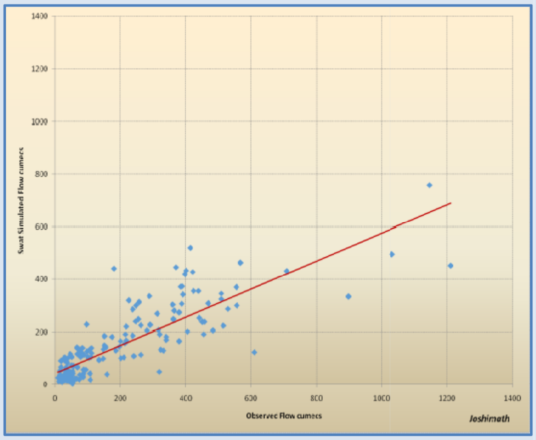
Source : Central Water Commission (CWC)

Observed Vs. Simulated Scatter Plots

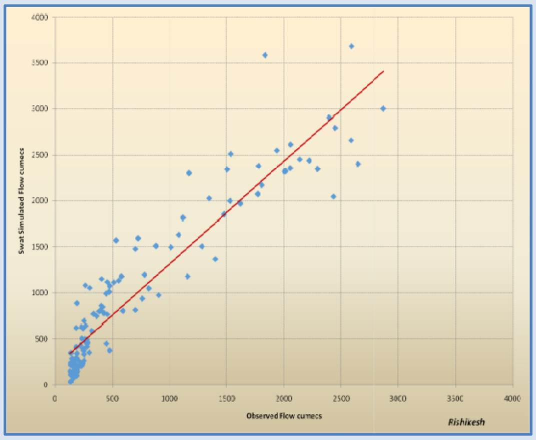
Rudraprayag on Alaknanda (Ganga/Alaknanda) river



Joshimath on Alaknanda (Ganga/Alaknanda) river



Rishikesh on Ganga river



Yashwant Nagar on Giri (Yamuna/Giri) river

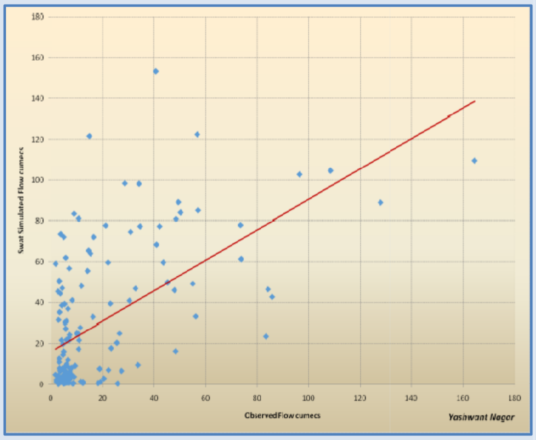
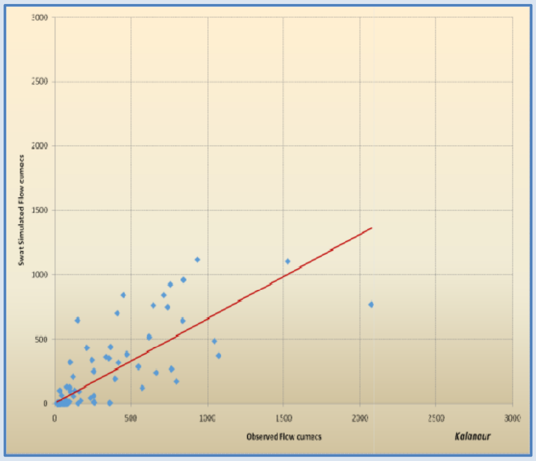
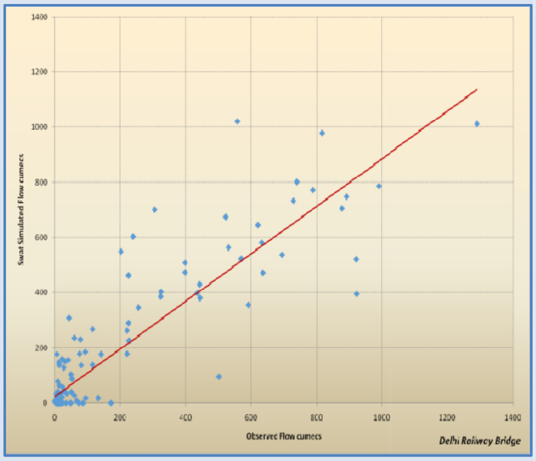


Figure 12: SWAT Calibration Locations for the Ganga river basin

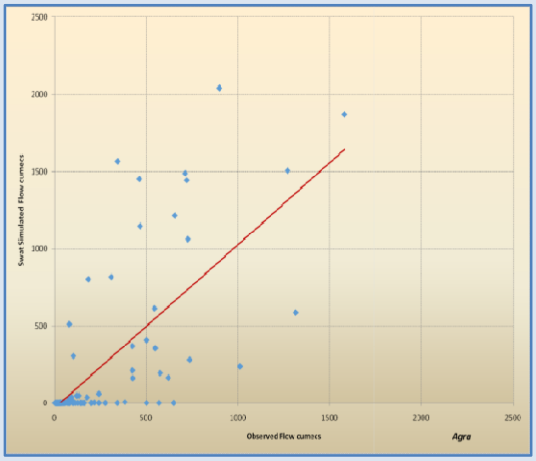
Kalanaur on Yamuna (Ganga/Yamuna) river



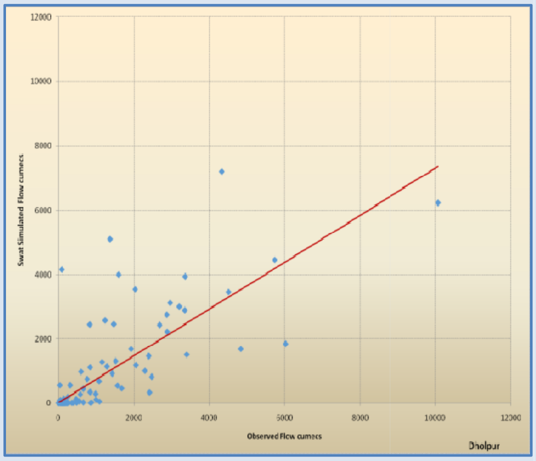
Delhi Railway Bridge on Yamuna (Ganga/Yamuna) river



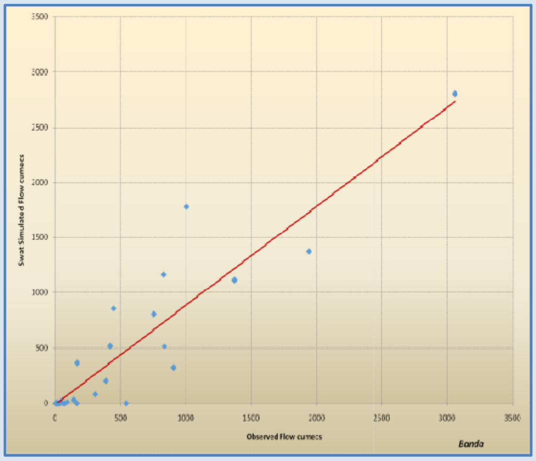
Agra P.G. on Yamuna (Ganga/Yamuna) river



Dholpur on Chambal (Ganga/Yamuna/Chambal) river



Banda on Ken (Ganga/Yamuna/Ken) river



Mohana on Betwa (Ganga/Yamuna/Betwa) river

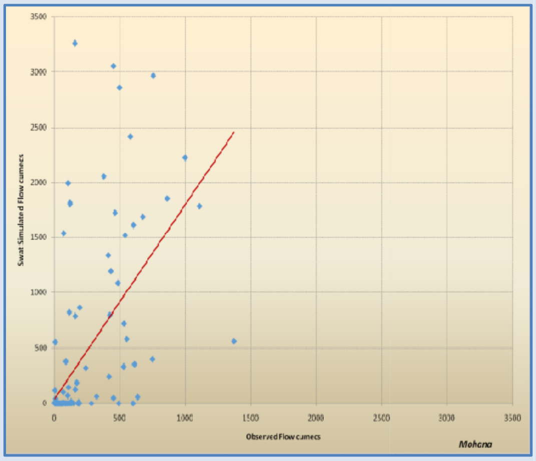
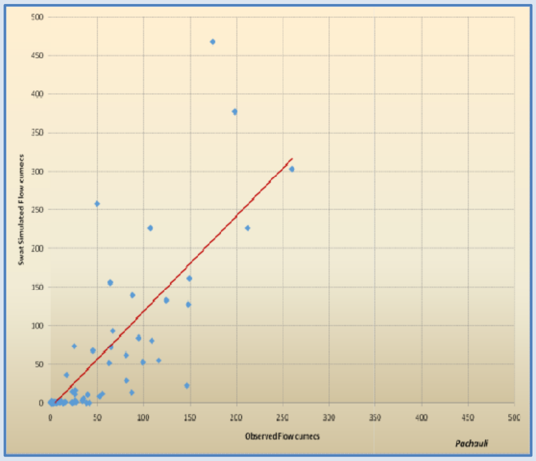
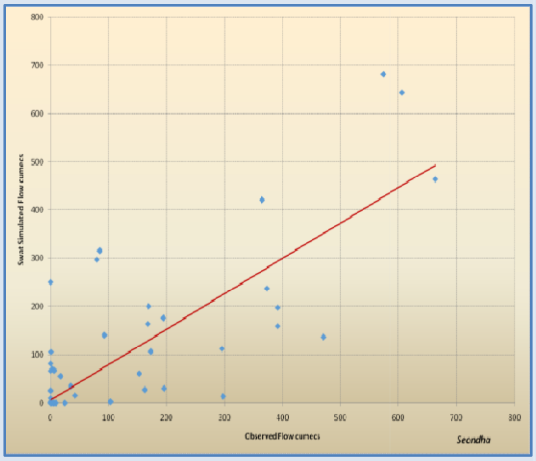


Figure 12: SWAT Calibration Locations for the Ganga river basin

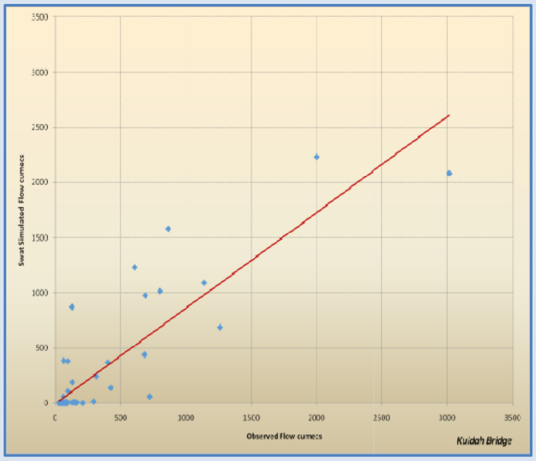
Pachauli on Sind (Ganga/Yamuna/Sind) river



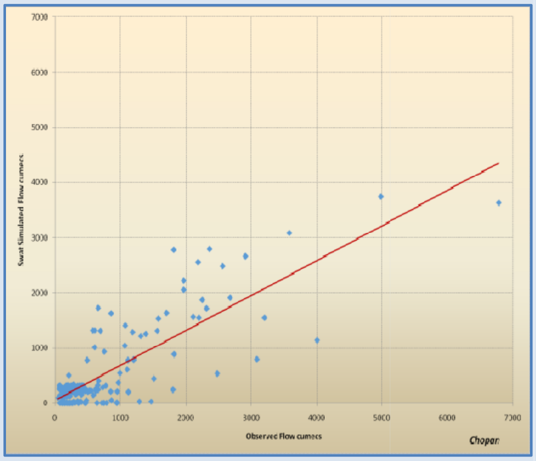
Seondha on Sone (Ganga/Yamuna/Sind) river



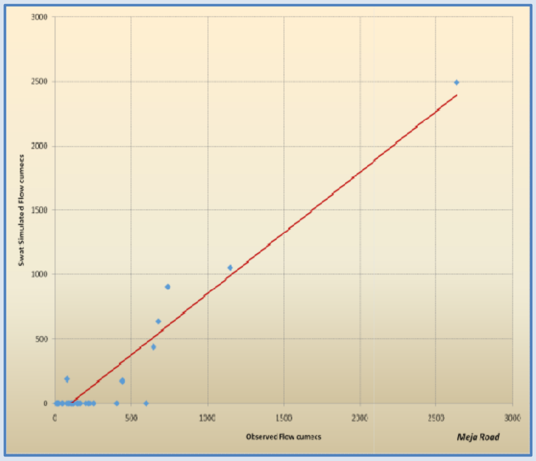
Kuldahbridge on Sind (Ganga/Sone) river



Chopan on Sind (Ganga/Sone) river



Meja Road on Tons (Ganga/Tons) river



Elginbridge on Ghagra (Ganga/Ghagra) river

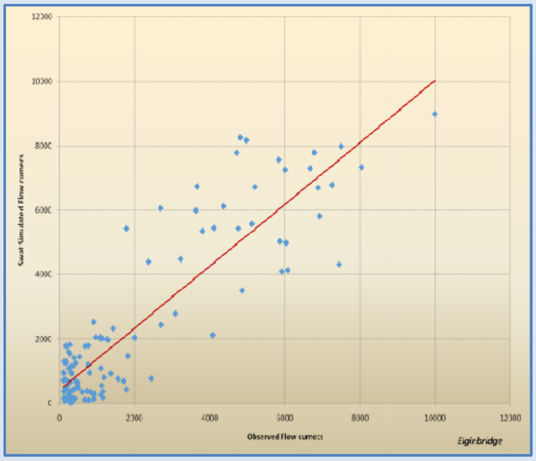
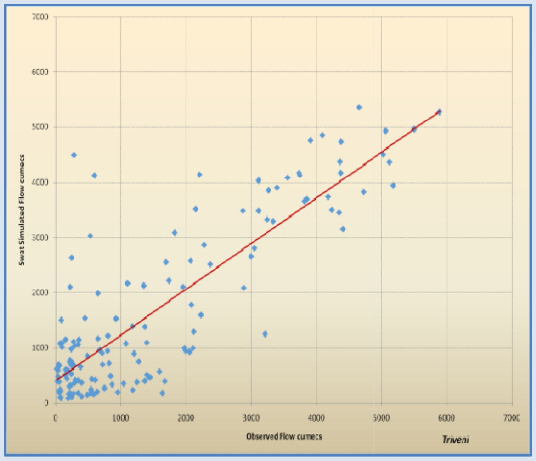
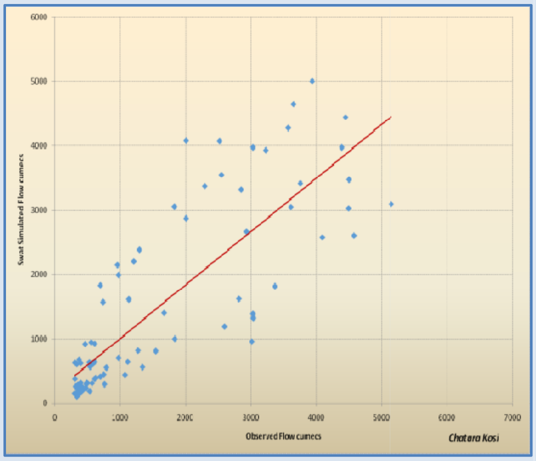


Figure 12: SWAT Calibration Locations for the Ganga river basin

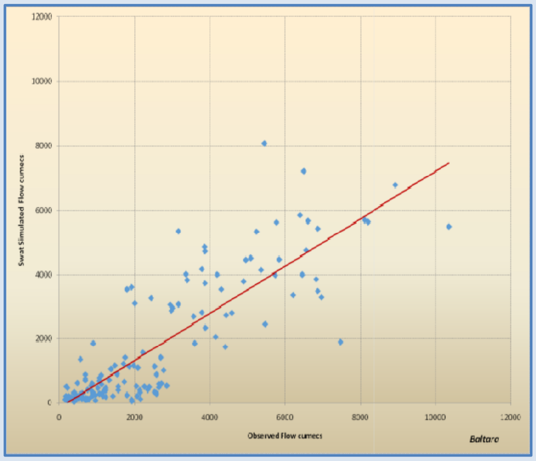
Tribeni on Gandak (Ganga/Gandak) river



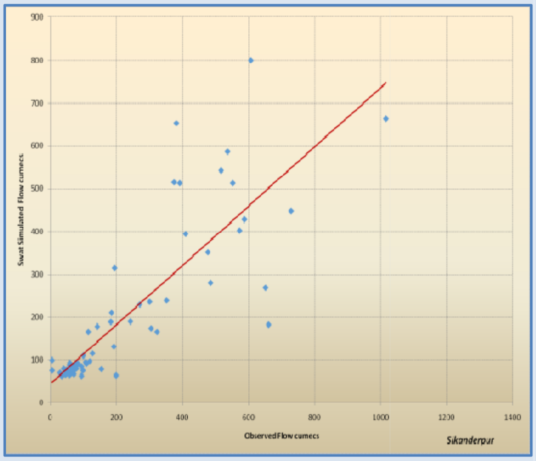
Chatara Kosi on Kosi (Ganga/Kosi) river



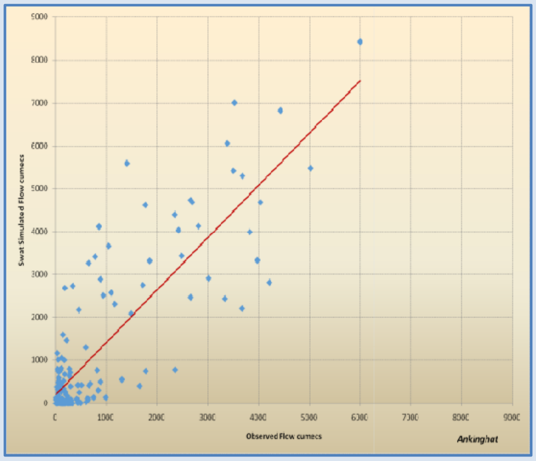
Baltara on Kosi (Ganga/Kosi) river



Sikanderpur on Burhi Gandak (Ganga/Burhi Gandak) river



Ankinghat on Ganga river



Kanpur on Ganga river

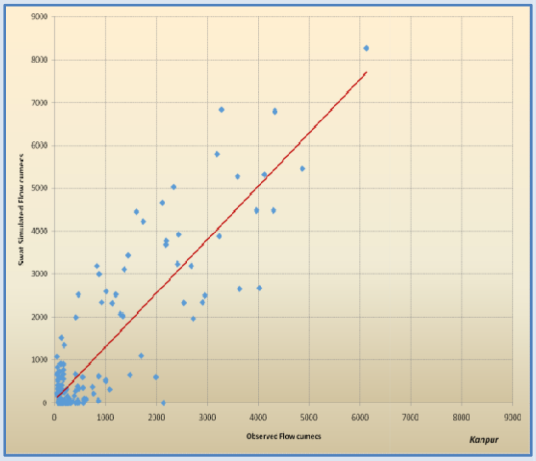
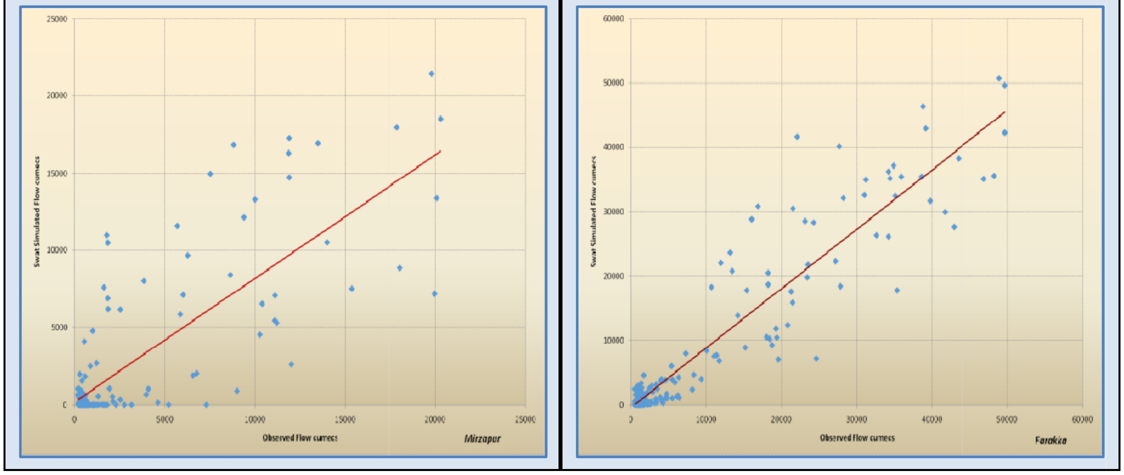


Figure 12: SWAT Calibration Locations for the Ganga river basin


Mirzapur on Ganga river

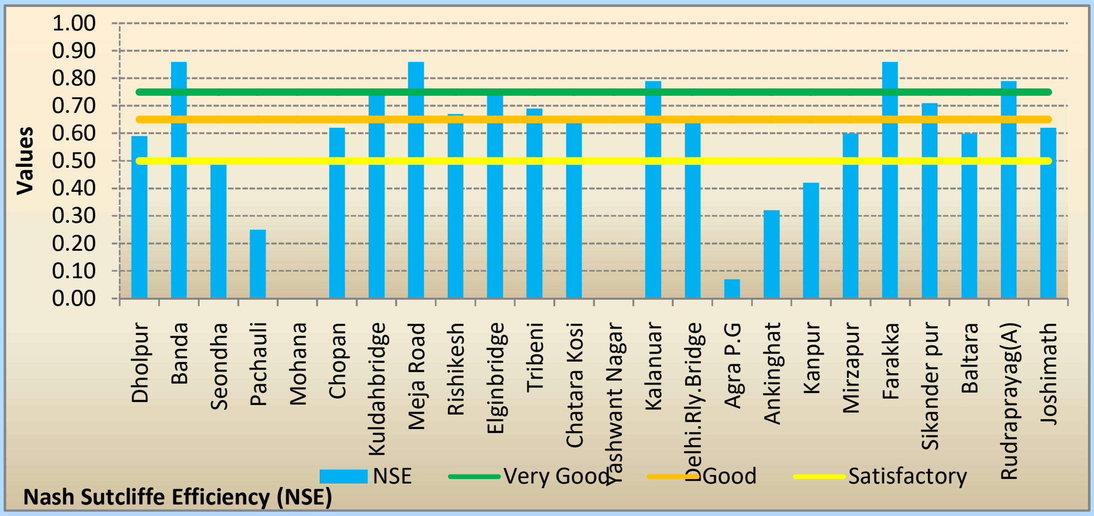
Farakka on Ganga river

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.

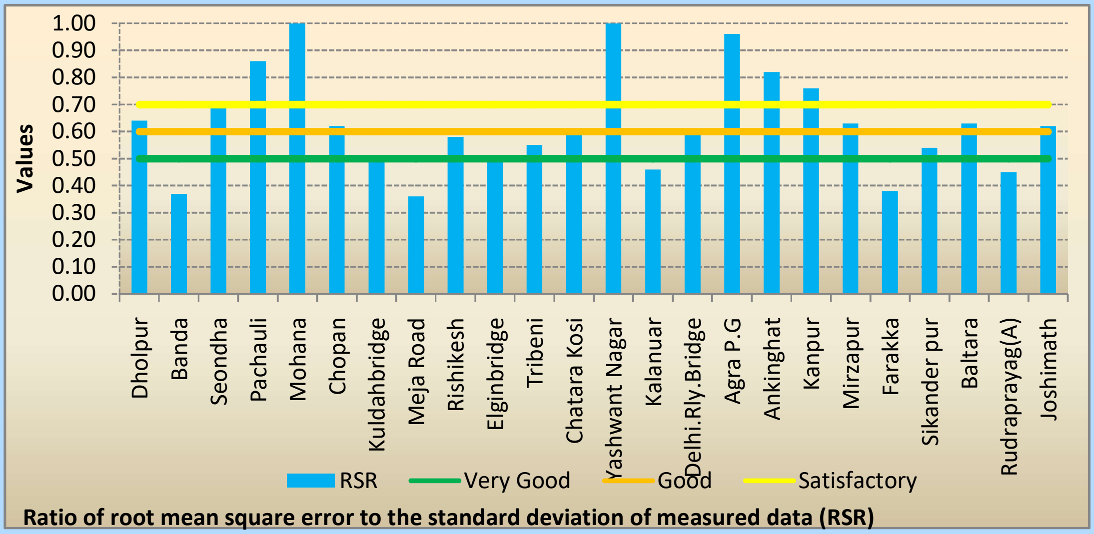
In the present case, in the absence of the data on snow/glacier depths assumptions made regarding these depths and thus were part of the calibration process. It is very likely that with additional information on snow and glacier and also with better precipitation network in the hilly area the simulation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

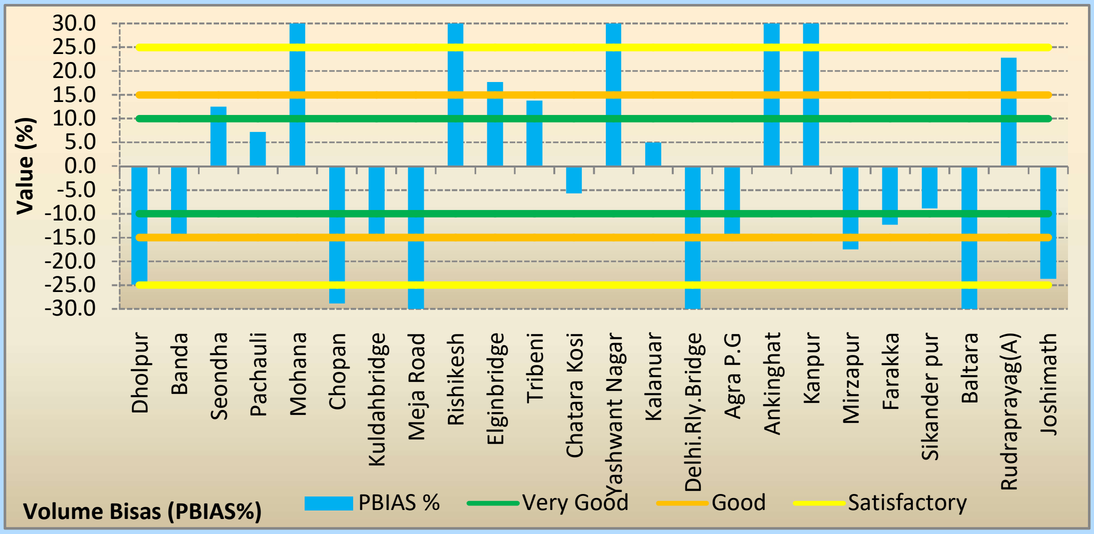
Figure 13: Model performance graph for the Ganga river basin



Nash Sutcliffe Efficiency (NSE)



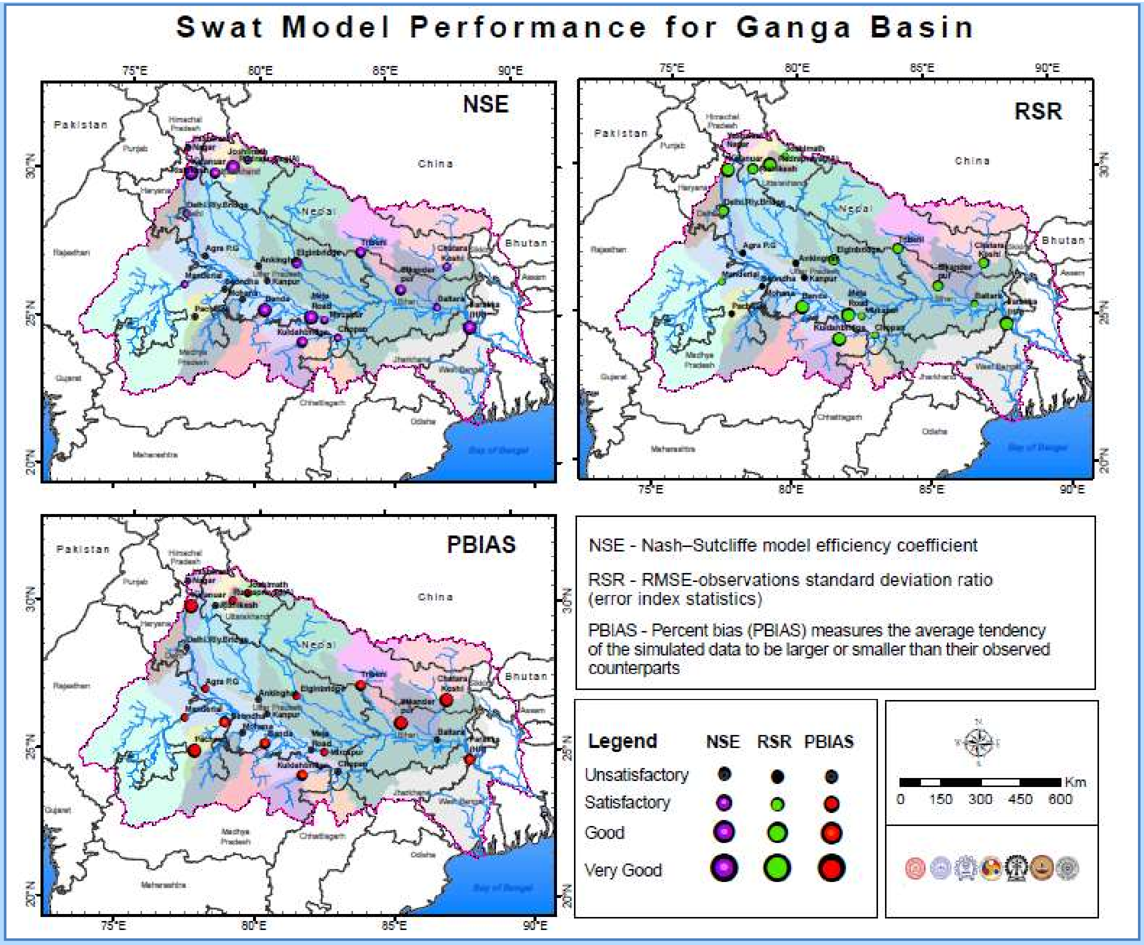
Ratio of root mean square error to the standard deviation of measured data (RSR)



Volume Bisas (PBIAS%)

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

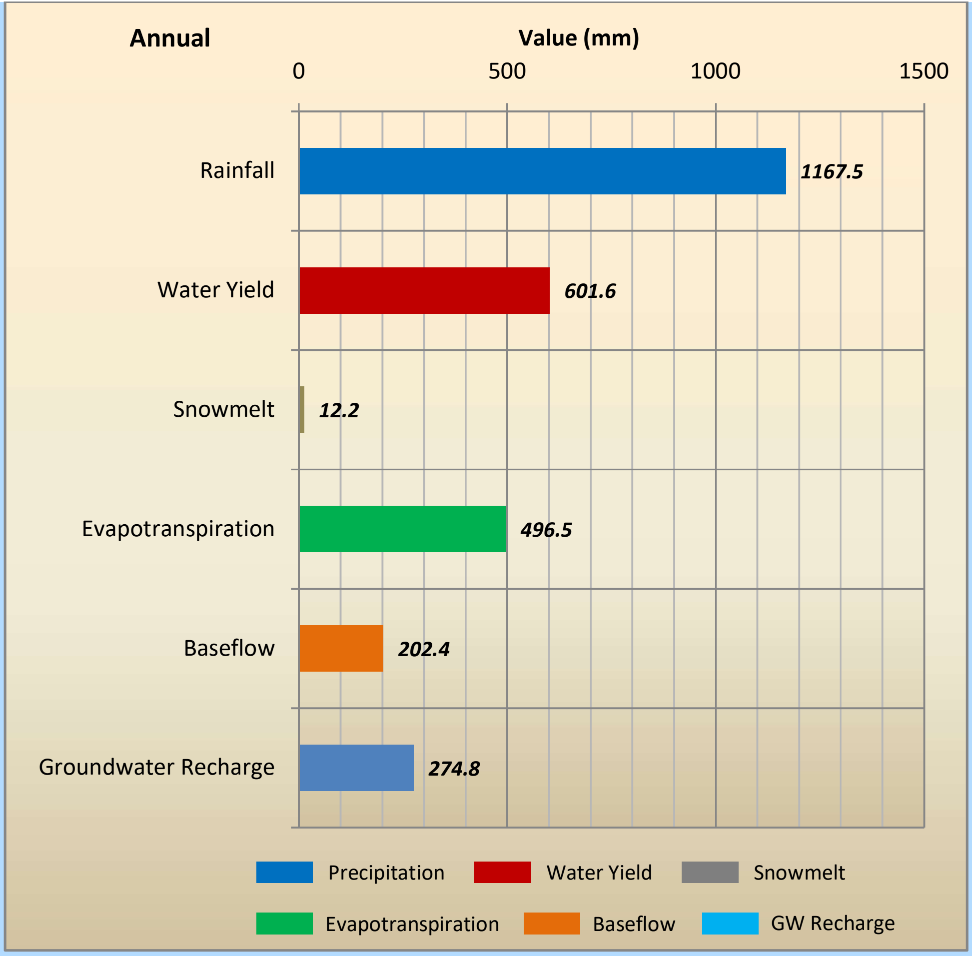
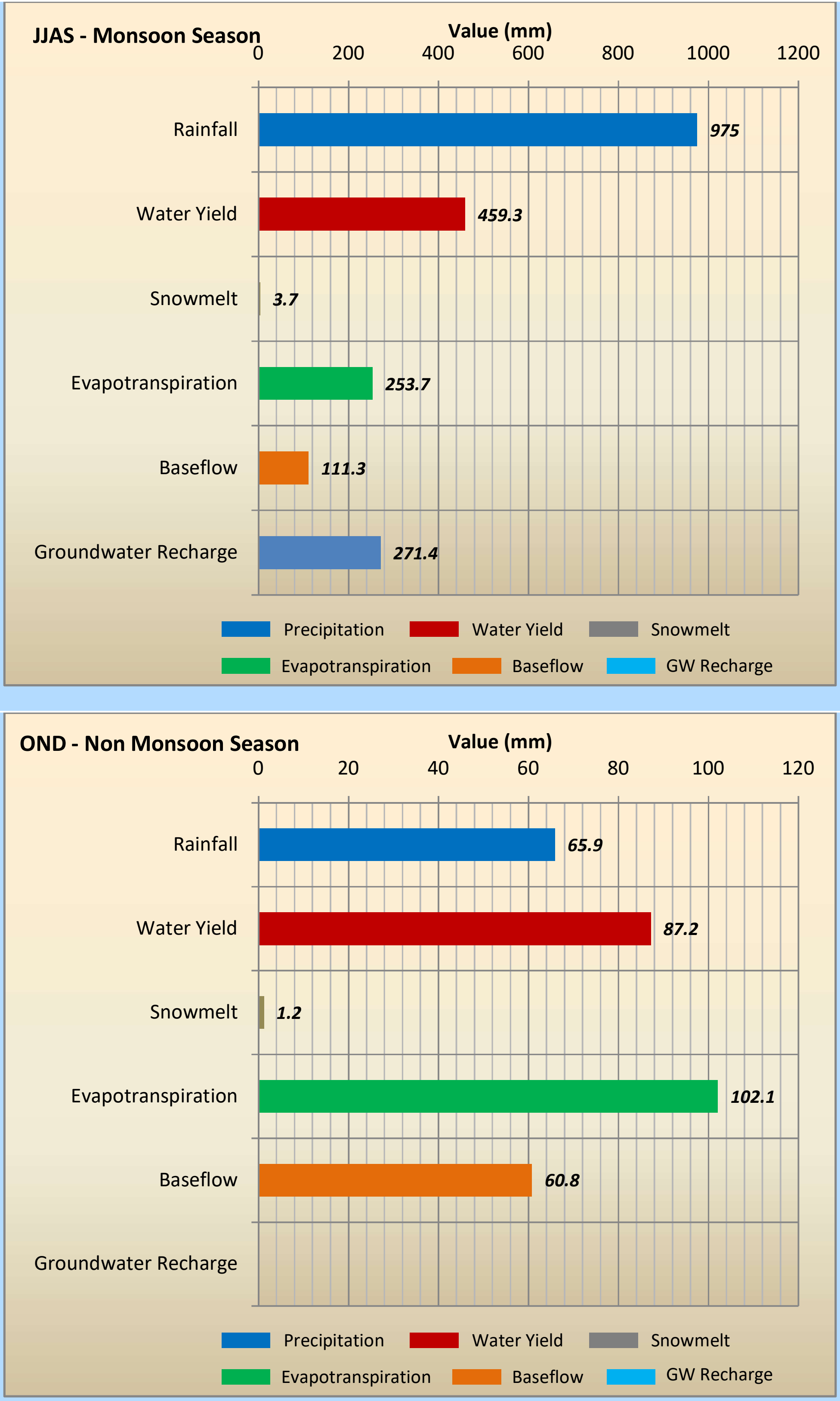
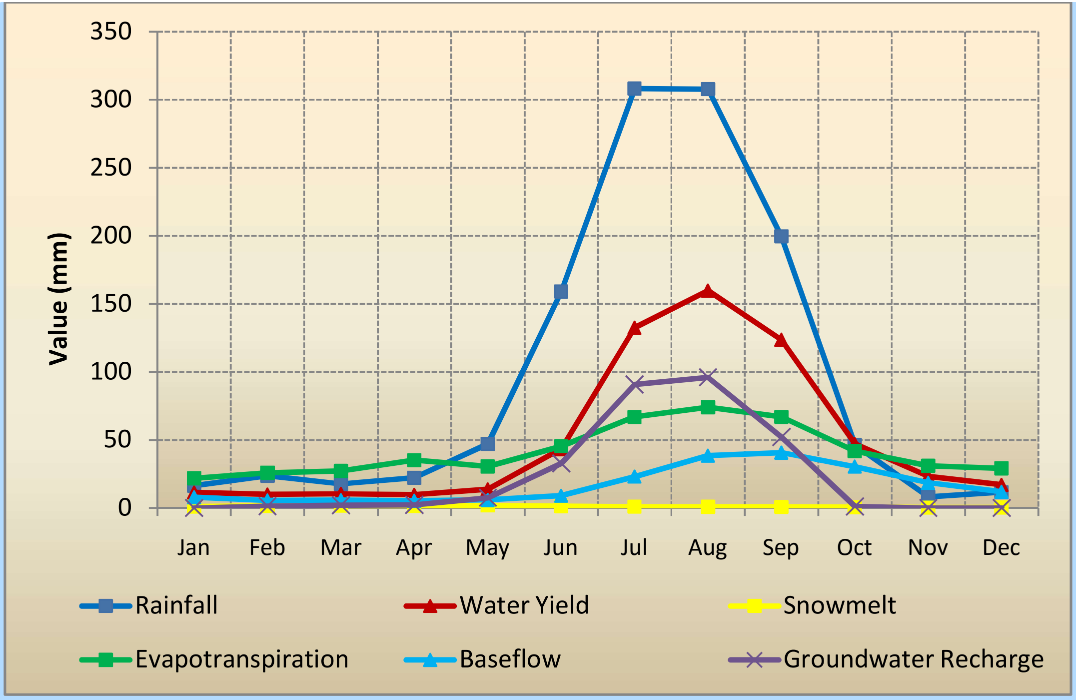


Figure 15: Annual and seasonal water balance components for the Ganga river basin



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

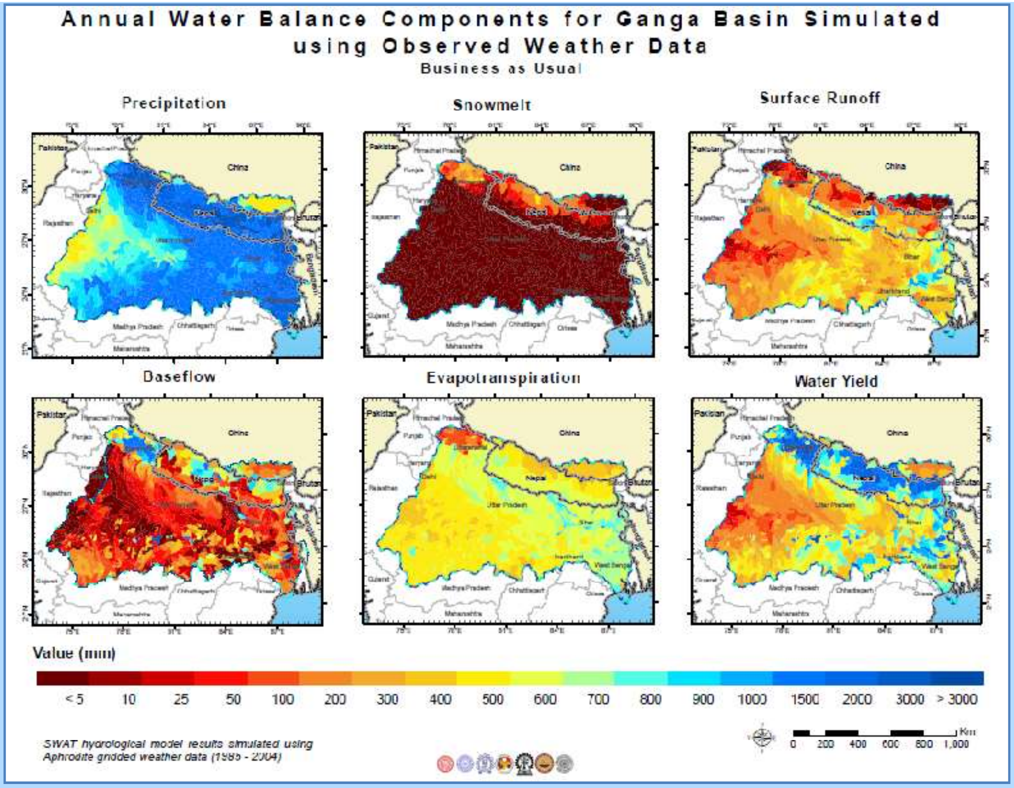
Figure 16: Long-term Monthly water balance componentsforthe Ganga river basin



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.

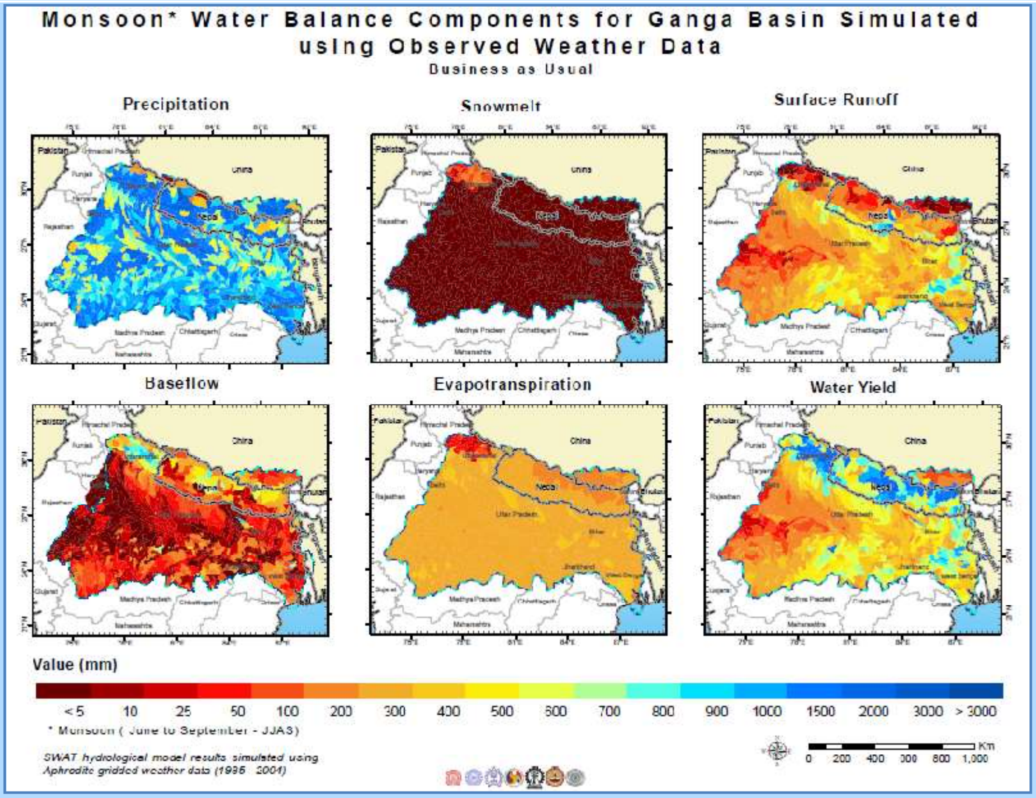
Figure 17: Spatial distribution of Annual and seasonal water balance componentsforthe Ganga river basin



Annual Water Balance Components for Ganga Basin Simulated using Observed Weather Data

Business as Usual

SWAT hydrological model results simulated using Aphrodite gridded weather data (1985 - 2004)



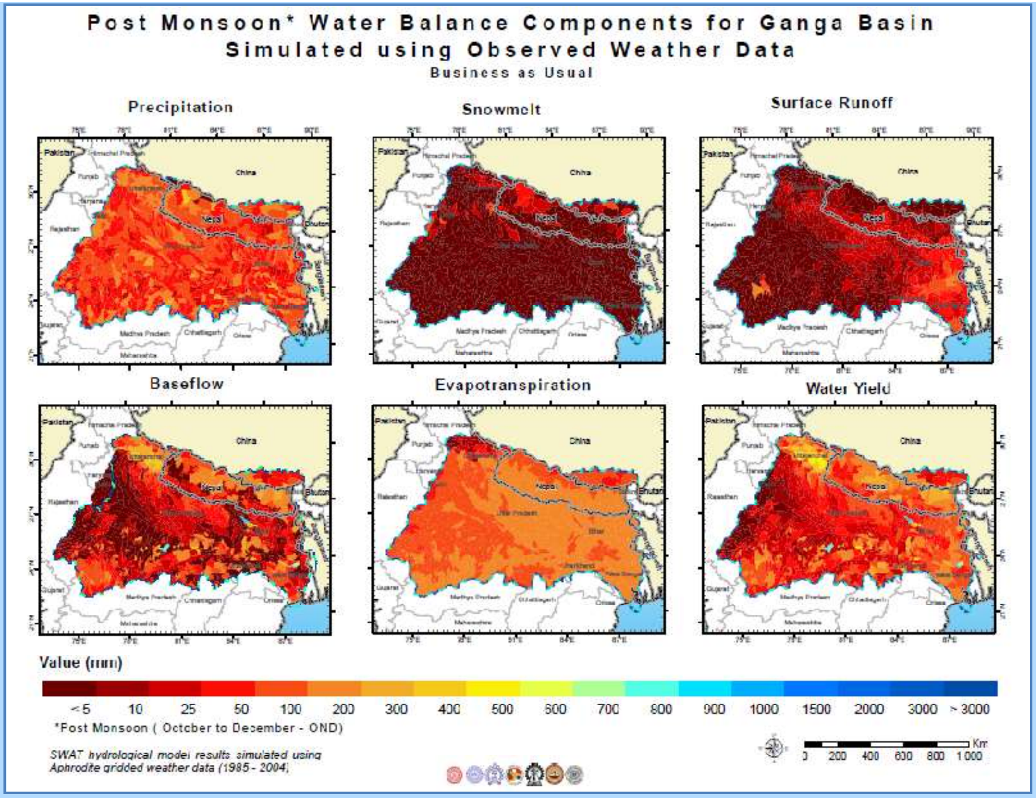
Monsoon* Water Balance Components for Ganga Basin Simulated using Observed Weather Data

Business as Usual

* Monsoon (June to September - JJAS)

SWAT hydrological model results simulated using Aphrodite gridded weather data (1985 - 2004)

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



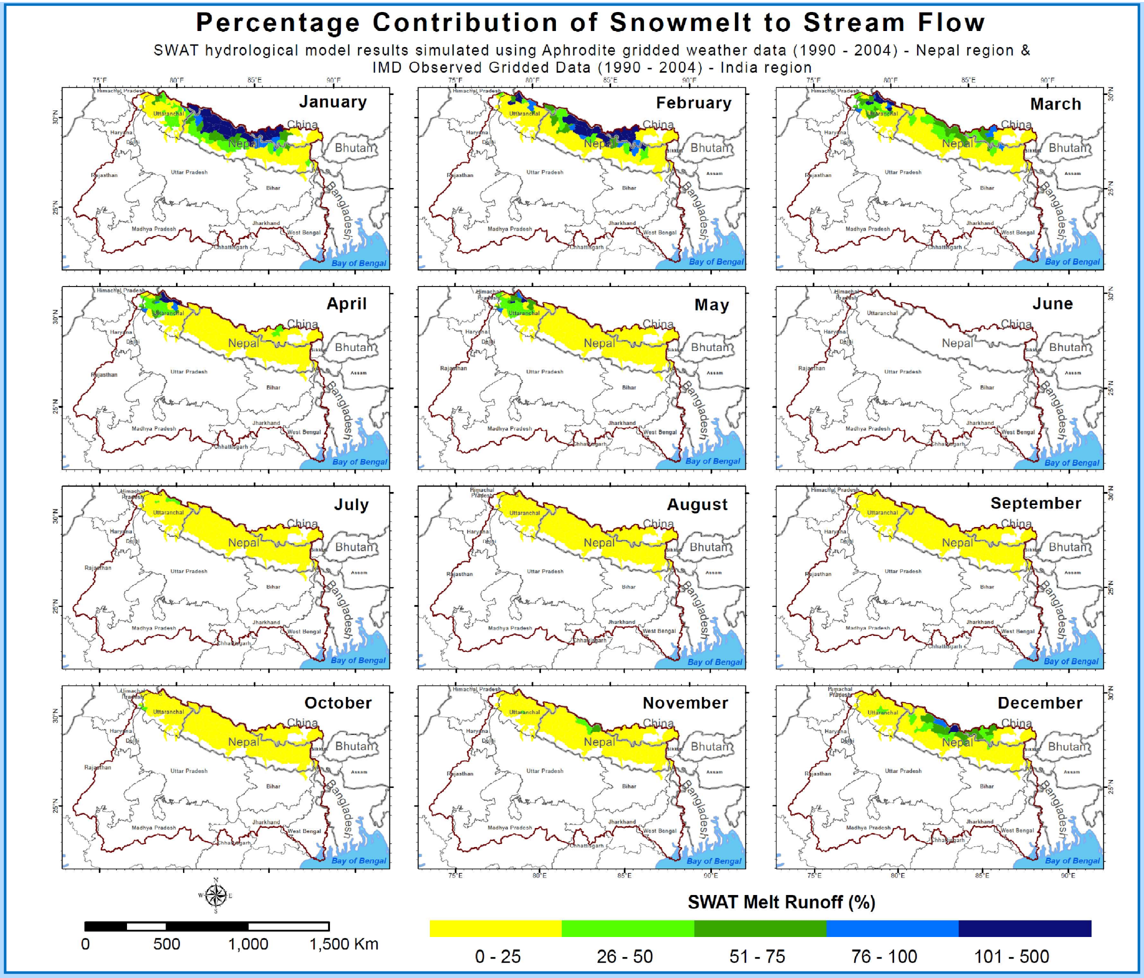
*Post Monsoon (October to December - OND)

SWAT hydrological model results simulated using Aphrodite gridded weather data (1985 - 2004)

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°C/km to -6.5°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

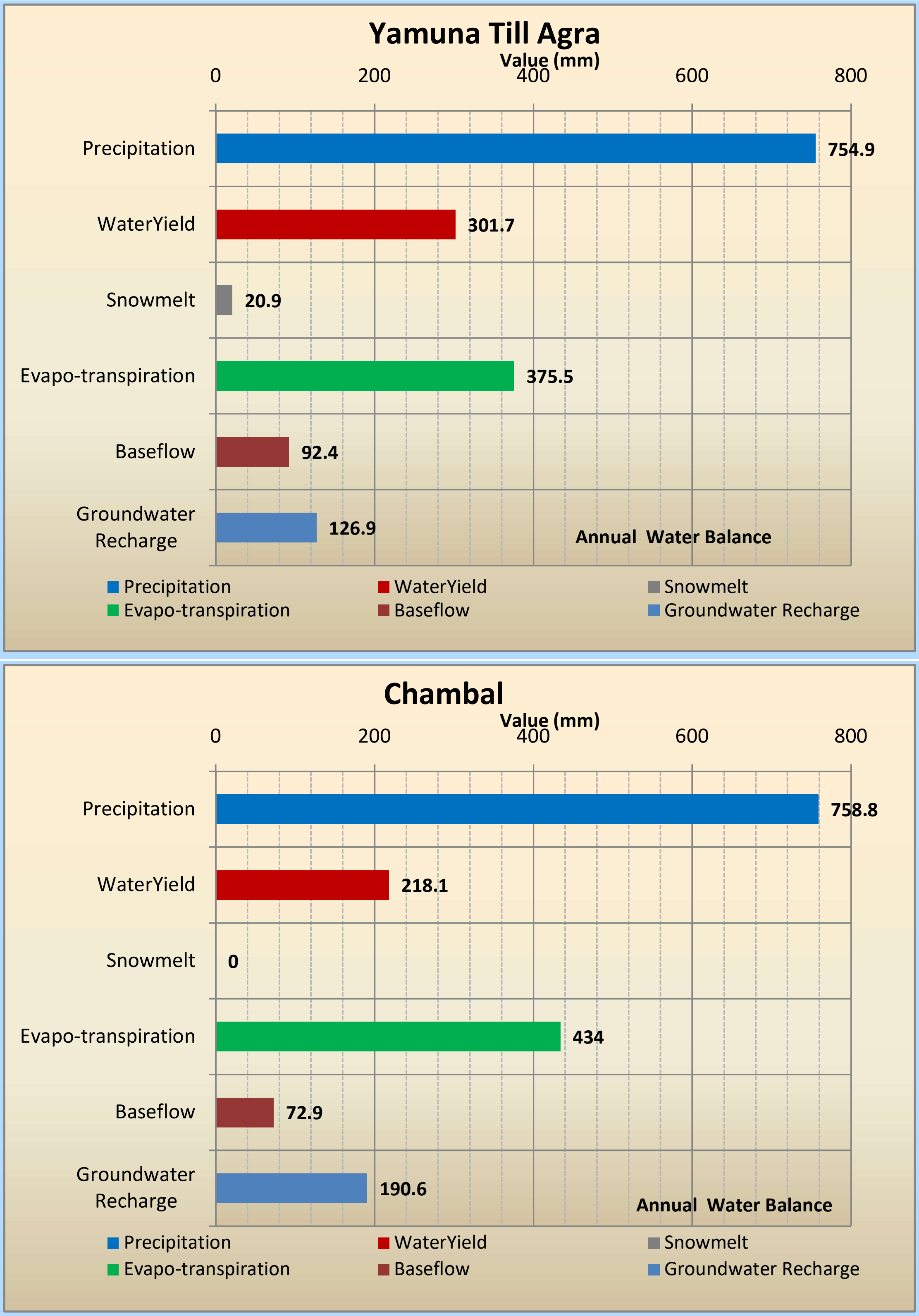
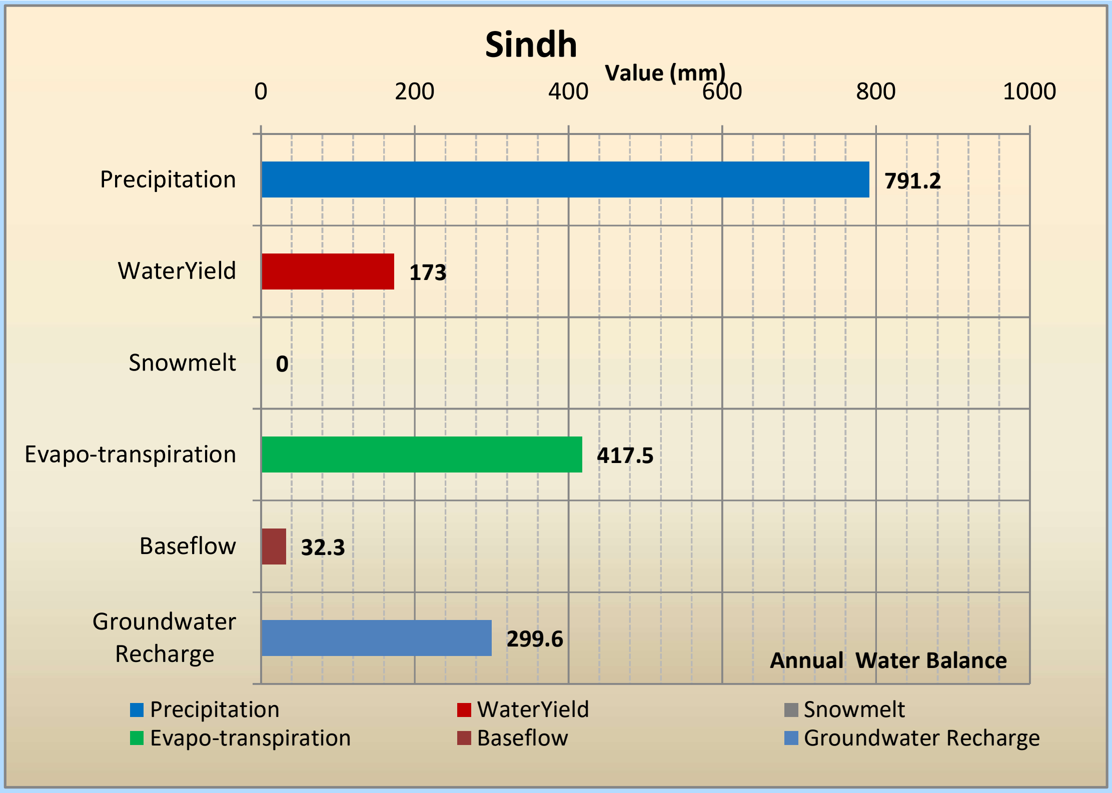


Figure 19: Annual water balance components for major tributaries of the Ganga river basin



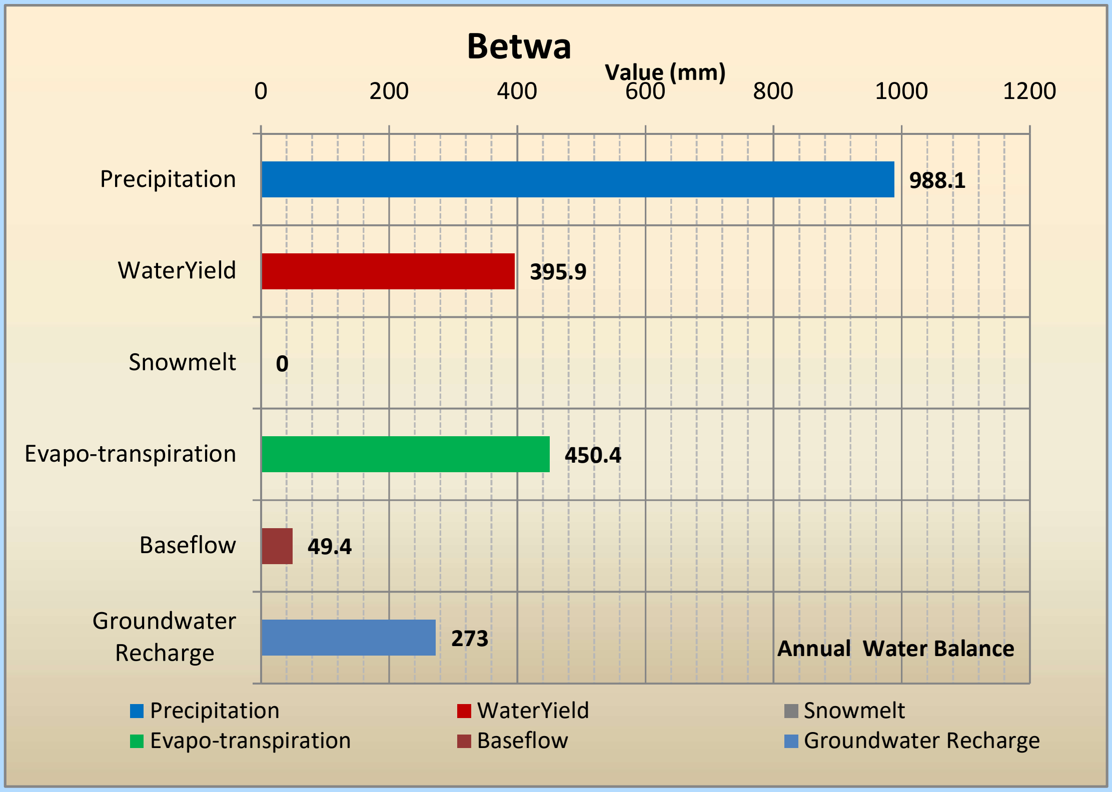
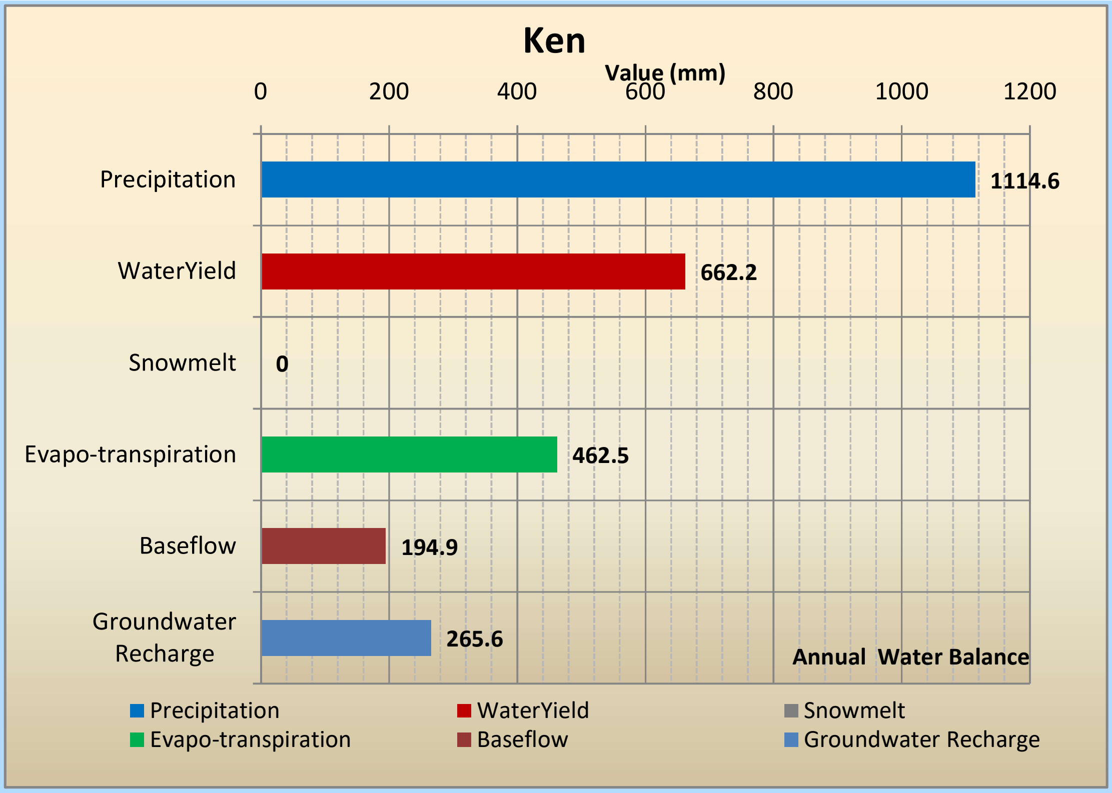


Figure 19: Annual water balance components for major tributaries of the Ganga river basin



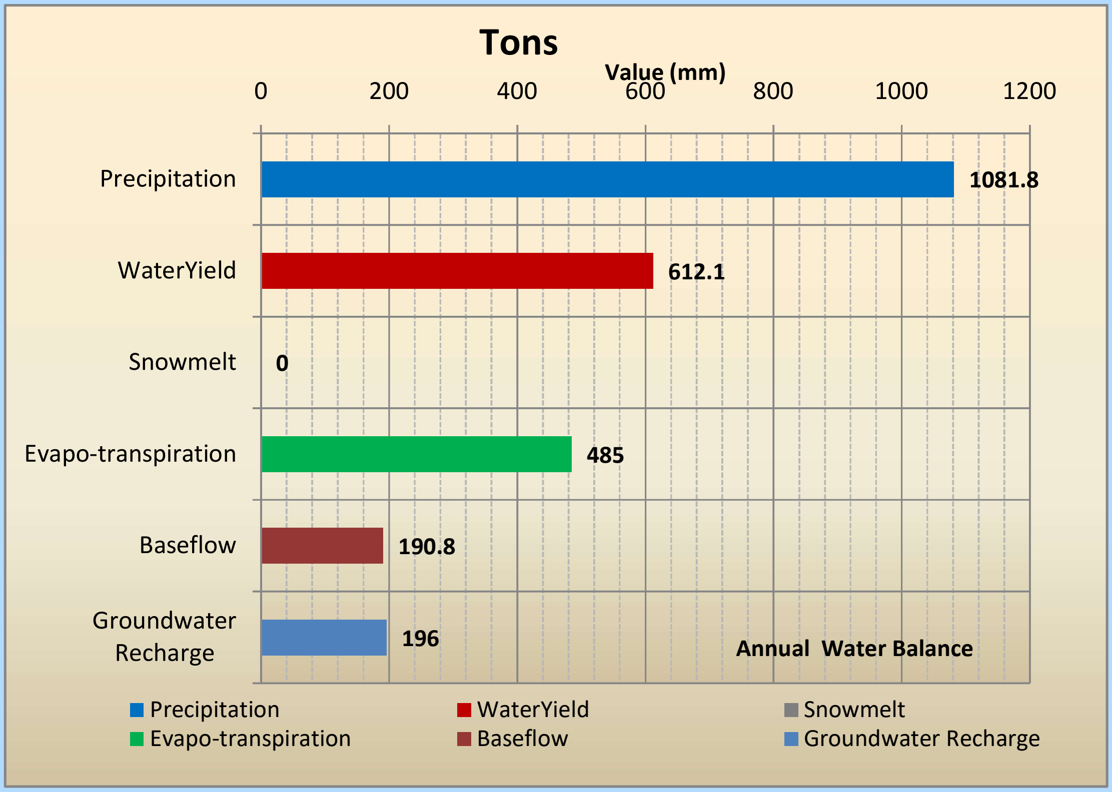


Figure 19: Annual water balance components for major tributaries of the Ganga river basin

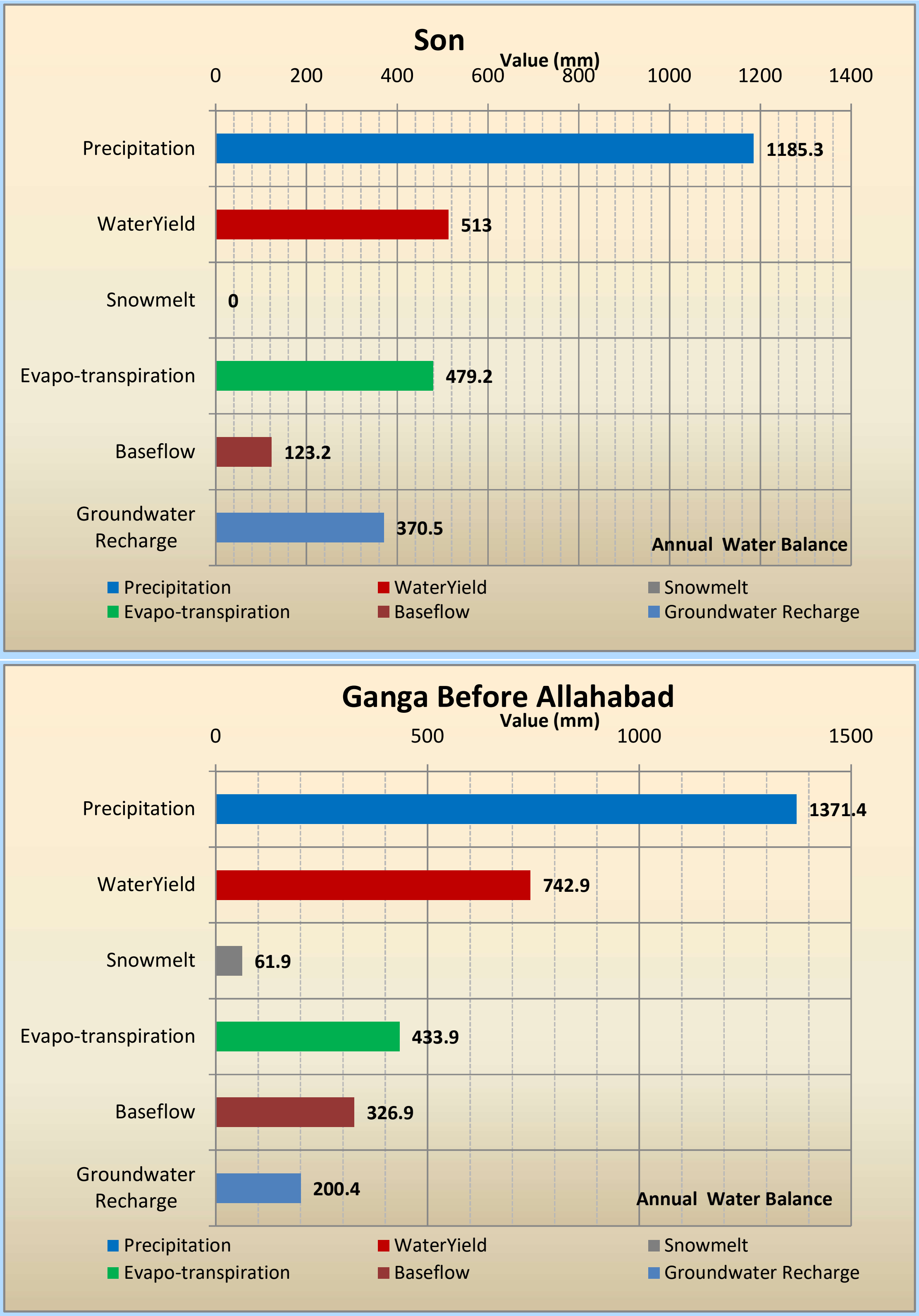
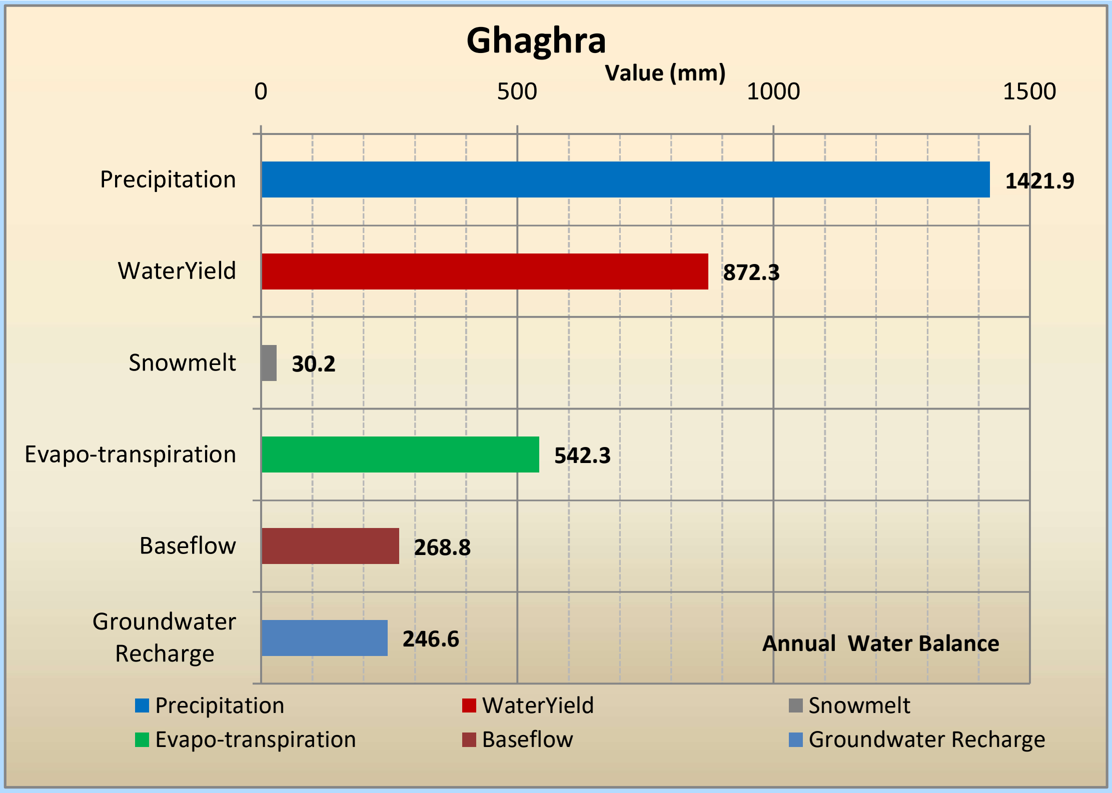


Figure 19: Annual water balance components for major tributaries of the Ganga river basin



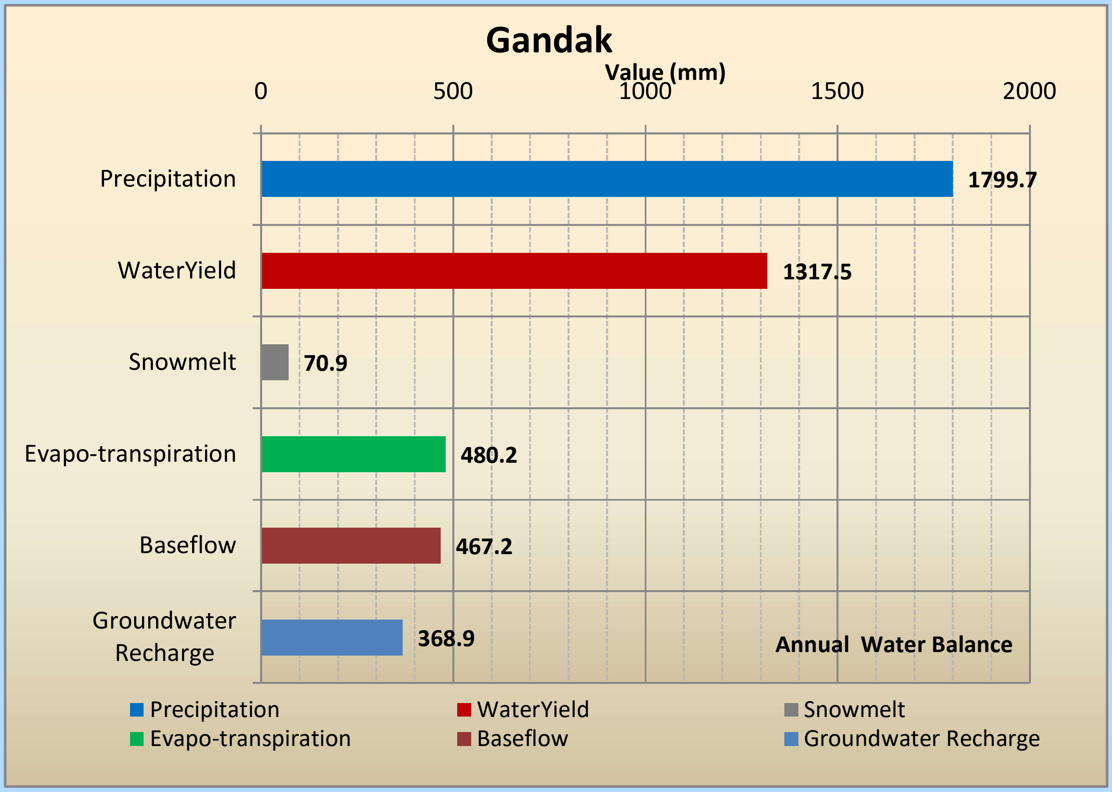
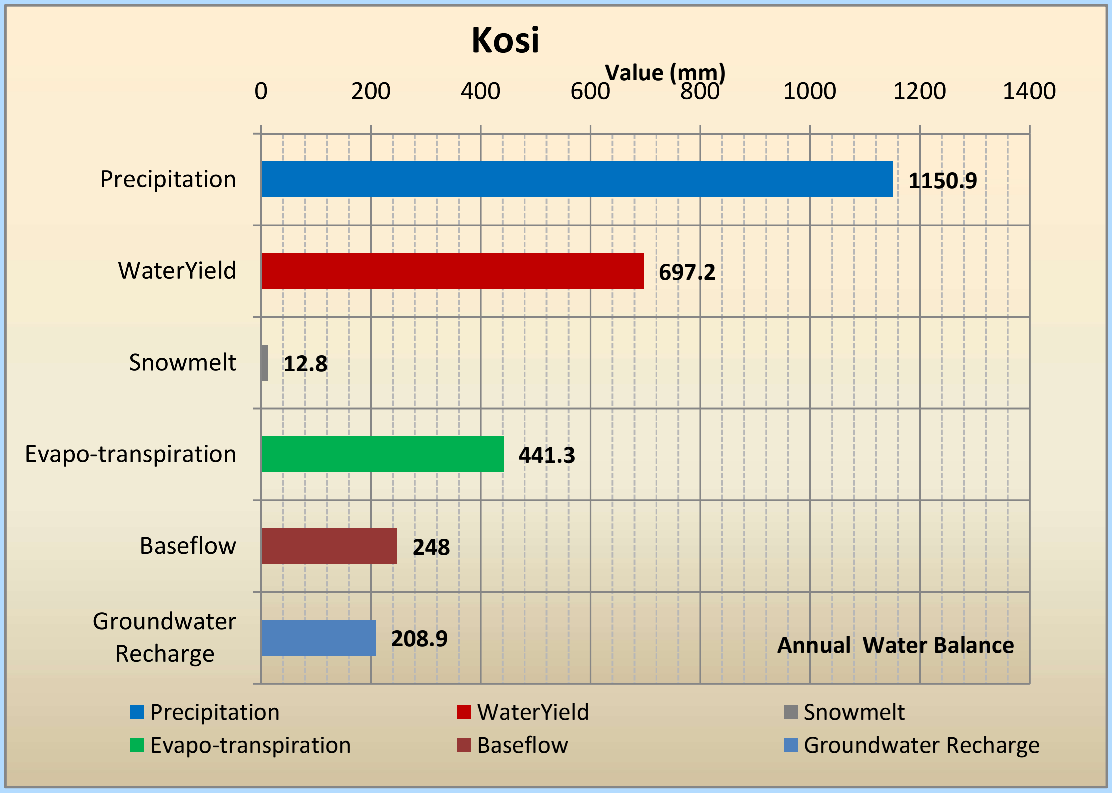


Figure 19: Annual water balance components for major tributaries of the Ganga river basin

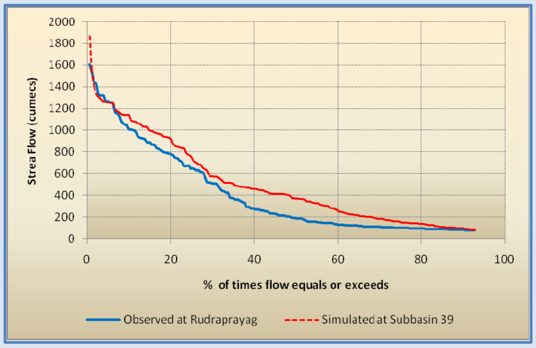


Flow Duration Curve and Flow Dependability

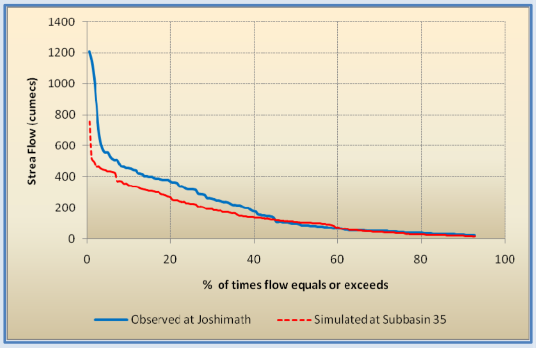
Assessment of dependable lean season flows along with their distribution in time is essential for planning and development of water supply schemes. The dependability of the water yield of the river system has been analyzed with respect to three levels of 50, 75 and 90% dependability. 90% probability 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

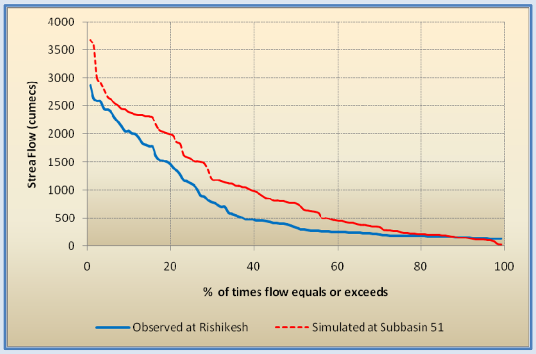
Rudraprayag on Alaknanda (Ganga/Alaknanda)



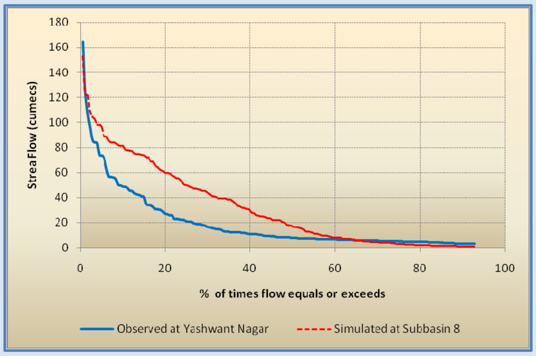
Joshimath on Alaknanda (Ganga/Alaknanda) river



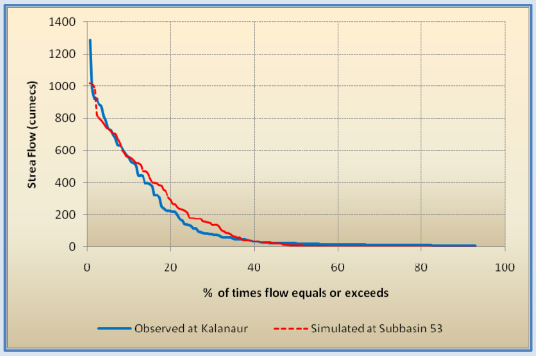
Rishikesh on Ganga river



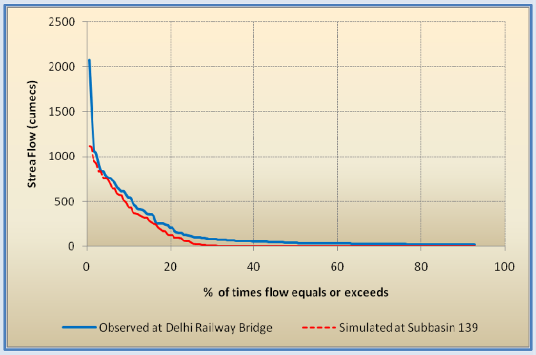
Yashwant Nagar on Giri (Yamuna/Giri) river



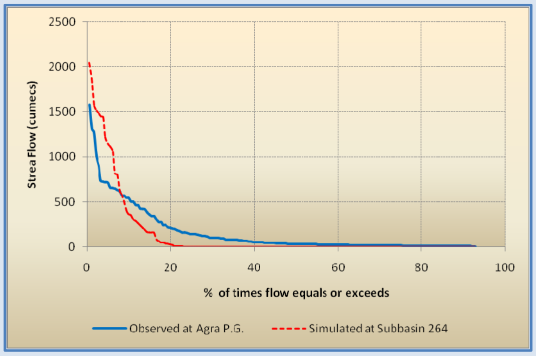
Kalanaur on Yamuna (Ganga/Yamuna) river



Delhi Rly Bridge on Yamuna (Ganga/Yamuna)



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



Dholpur on Chambal (Yamuna/Chambal)

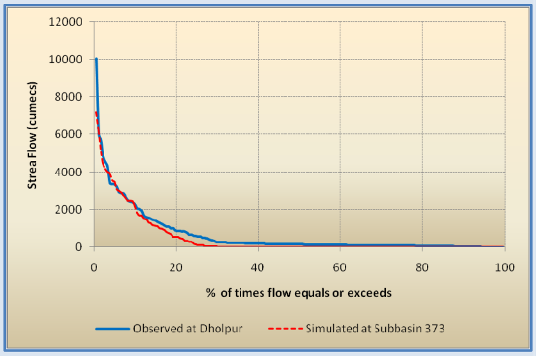
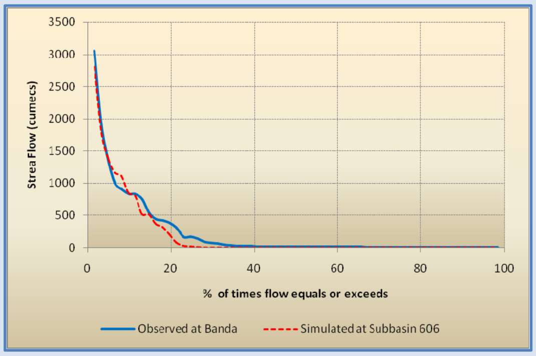
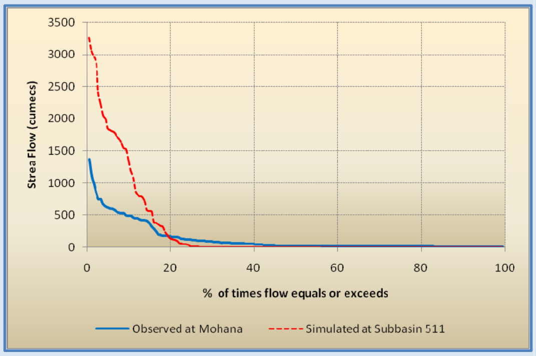


Figure 20: Flow Duration Curve at selected Locations for the Ganga river basin

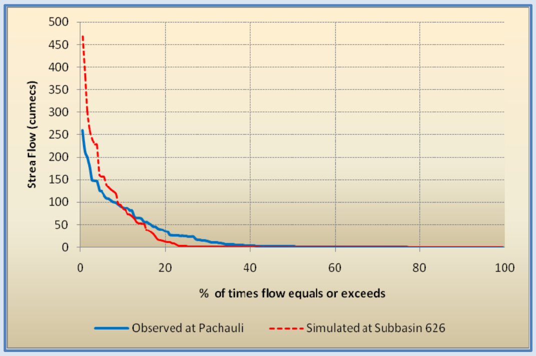
Banda on Ken (Ganga/Yamuna/Ken) river



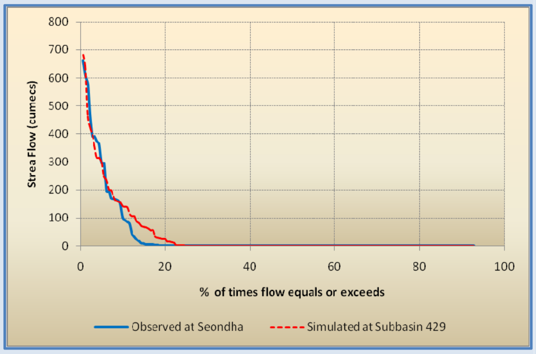
Mohana on Betwa (Ganga/Yamuna/Betwa)



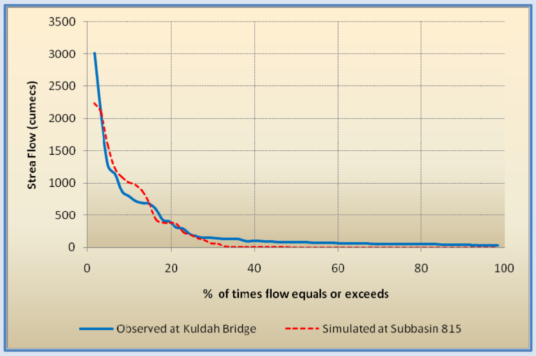
Pachauli on Sind (Ganga/Yamuna/Sind) river



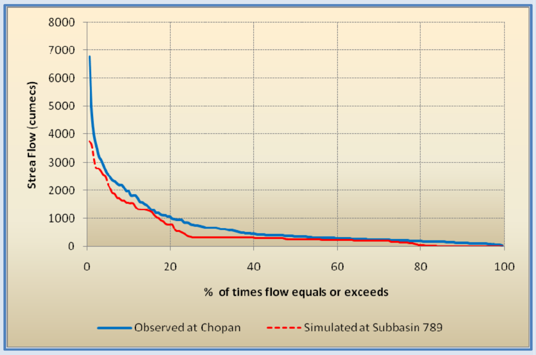
Seondha on Sone (Ganga/Yamuna/Sind) river



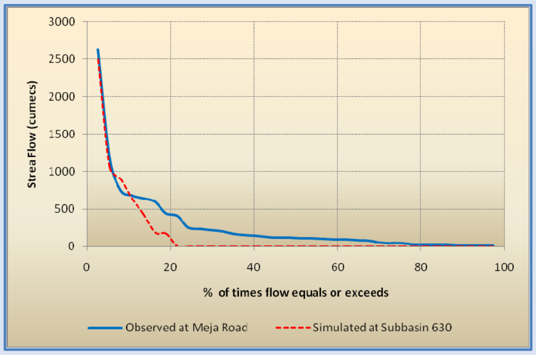
Kuldahbridge on Sind (Ganga/Sone) river



Chopan on Sind (Ganga/Sone) river



Meja Road on Tons (Ganga/Tons) river



Elginbridge on Ghagra (Ganga/Ghagra) river

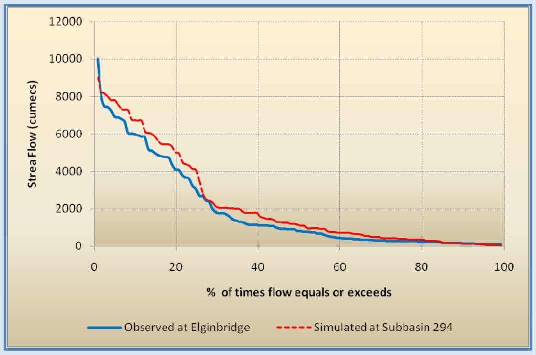
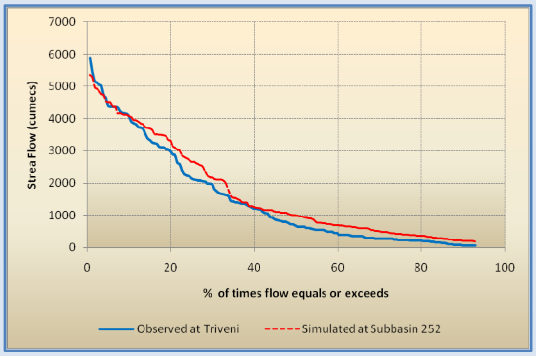
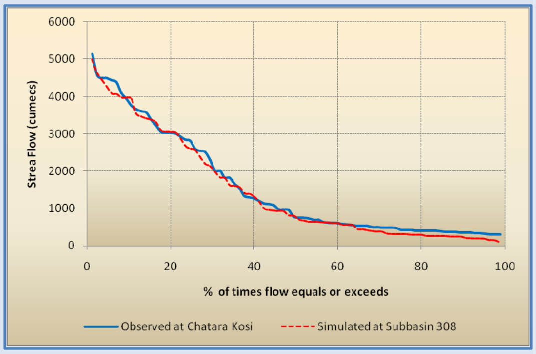


Figure 20: Flow Duration Curve at selected Locations for the Ganga river basin

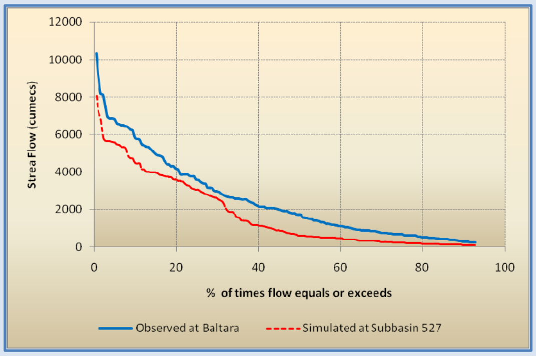
Tribeni on Gandak (Ganga/Gandak) river



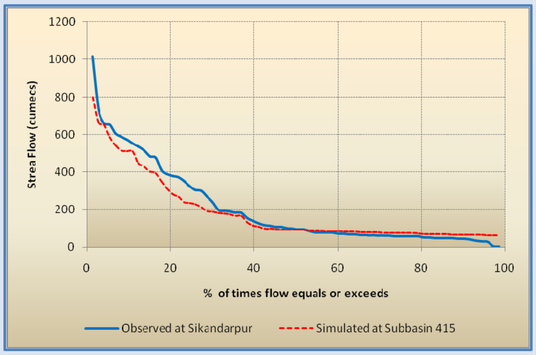
Chatara Kosi on Kosi (Ganga/Kosi) river



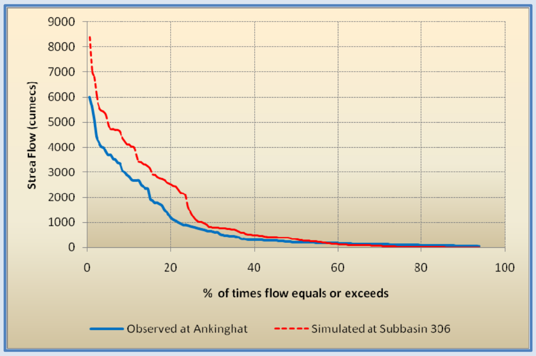
Baltara on Kosi (Ganga/Kosi) river



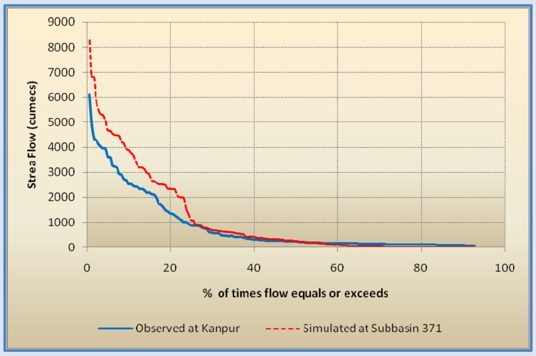
Sikanderpur on Burhi Gandak (Ganga/BurhiG)



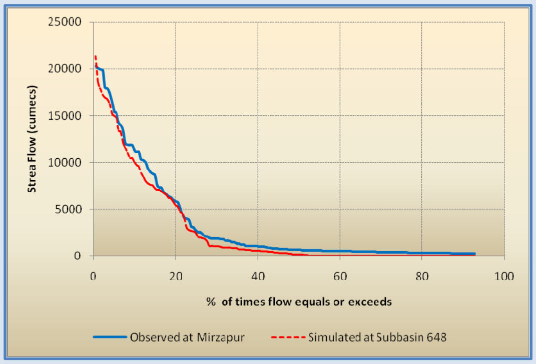
Ankinghat on Ganga river



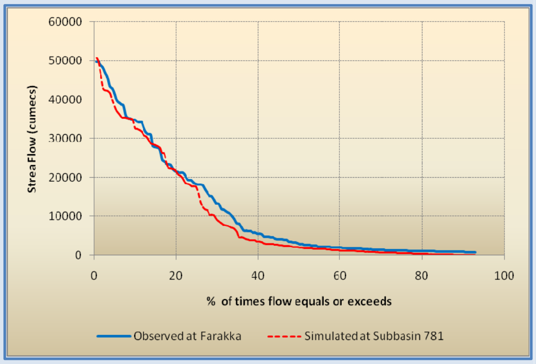
Kanpur on Ganga river



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.

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

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[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

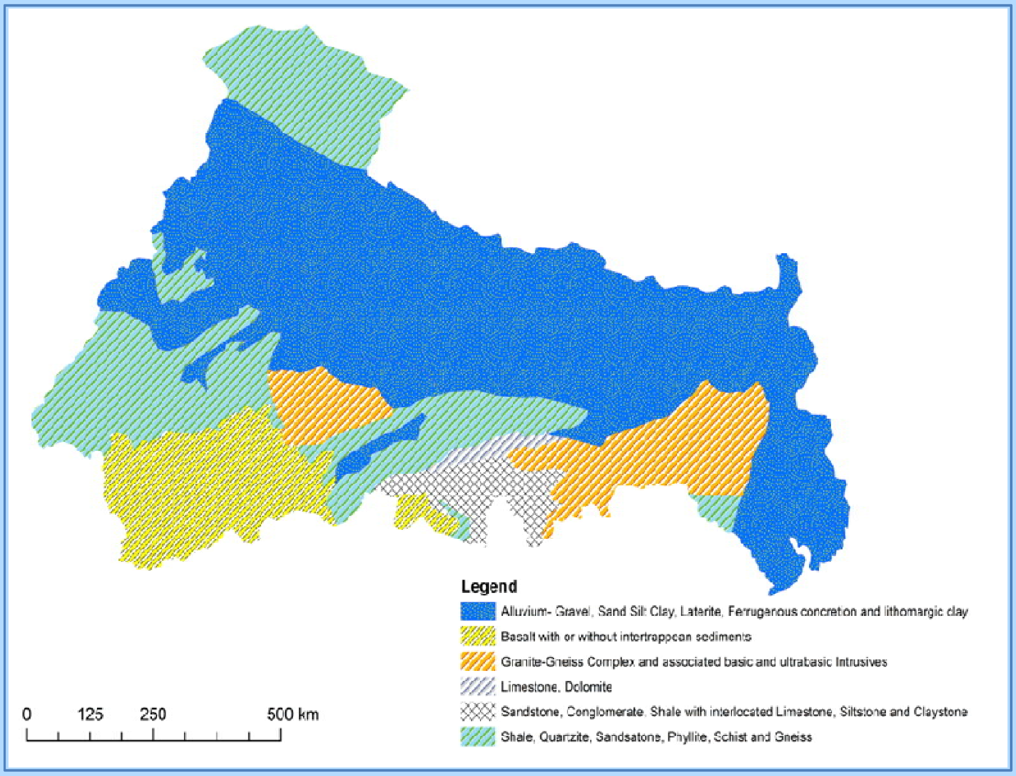
The following objectives are covered under the groundwater modelling:

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 effusives 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

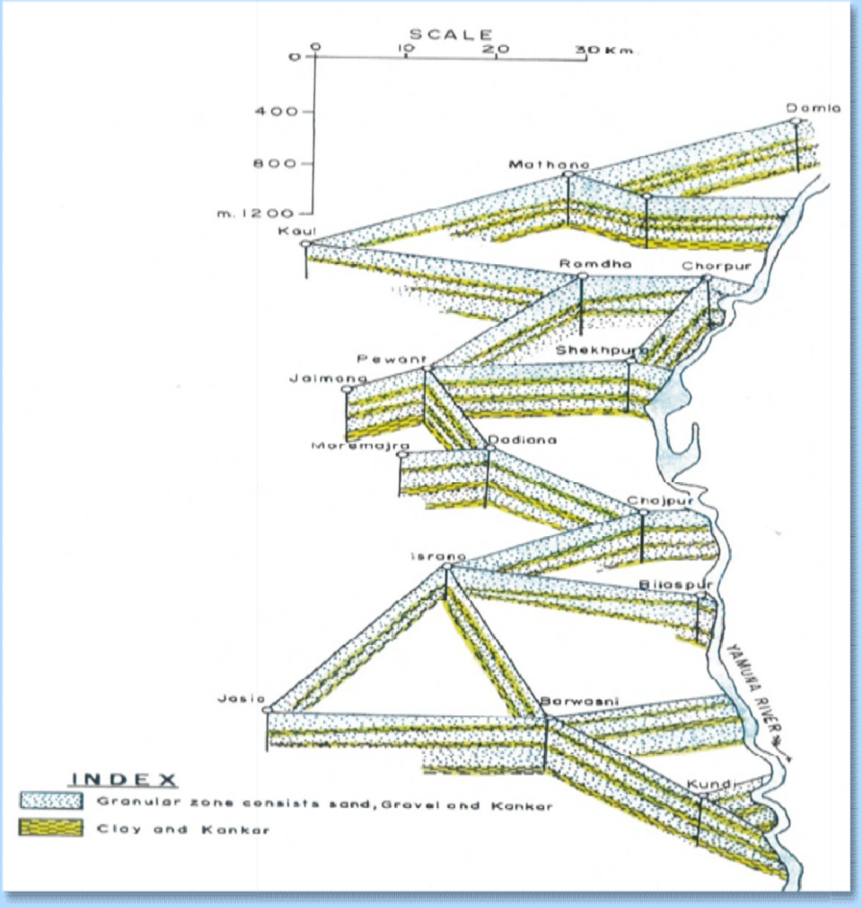
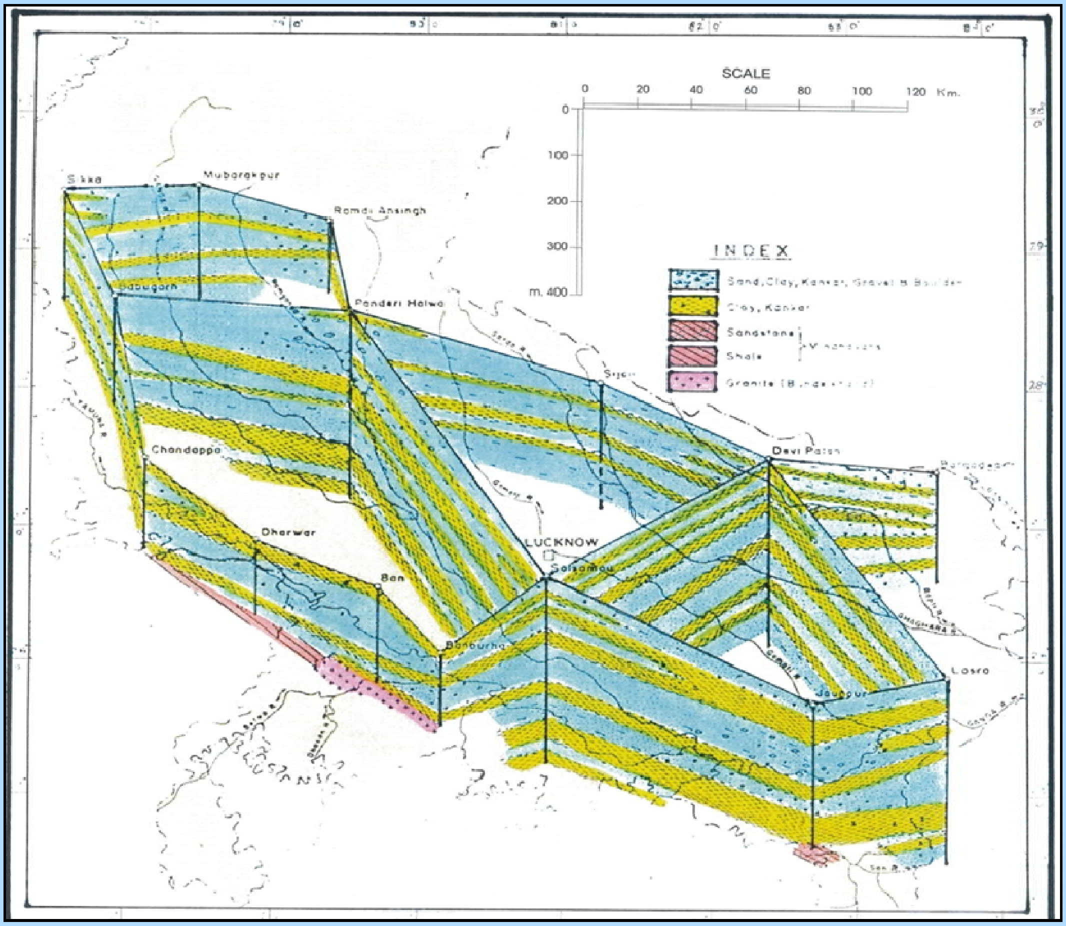


Figure 22: Fence diagrams for Yamuna, Uttar Pradesh, Bihar and West Bengal(CGWB Report,1996)

Parts of Ganga Basin in Uttar Pradesh



Parts of Ganga Basin in Bihar

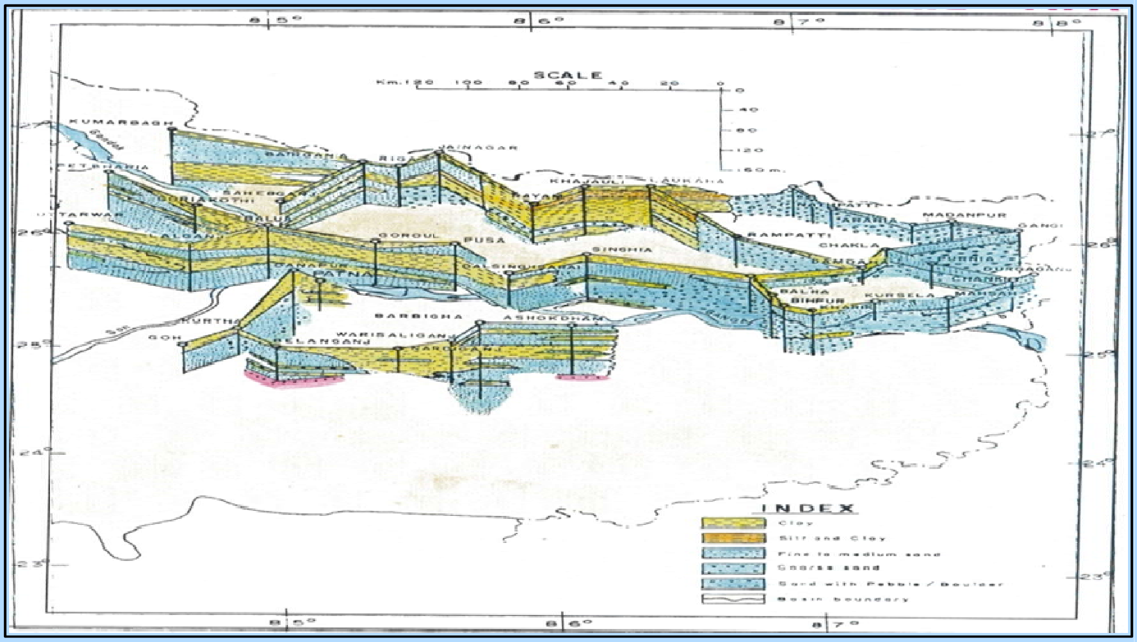
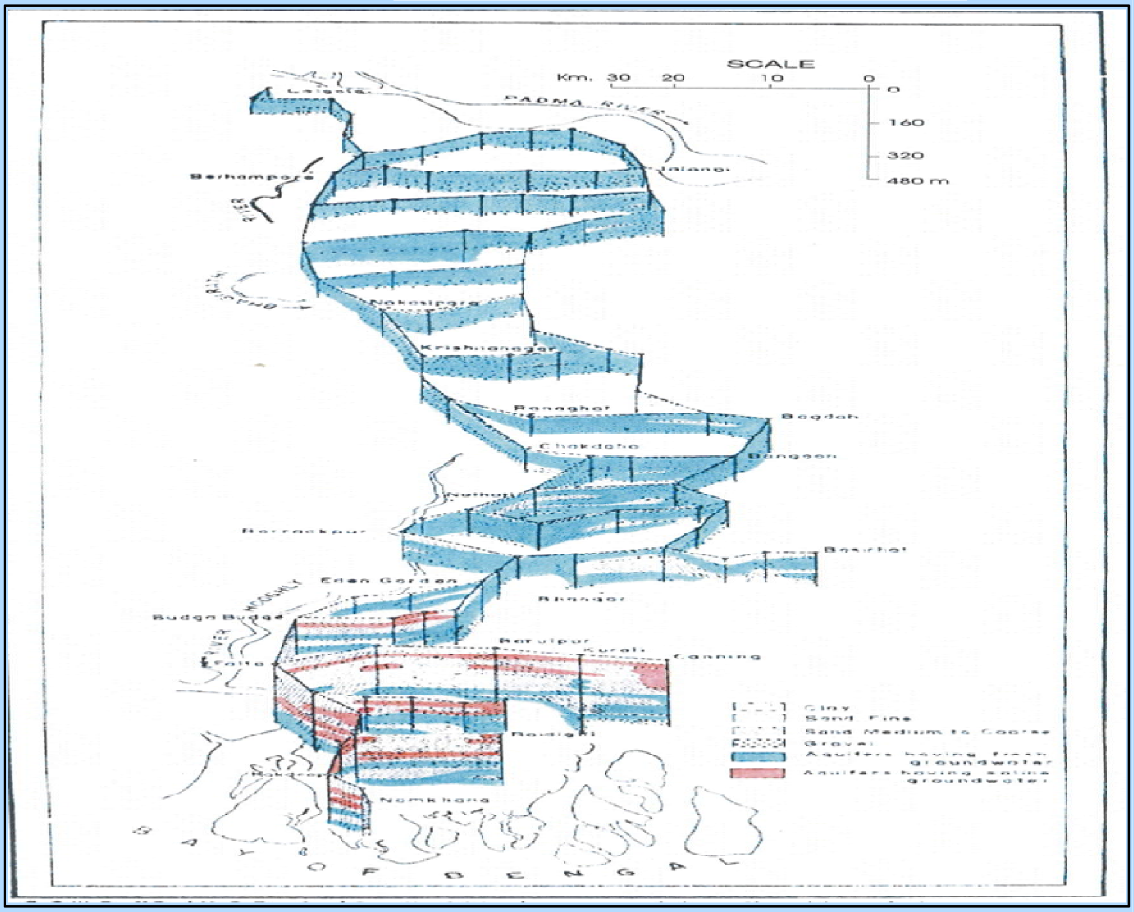


Figure 22: Fence diagrams for Yamuna, Uttar Pradesh, Bihar and West Bengal(CGWB Report,1996)

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.

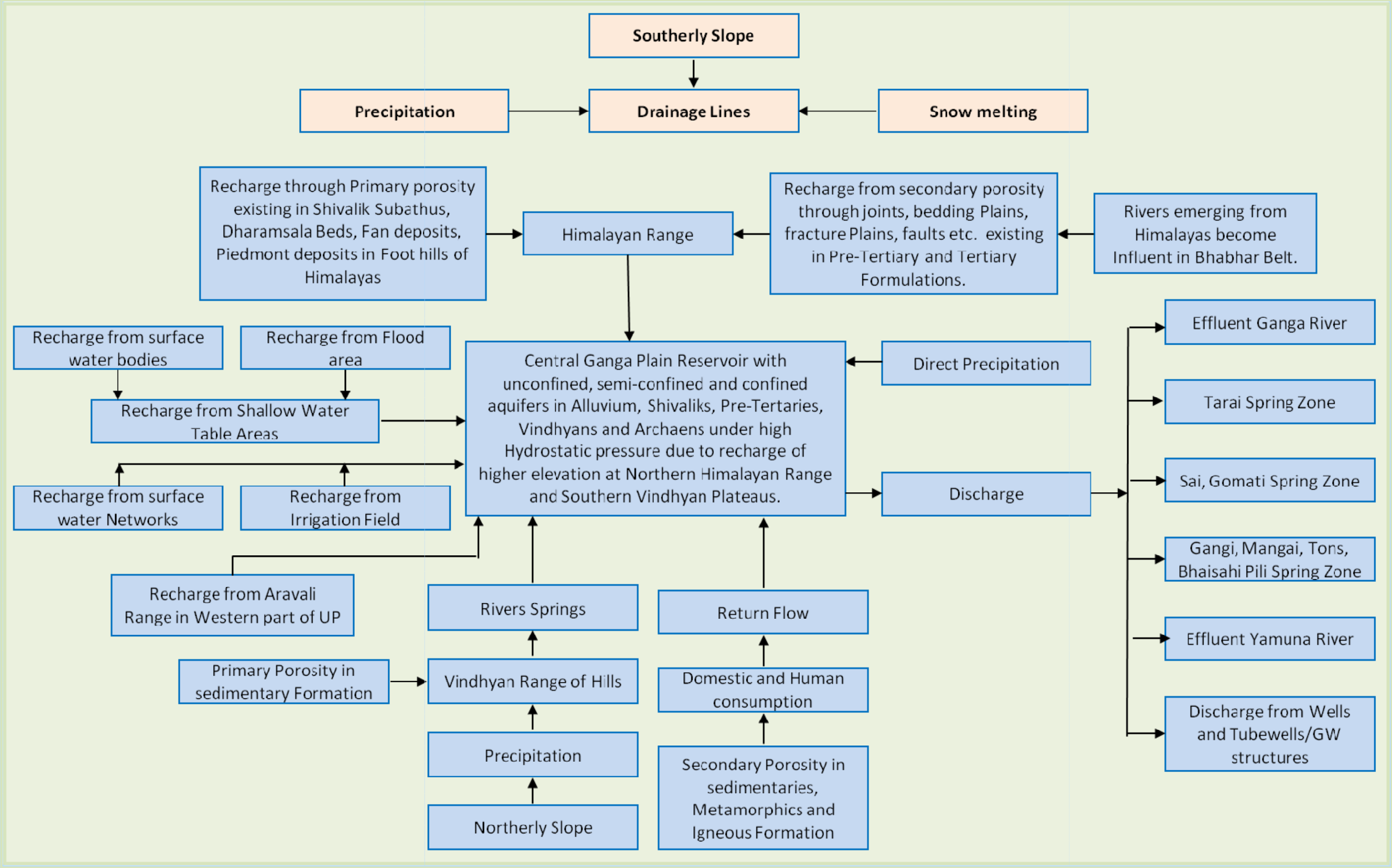
The thickness of foreland sediments shows a strong asymmetry. The younger Shivaliks shows overlapping towards south, which is an indication of the widening of the basin towards south over Bundelkhand massif. The sediments are coarse grained close to Himalayas and become finer towards the craton and show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

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

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[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.

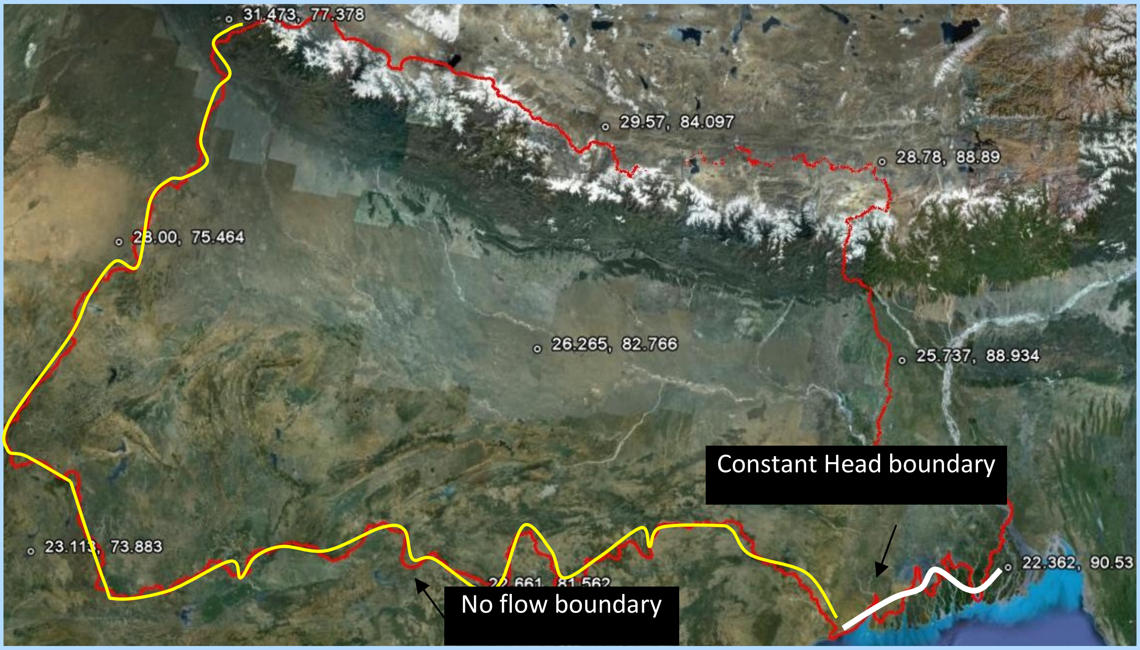
Model conceptualization and data acquisition

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

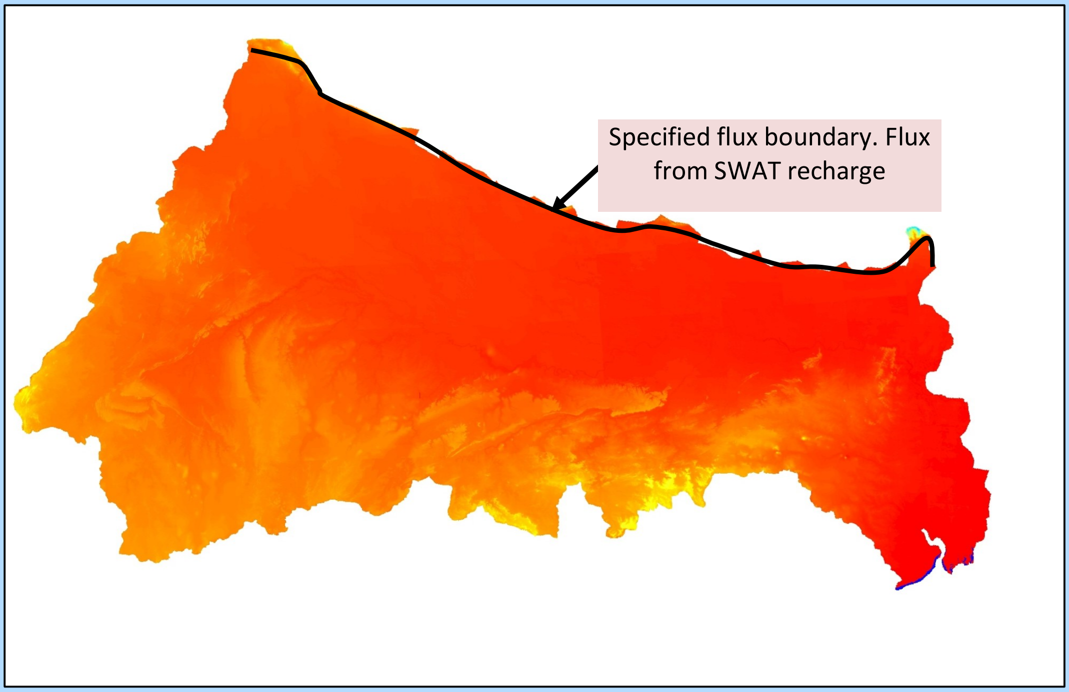
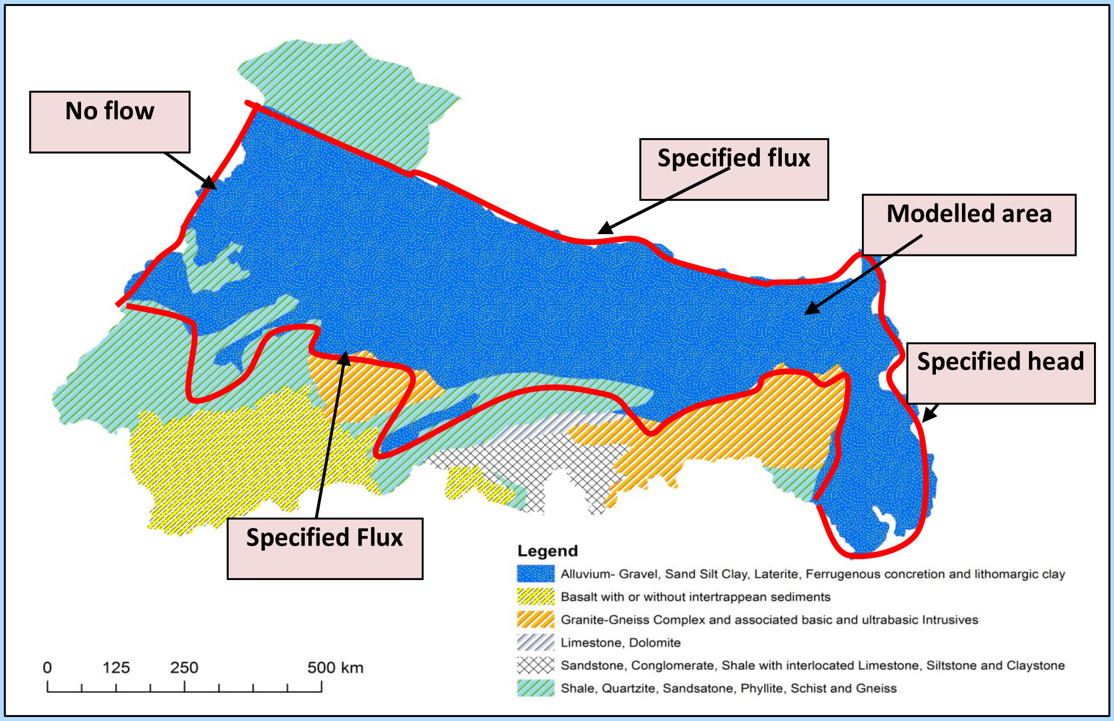


Figure 26:Final Portion of the Ganga basin used for Groundwater modelling



Aquifer Geometry

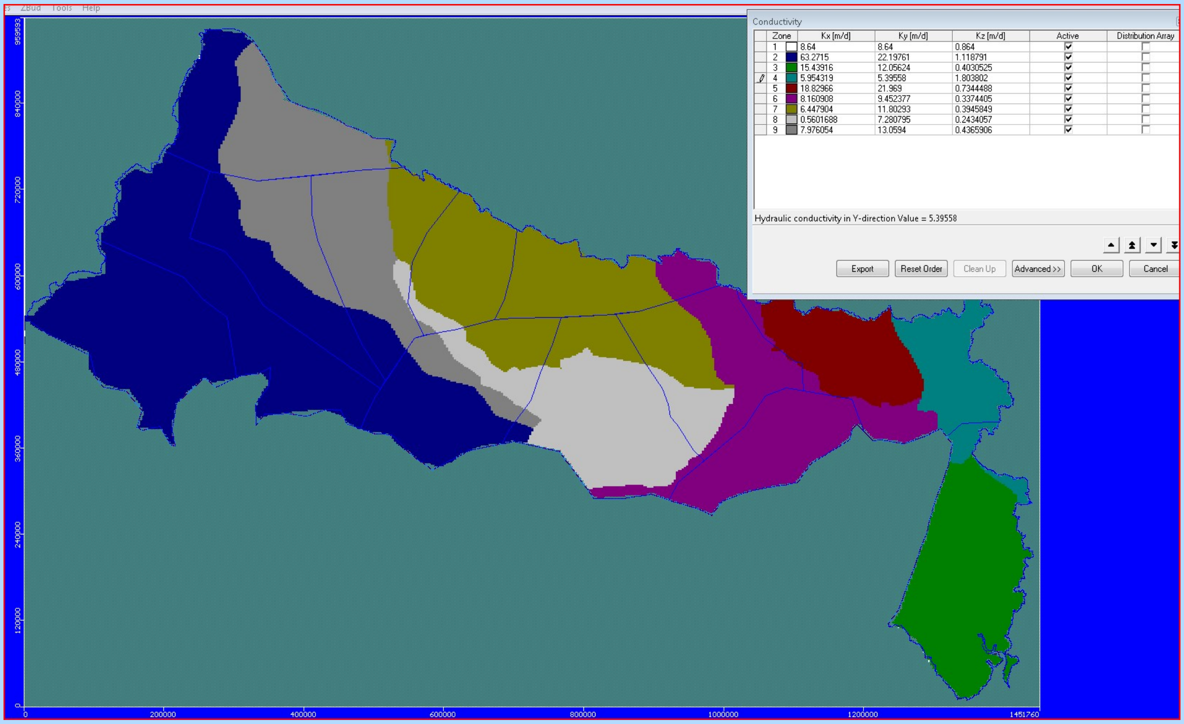
Geologic information including aquifers, cross sections and well logs were combined with information on hydrogeologic properties to define hydrostratigraphic units for the conceptual model. It was shown in previous section that the aquifer depth extends upto 750m below ground level in most places of 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.

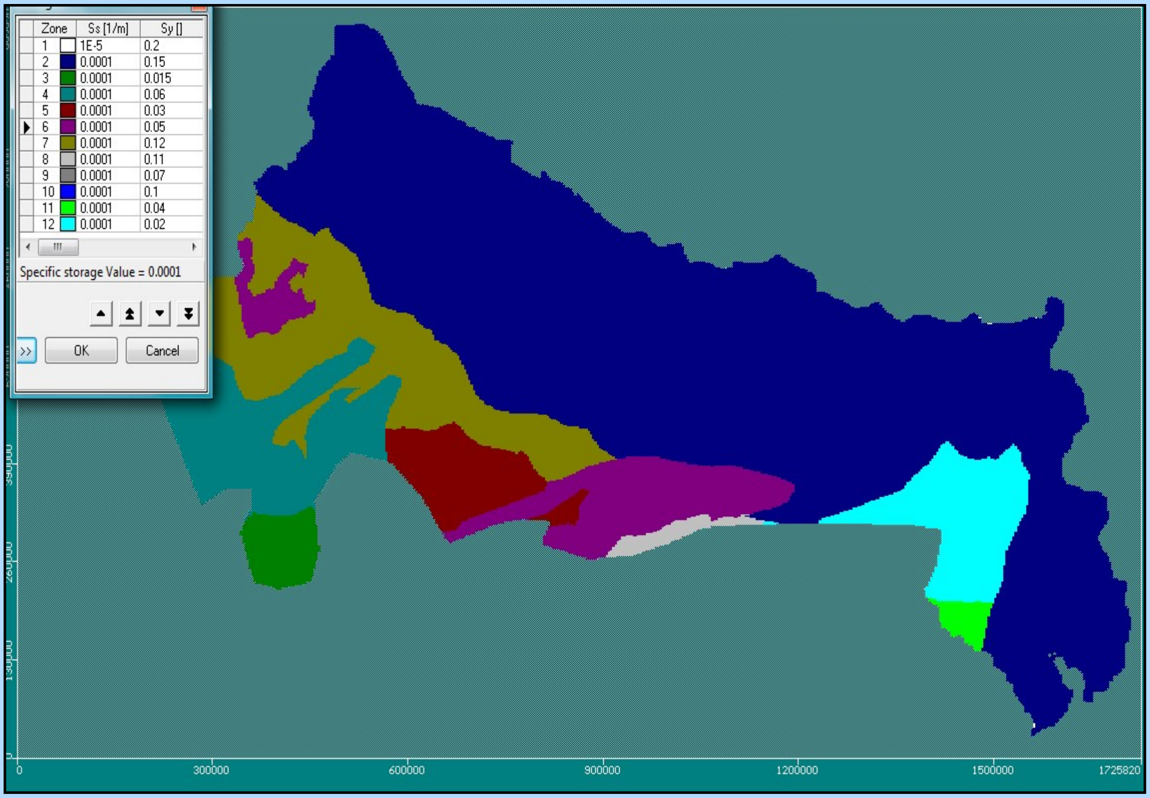
Figure 27:Conductivity zones of the entire Ganga Basin



Zone		Kx [m/d]	Ky [m/d]	Kz [m/d]	Active	Distribution Array
1	☐	8.64	8.64	0.864	☑	☐
2	■	63.2715	22.19761	1.118791	☑	☐
3	■	15.43916	12.05624	0.4030525	☑	☐
4	■	5.954319	5.39558	1.803802	☑	☐
5	■	18.82966	21.969	0.7344488	☑	☐
6	■	8.160908	9.452377	0.3374405	☑	☐
7	■	6.447904	11.80293	0.3945849	☑	☐
8	■	0.5601688	7.280795	0.2434057	☑	☐
9	■	7.976054	13.0594	0.4365906	☑	☐

Hydraulic conductivity in Y-direction Value = 5.39558

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



Zone		Ss [1/m]	Sy []
1	⬜	1E-5	0.2
2	🟦	0.0001	0.15
3	🟩	0.0001	0.015
4	🟦	0.0001	0.06
5	🟥	0.0001	0.03
6	🟪	0.0001	0.05
7	🟫	0.0001	0.12
8	⬜	0.0001	0.11
9	⬛	0.0001	0.07
10	🟦	0.0001	0.1
11	🟩	0.0001	0.04
12	🟦	0.0001	0.02

Specific storage Value = 0.0001

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

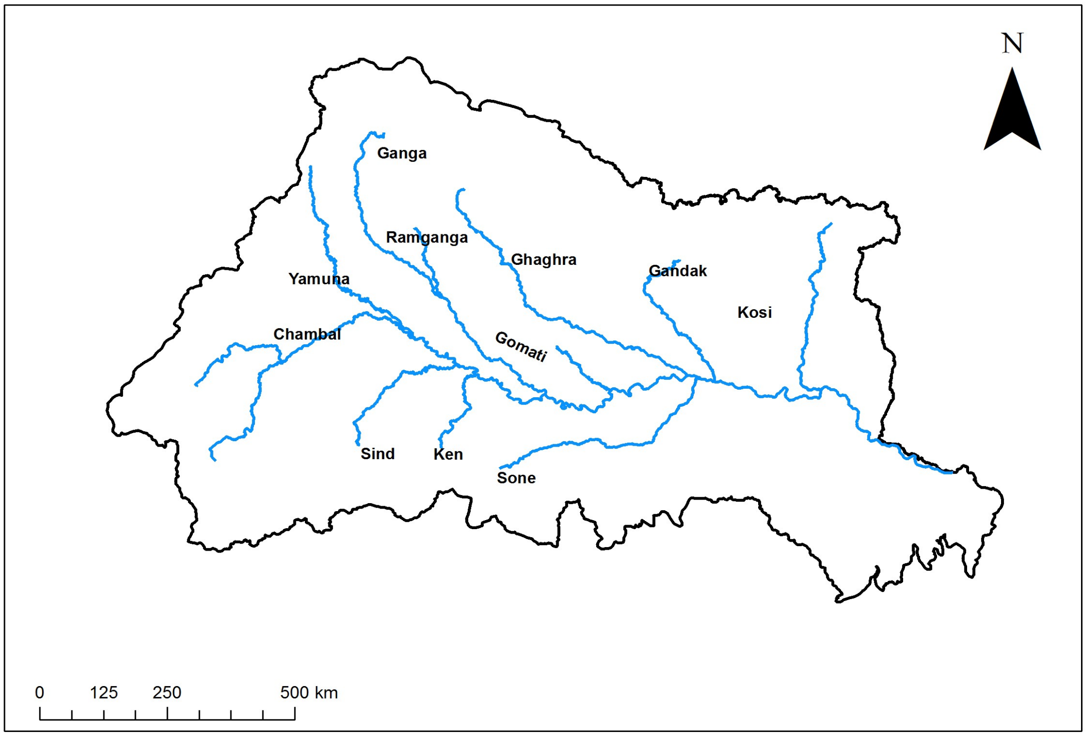
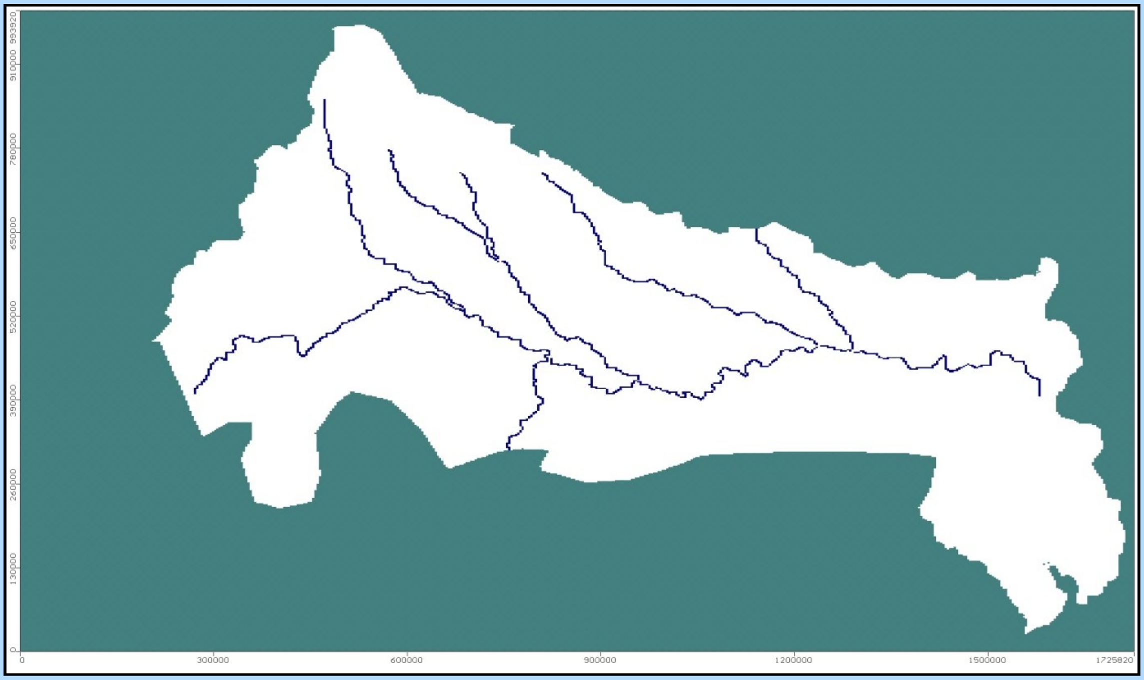


Figure 30: Incorporated River network boundary conditions in the Groundwater model



General head boundaries (GHB)

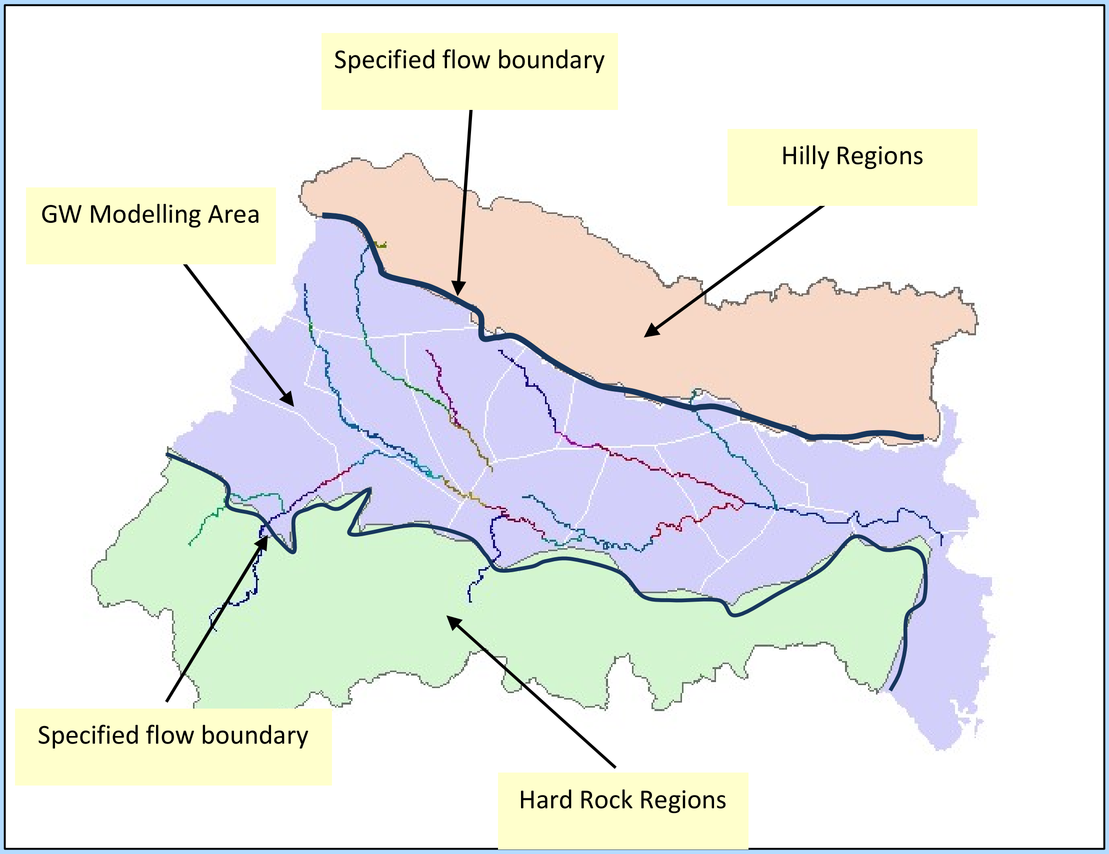
were assigned at the eastern edges (edges near the sea) of the model. Heads were assigned to the GHB with the help of historical water level data.

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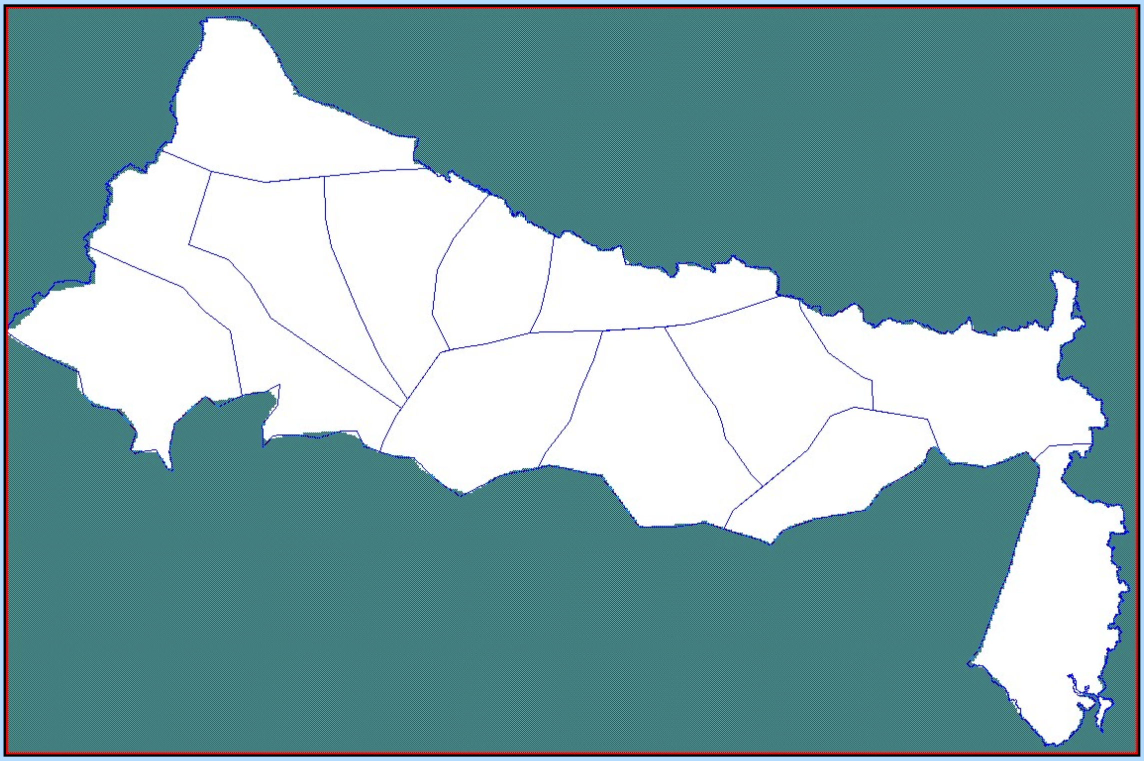
[31] Umar R 2008 Groundwater Flow Modeling and Aquifer Vulnerability Assessment studies in Yamuna–Krishni sub-basin, Muzaffarnagar District, Ministry of Water Resources, Government of India (Report)

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

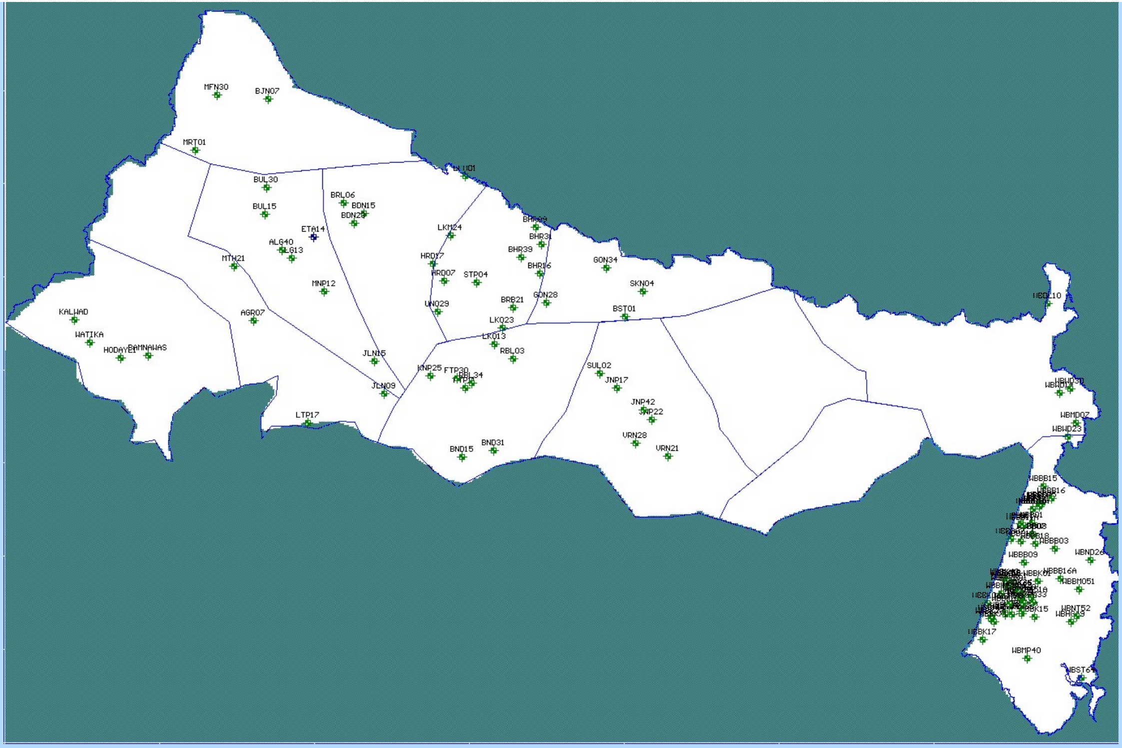
The purpose of model calibration is to establish that the model can reproduce field measured heads and flows. Calibration is carried out by trial and error adjustment of parameters.

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.

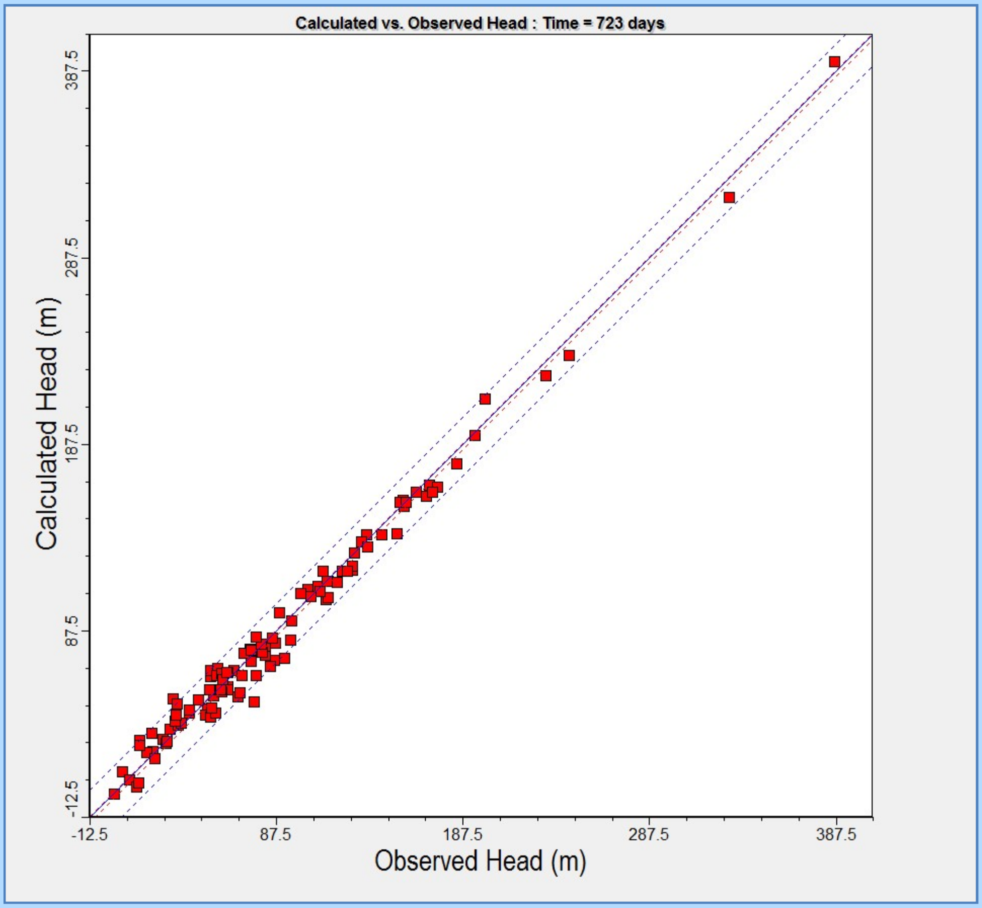
Figure 33:Location of the observation wells



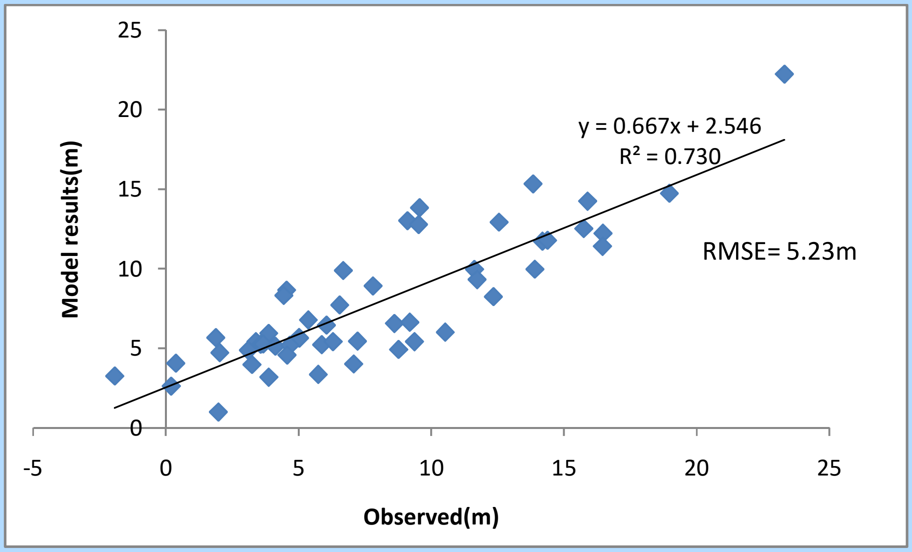
PEST (Parameter Estimation by Sequential Testing) Run

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

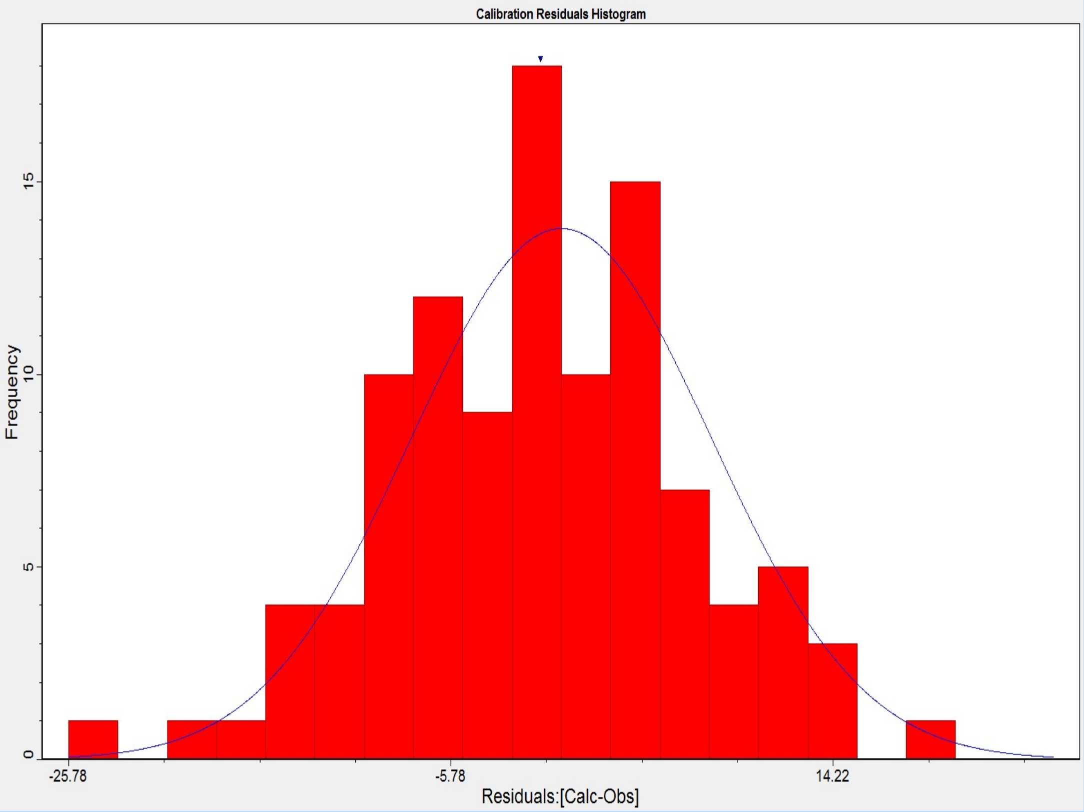


Figure 36:Time series plot of the Model results and observations for three observation wells

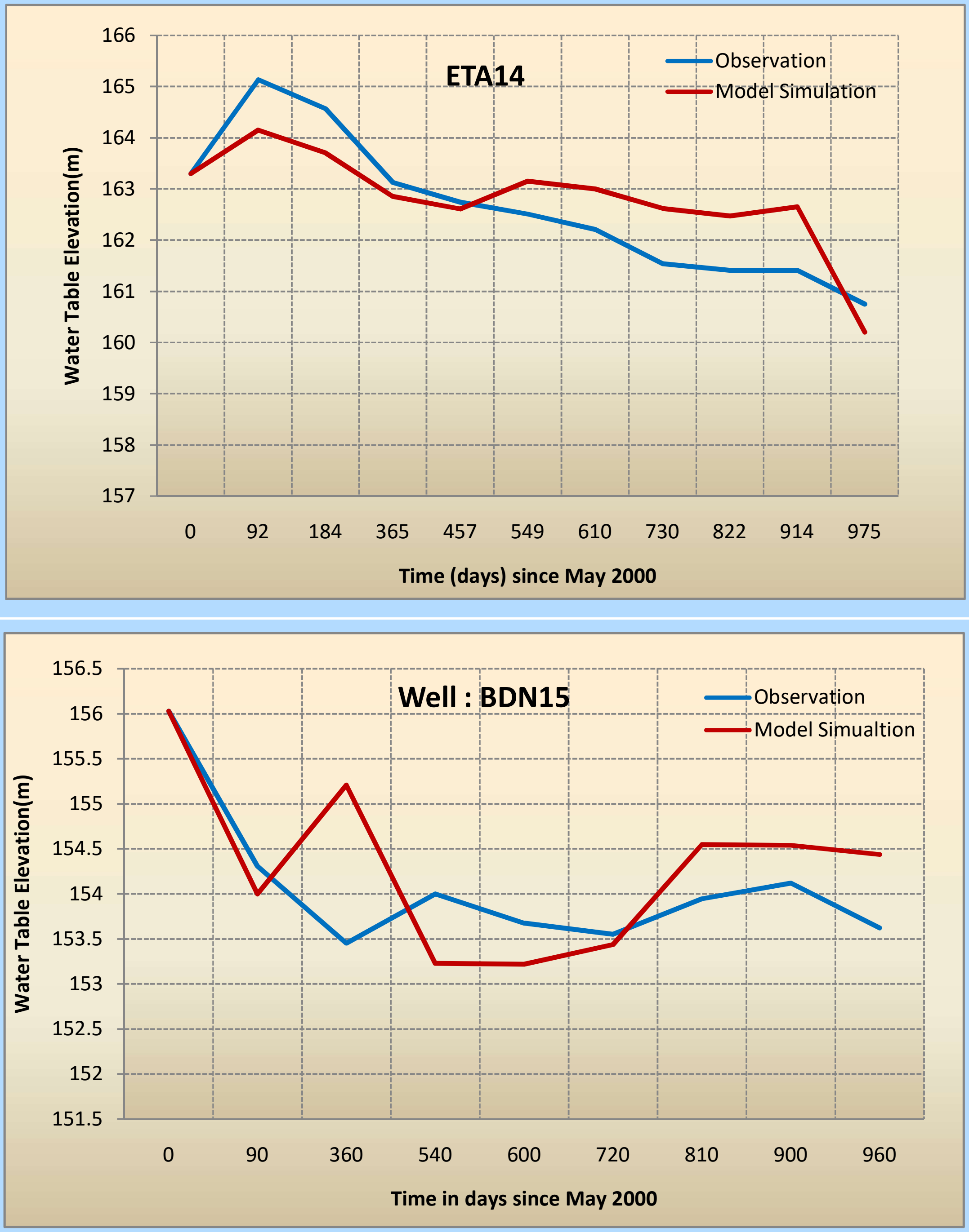


Figure 36:Time series plot of the Model results and observations for three observation wells

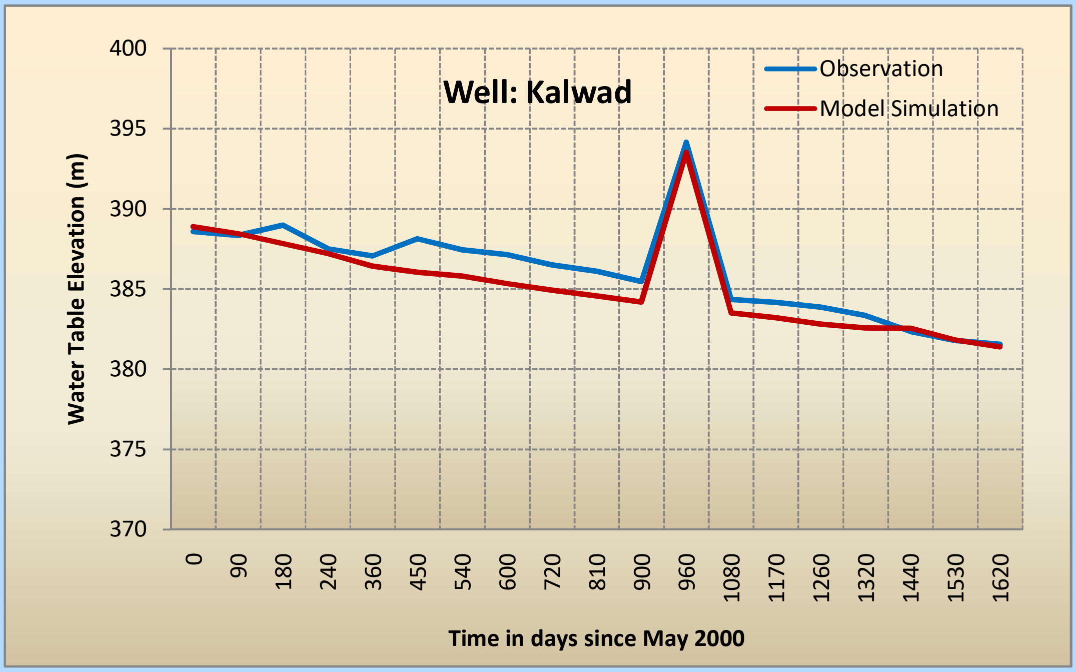


Figure 37 shows the contour plot of the water levels obtained from the model. The contour and the directions of the water flow was verified using the water level contour map produced by CGWB. It was observed that the flow pattern and direction obtained from the model was matching with the observed one. 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 in Table 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

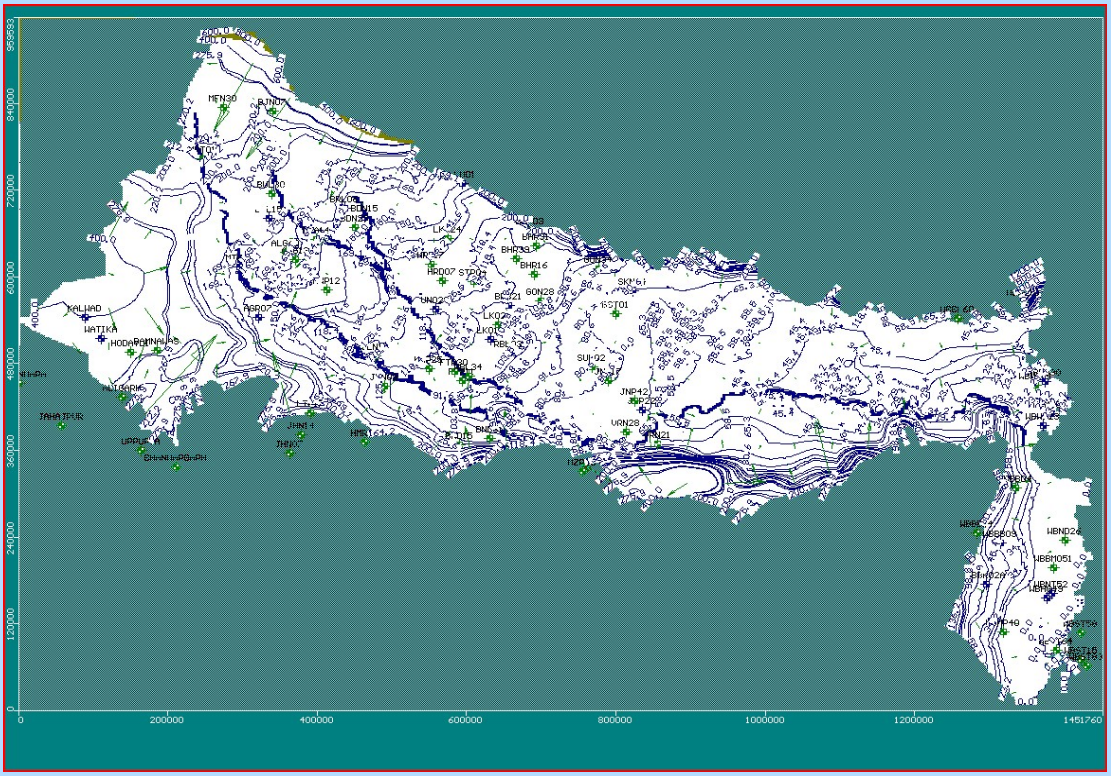


Figure 38:Depth to water Table in Ganga basin (Pre monsoon and Post monsoon average)

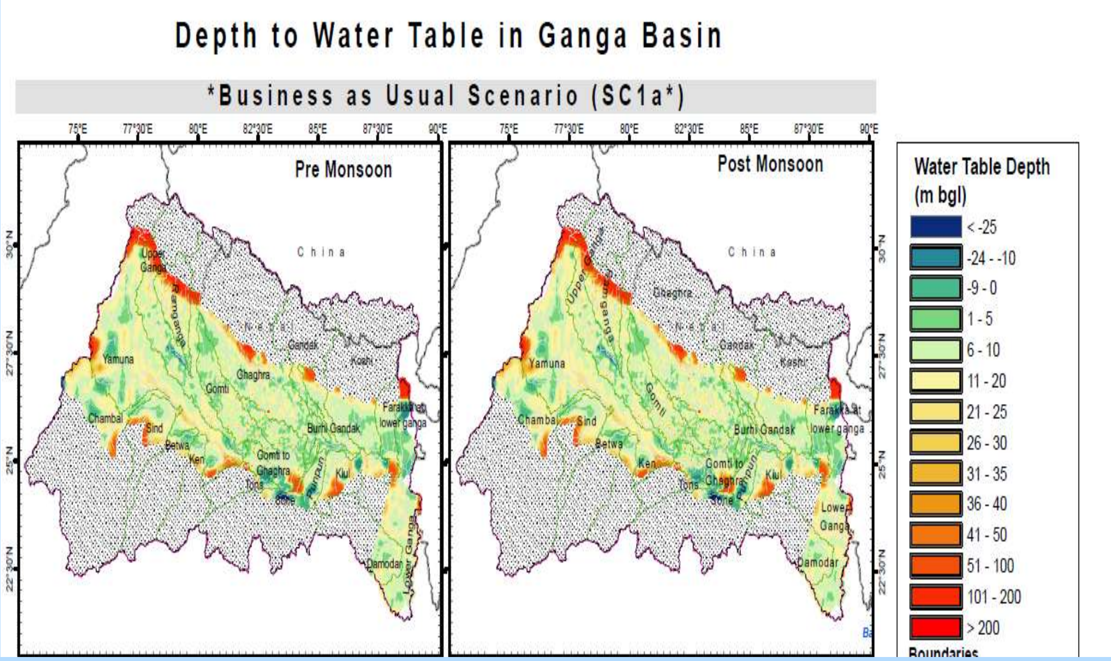


Figure 39:Scatter plot between the simulated water levels using auto calibration and observed water levels.

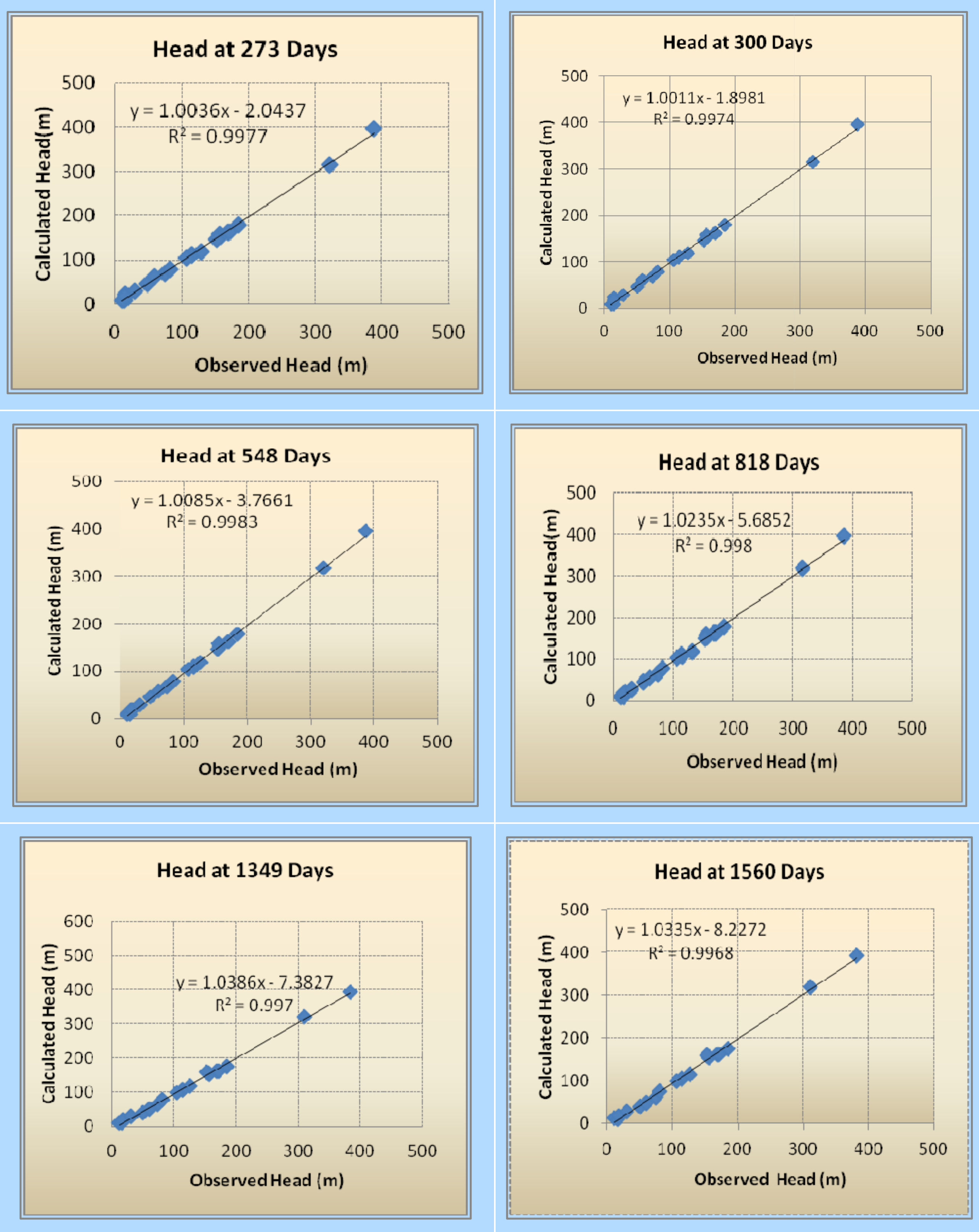
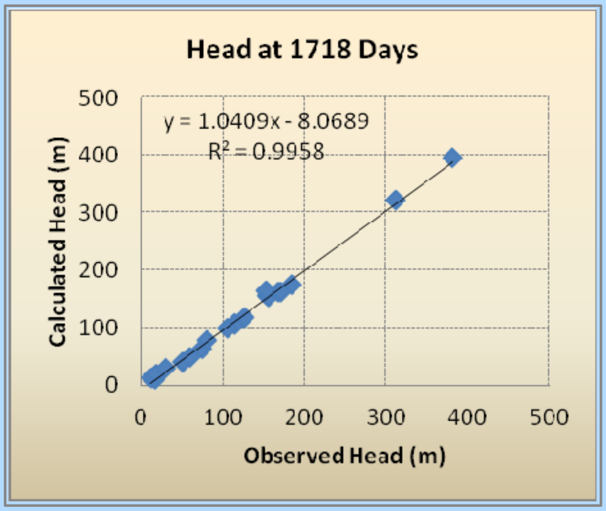


Figure 39:Scatter plot between the simulated water levels using auto calibration and observed water levels.



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,

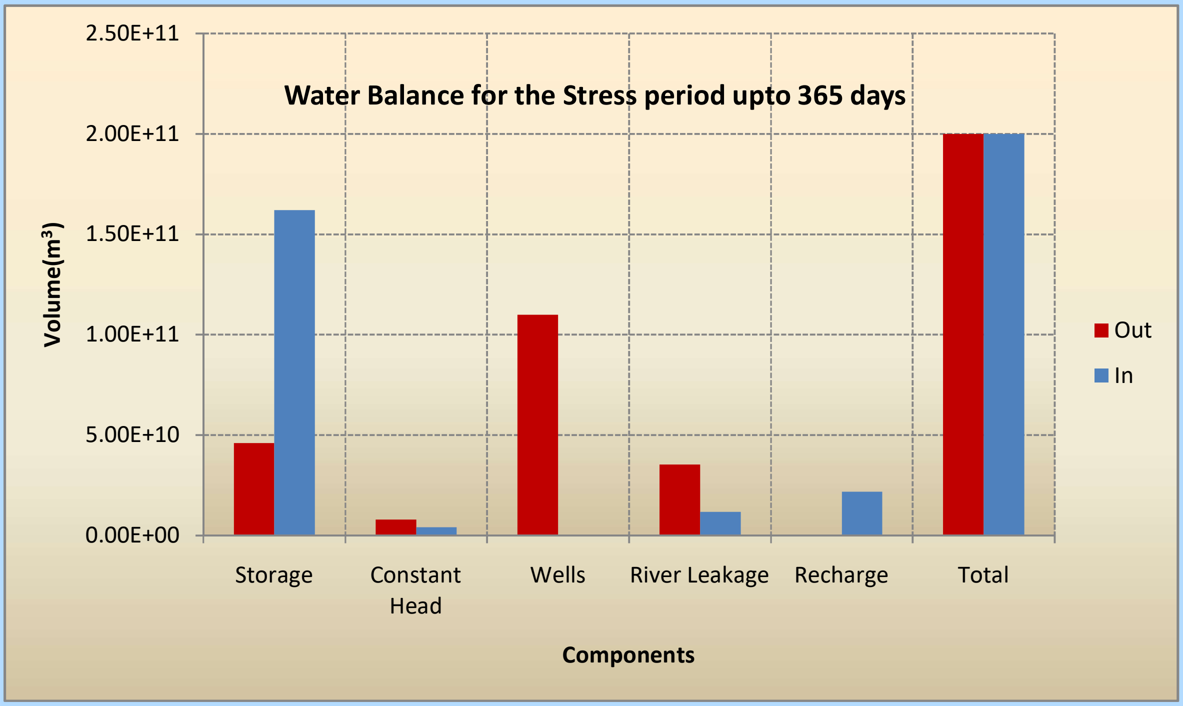
Storage is the amount of water going as storage in the ground water

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

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

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

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.

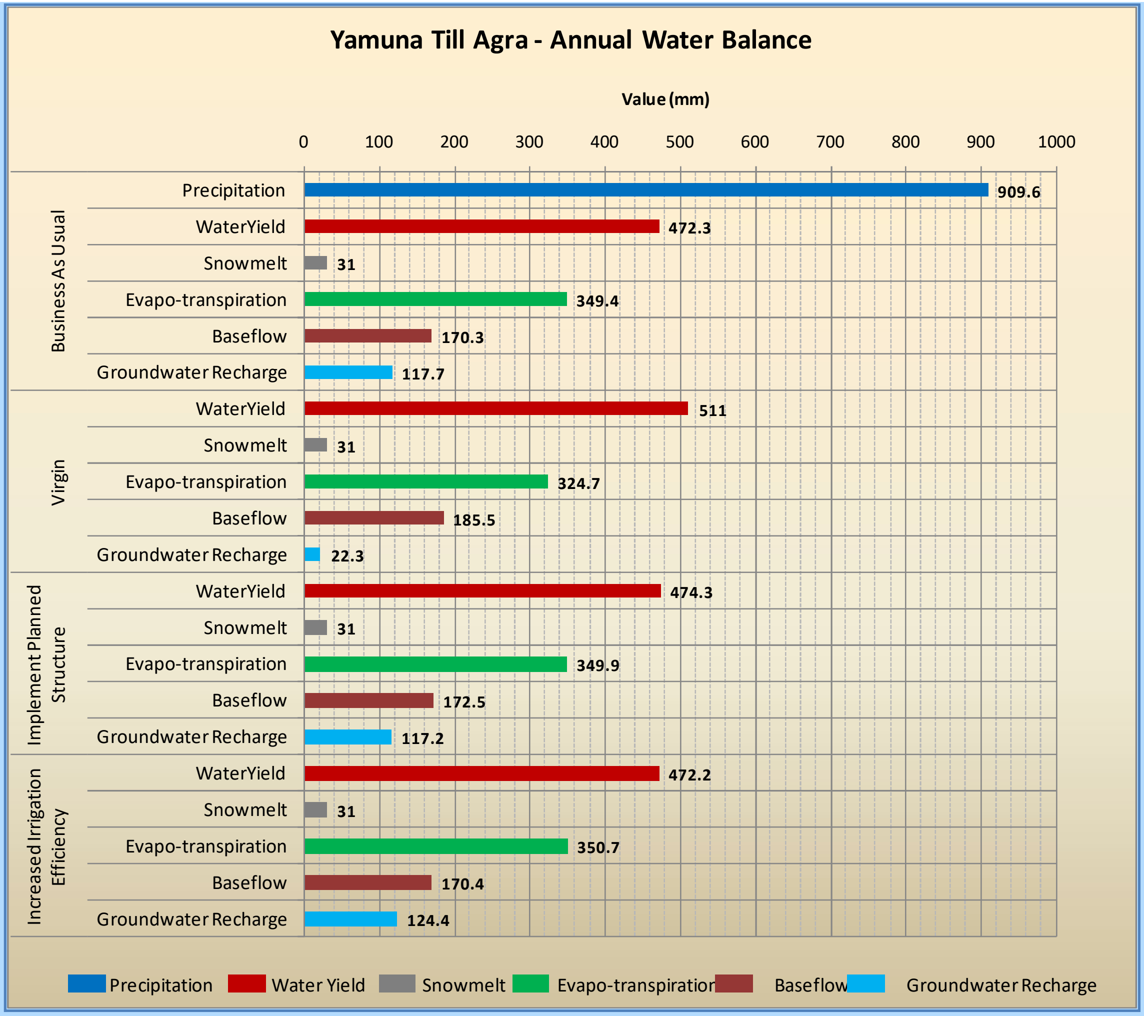
The Scenario 2, generated a very important output for pre-development (Virgin) conditions. It may be observed that in comparison with the virgin condition, there is a considerable deviation in the present status of the system. Except for the head water regions such as Kosi, Yamuna and Ram Ganga basin, 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.

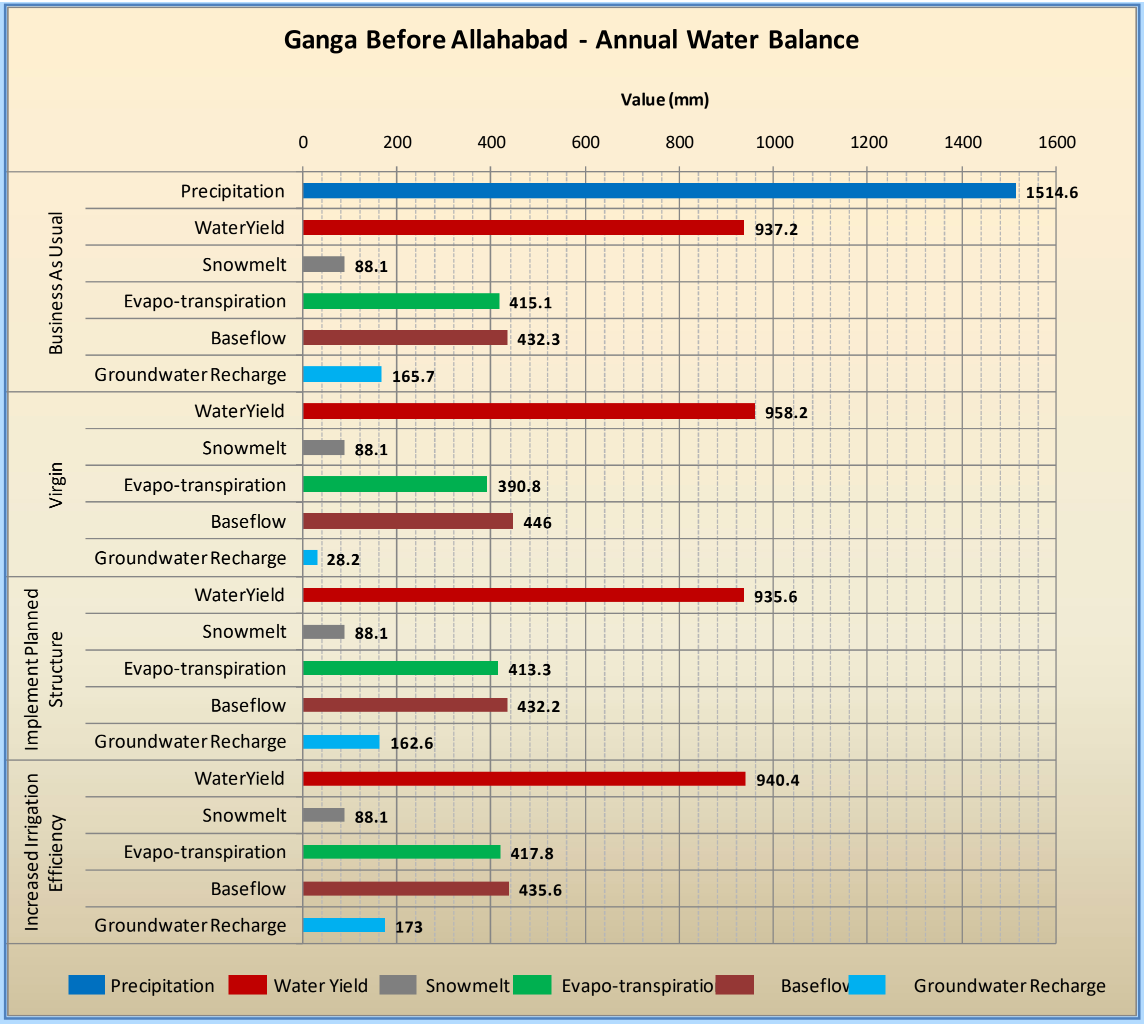
Figure 41: Annual Water Balance for Yamuna Basin Till Agra



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

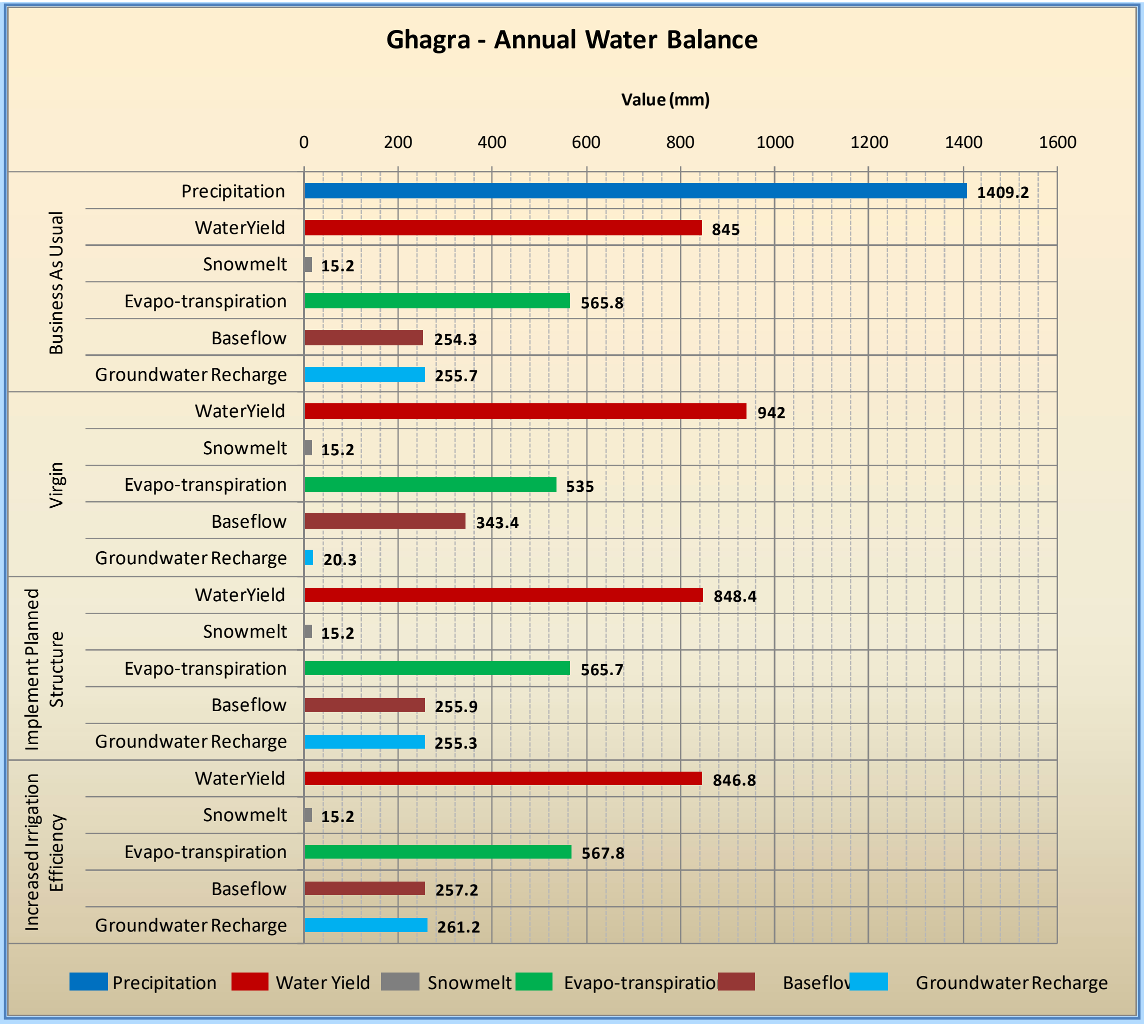


Ghaghra Basin

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.

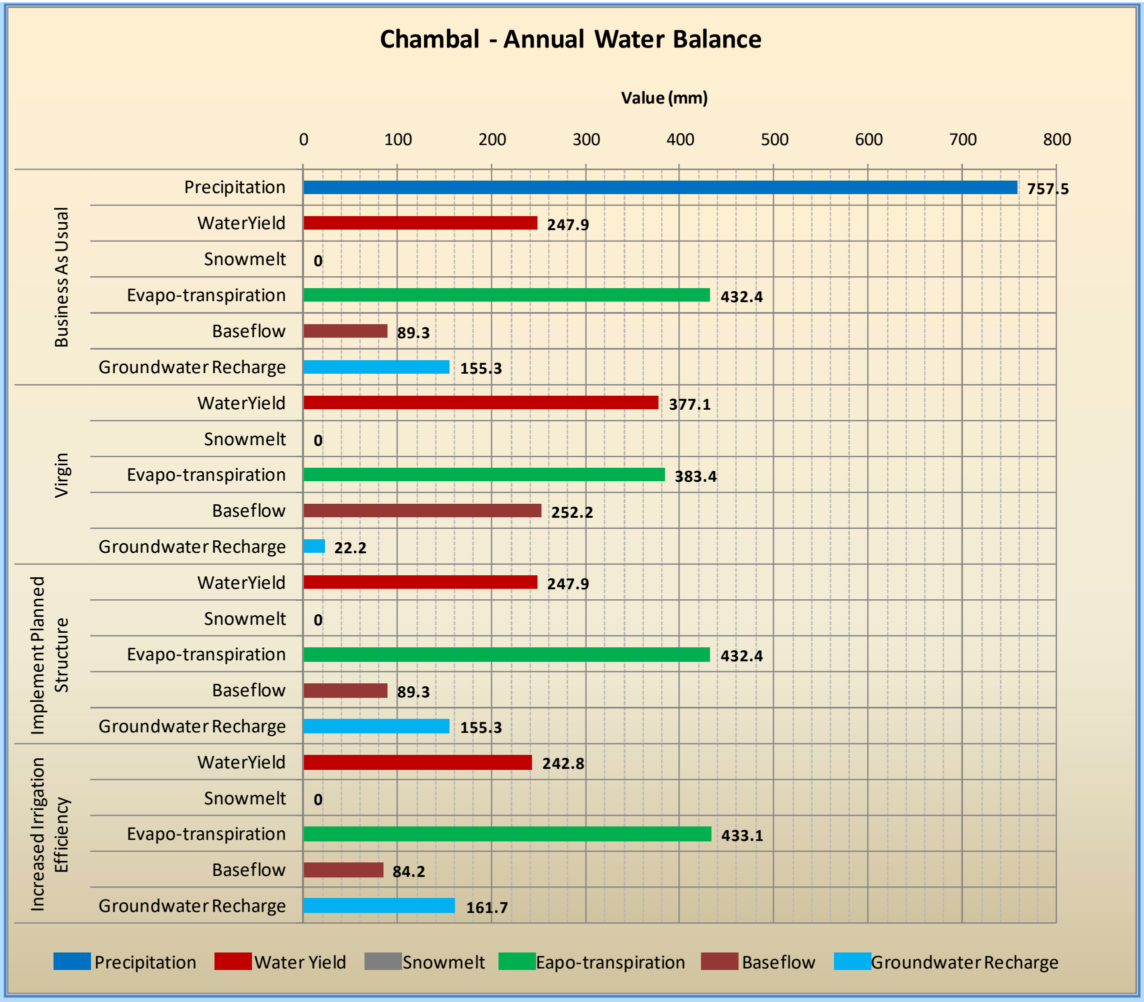
Figure 43: Annual Water Balance for Ghagra Basin



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.

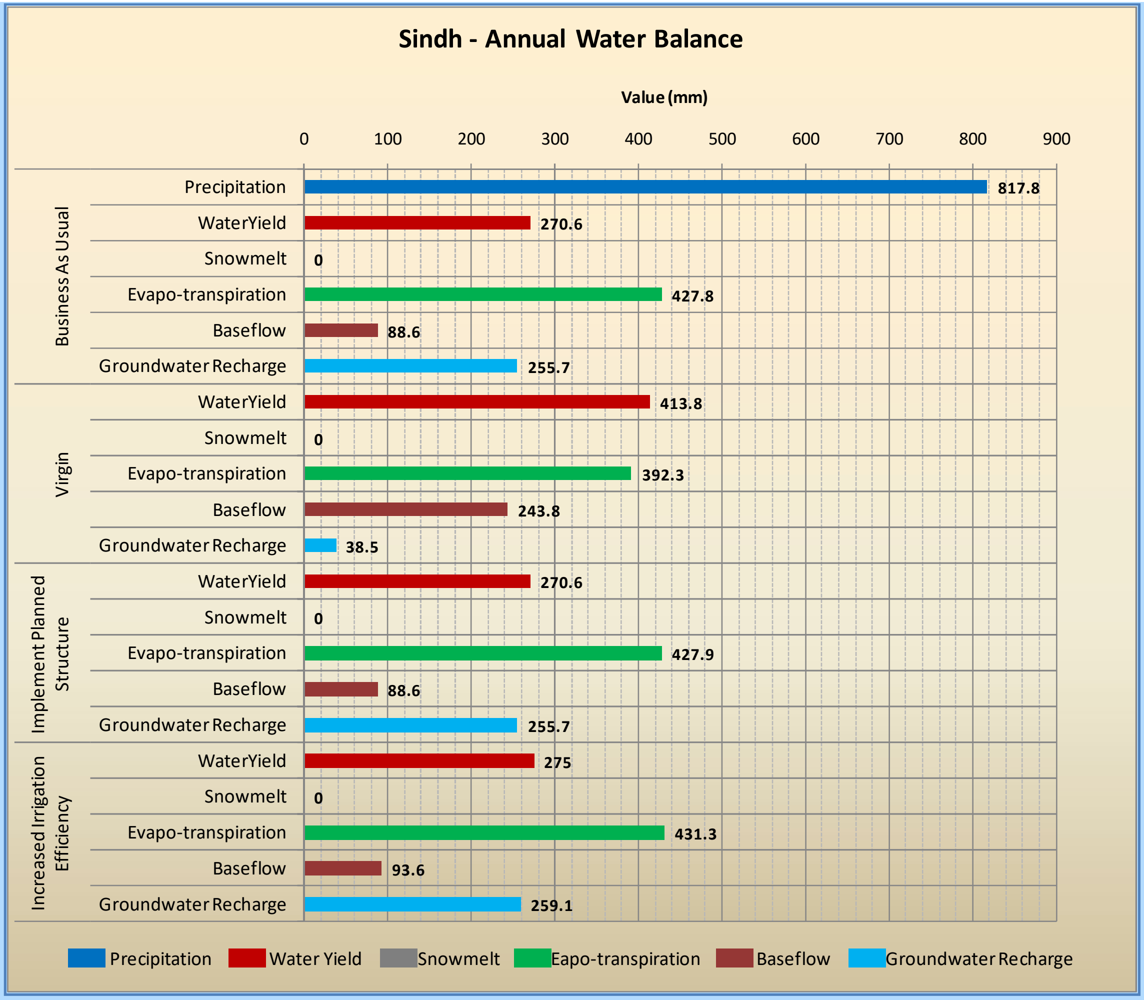
Figure 44: Annual Water Balance for Chambal Basin



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.

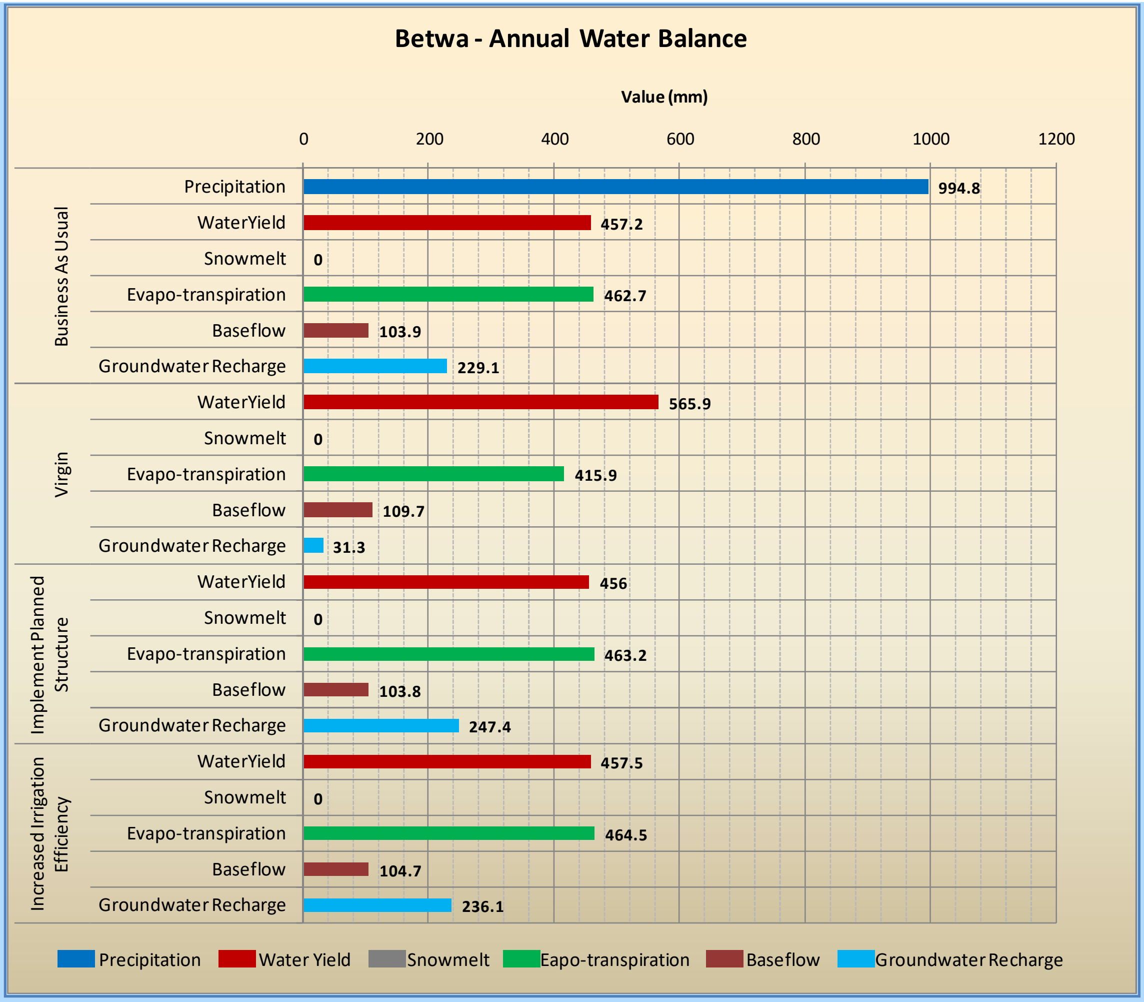
Figure 45: Annual Water Balance for Sindh Basin



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.

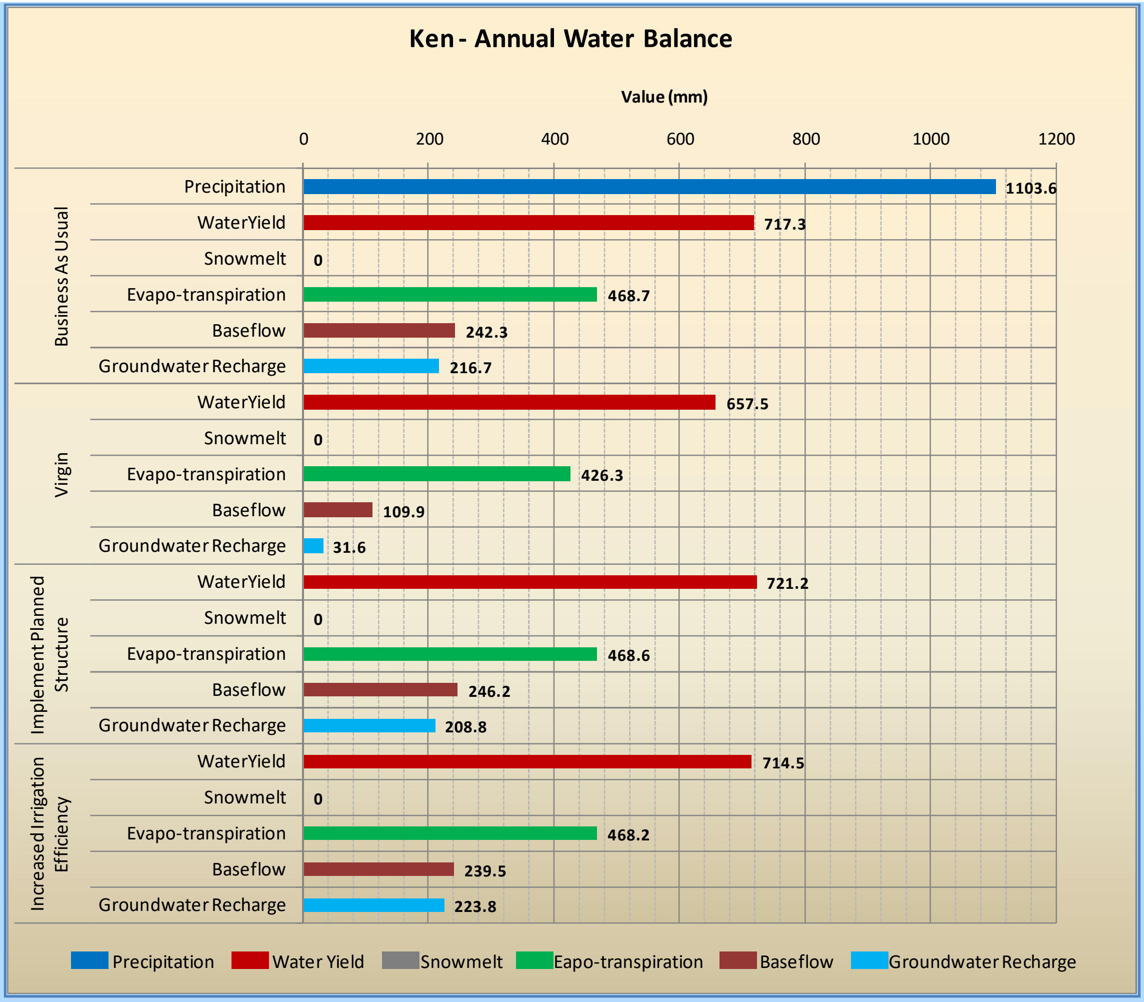
Figure 46: Annual Water Balance for Betwa Basin



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

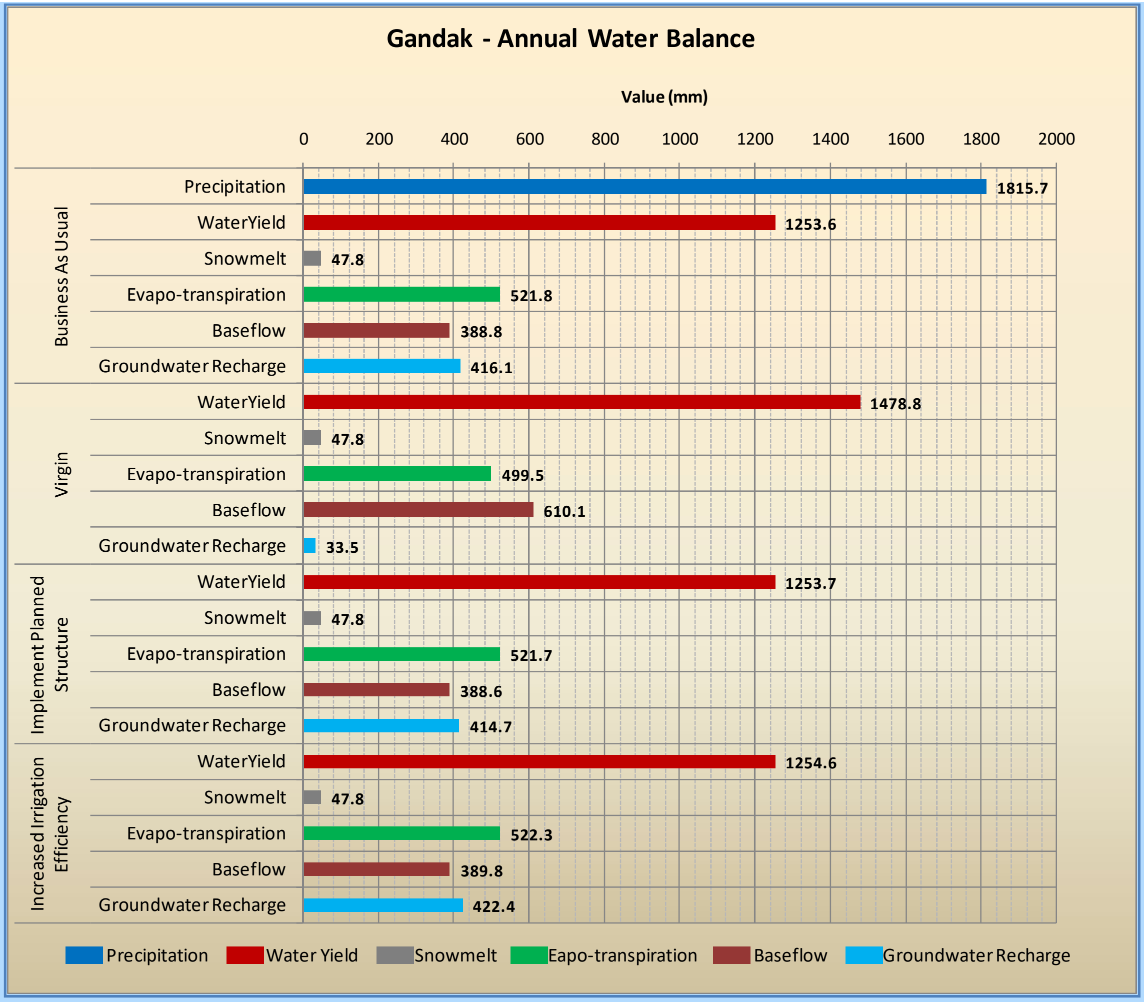
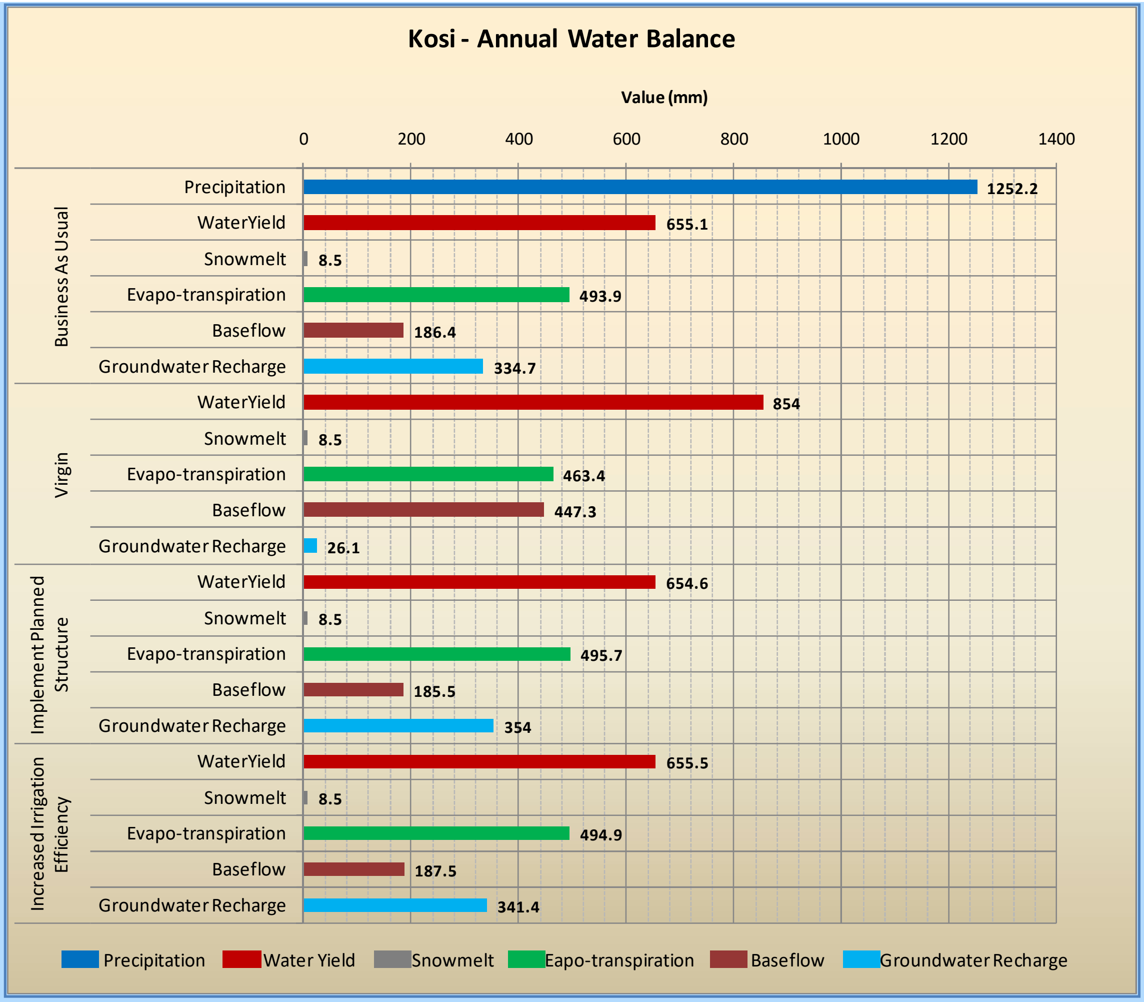


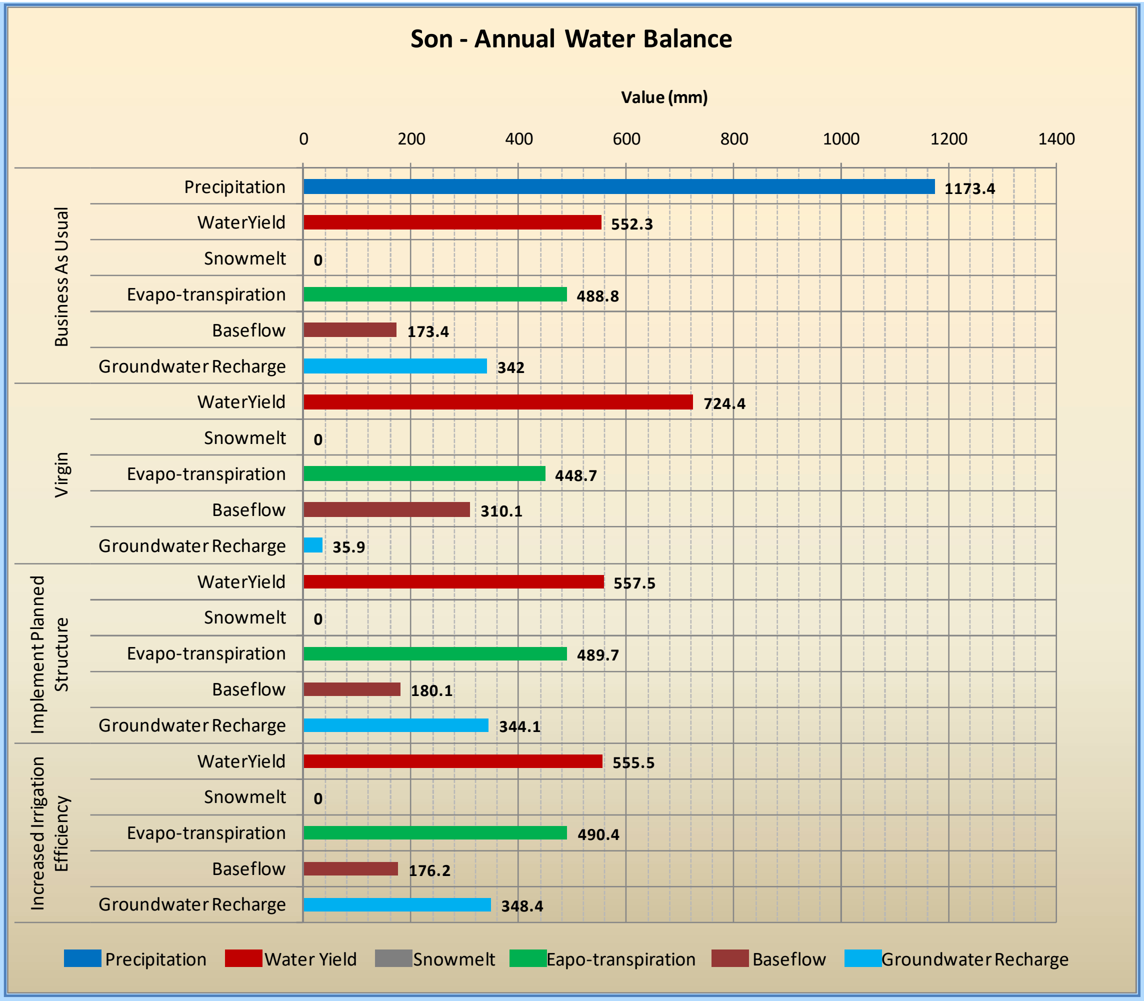
Figure 49: Annual Water Balance for Kosi Basin



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.

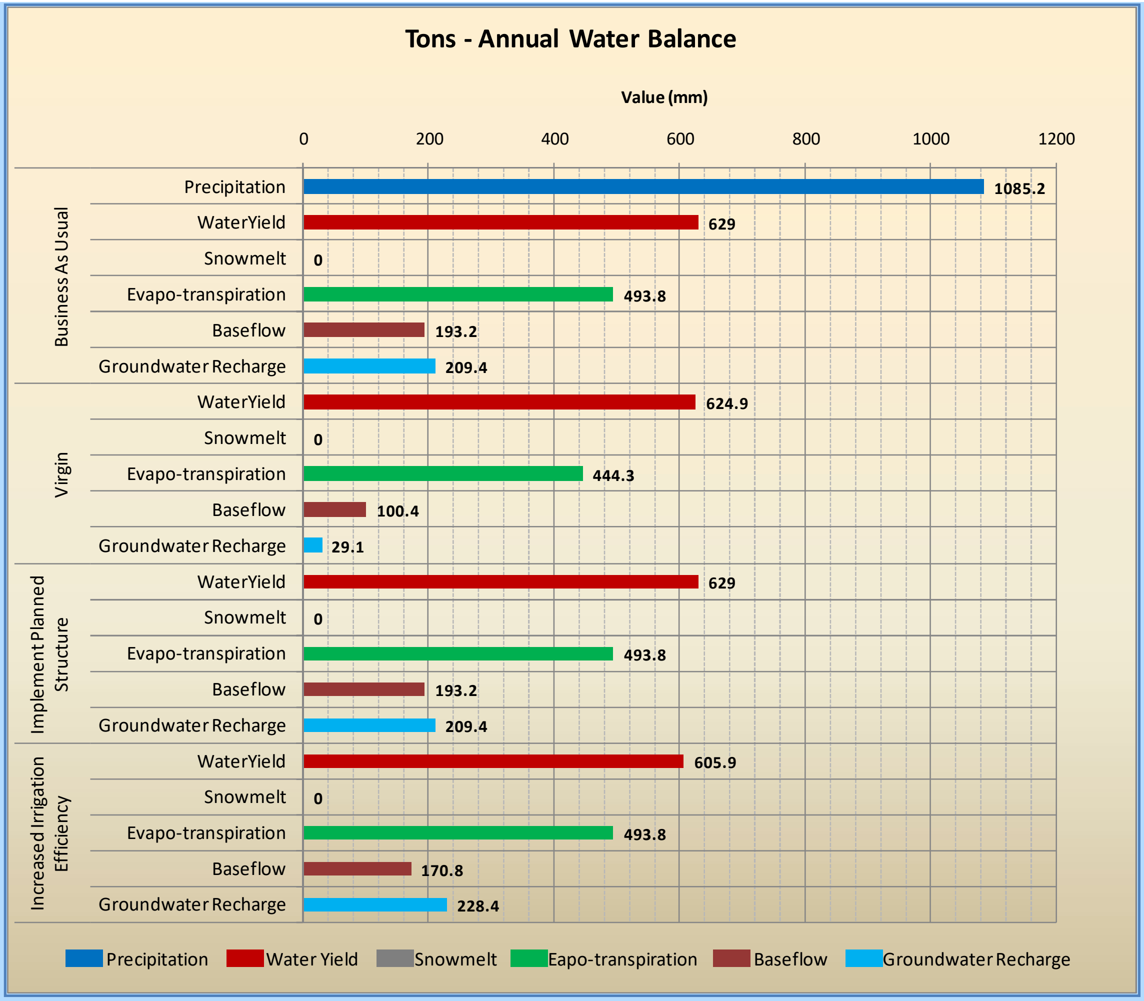
Figure 50: Annual Water Balance for Son Basin



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

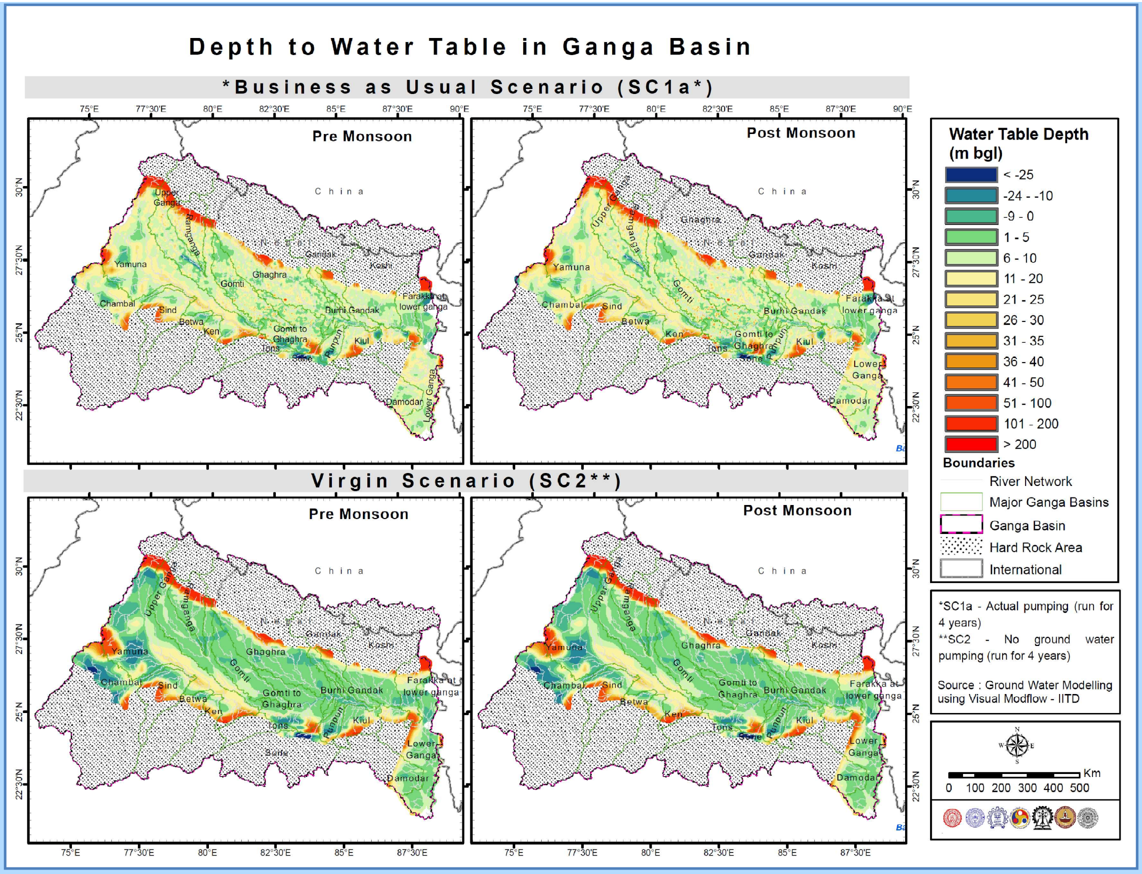
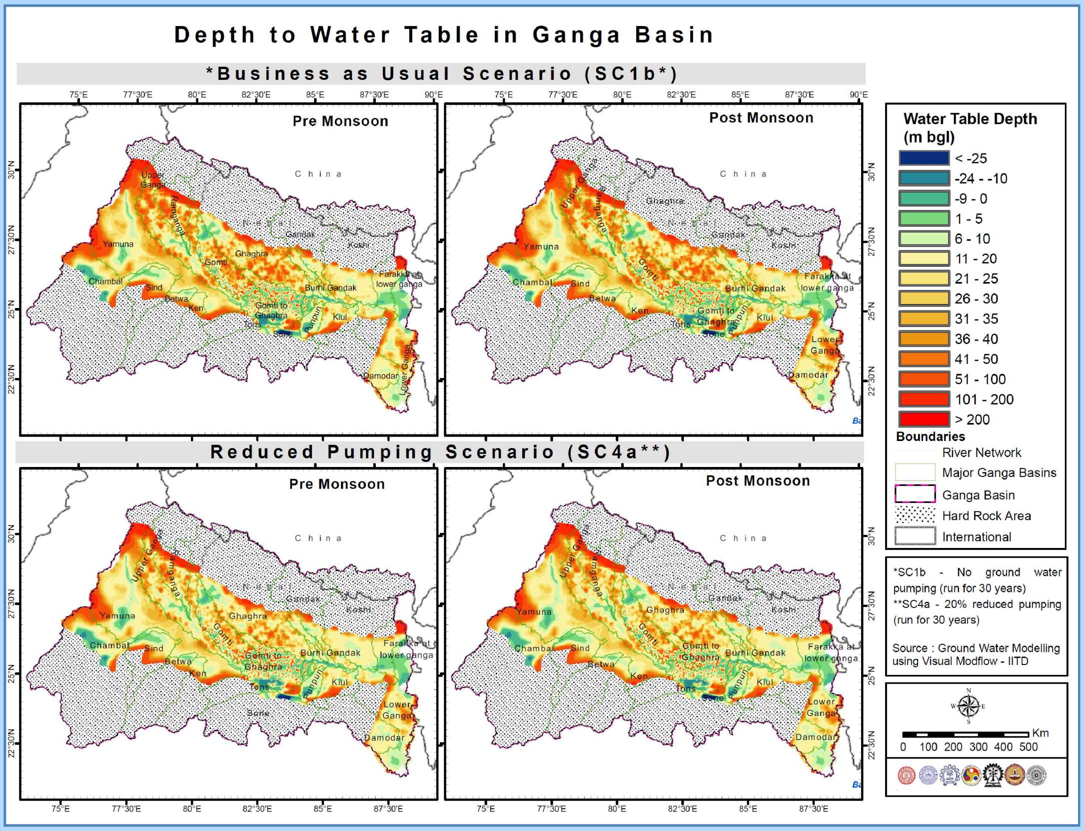


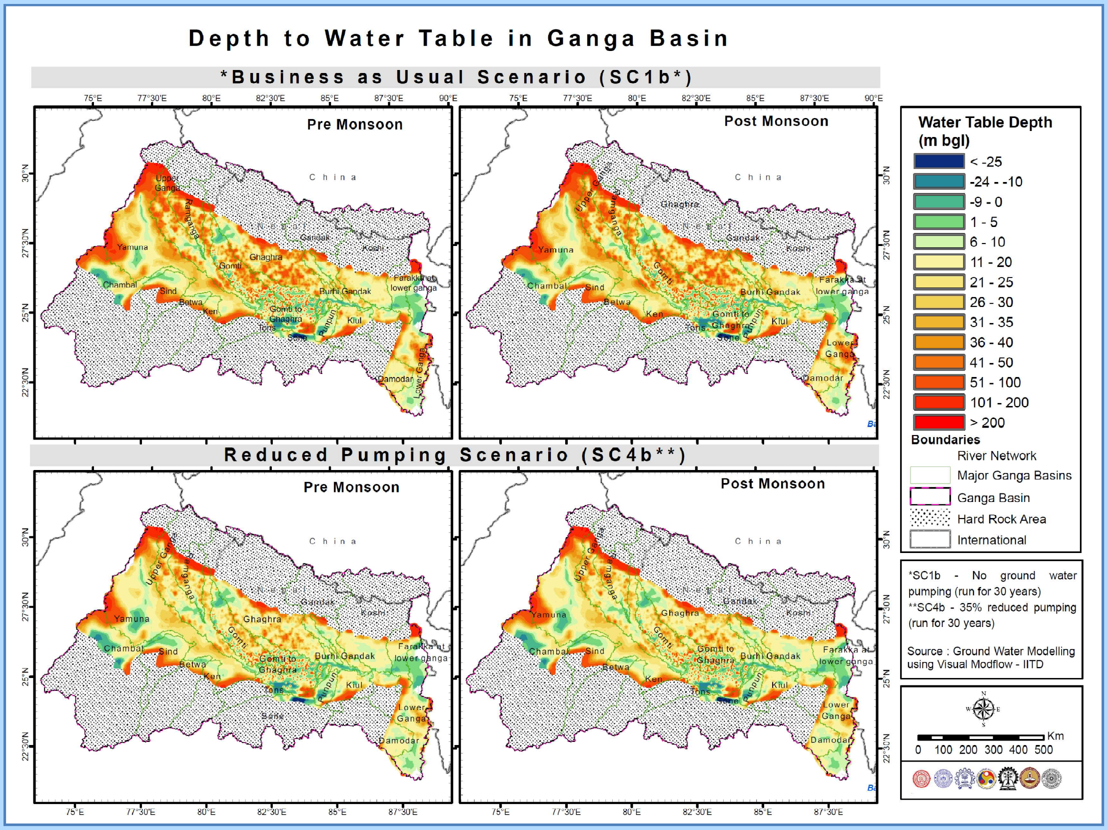
Figure 53 shows results from the scenarios where a comparison has been made between the present scenario and the scenarios where reduction in pumping due to increase efficiency has been made. It can be observed with the improved efficiency in irrigation, there is some reduction in pumping and thereby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

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



*SC1b - No ground water pumping (run for 30 years)
**SC4a - 20% reduced pumping (run for 30 years)

Source : Ground Water Modelling using Visual Modflow - IITD

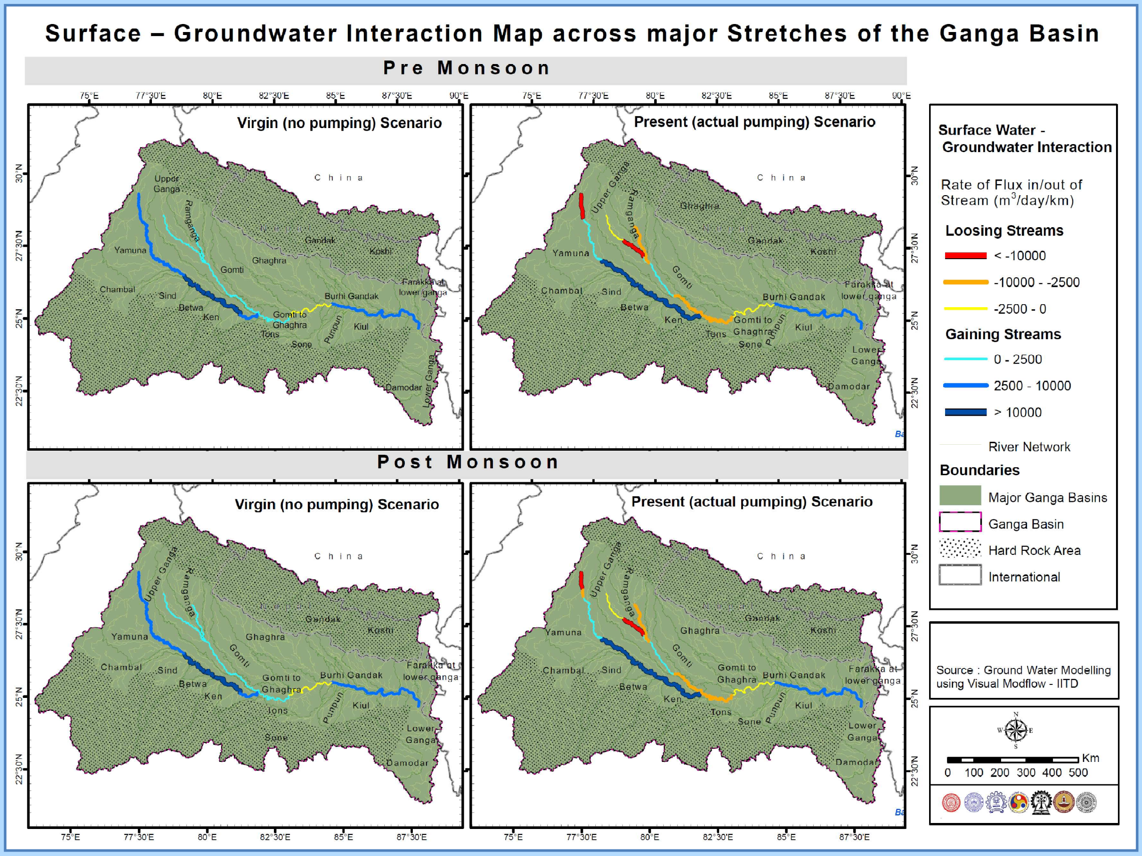


*SC1b - No ground water pumping (run for 30 years)
**SC4b - 35% reduced pumping (run for 30 years)

Source : Ground Water Modelling using Visual Modflow - IITD

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.

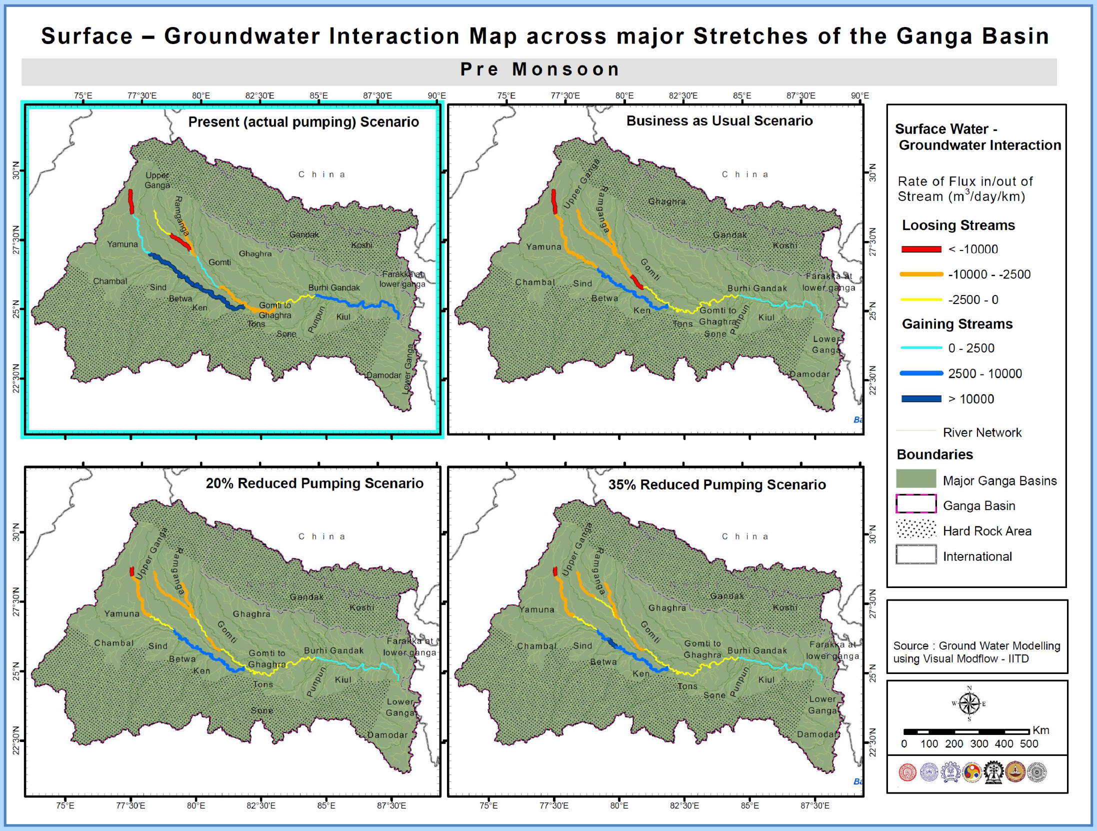
Figure 54: Plot showing the Surface GW interaction for Present and Virgin

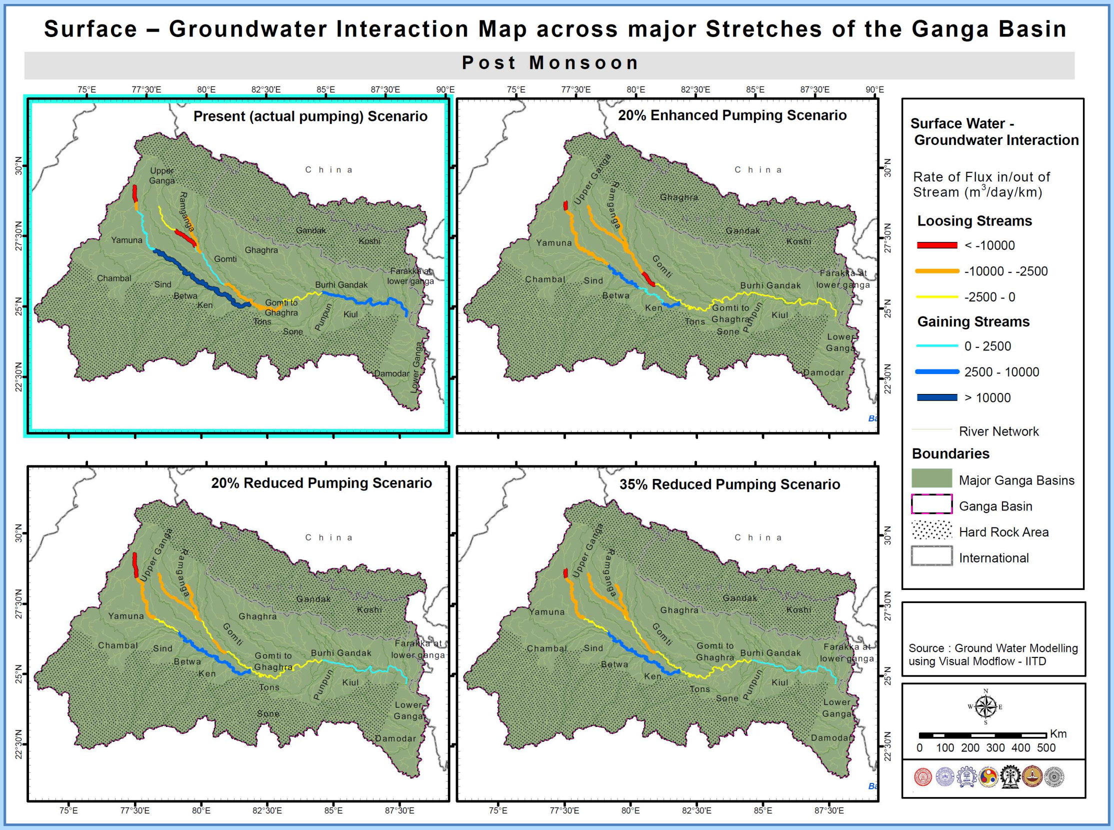


Source : Ground Water Modelling using Visual Modflow - IITD

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.

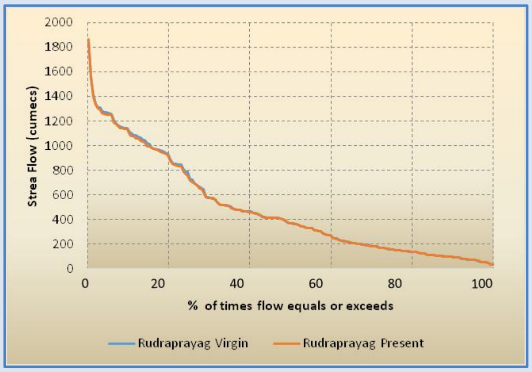
4. The framework developed is also ready to handle the "Nirmal" aspects of the river by modelling the point and non-point sources of pollution of surface and ground water. The attempt could not be made due to the paucity of required data on the source and quantum of the point sourcedomestic pollution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

Appendix

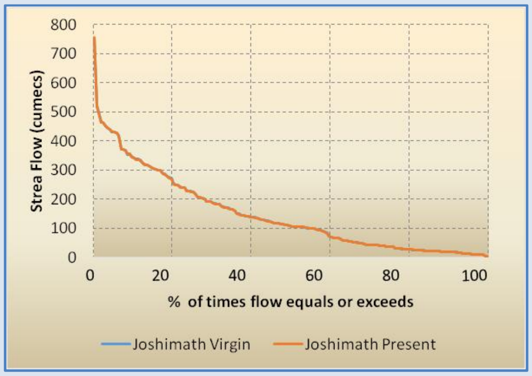
Appendix A: Flow Duration Curve at selected Locations for the Ganga river basin

Flow Duration Curve at selected Locations for the Ganga river basin

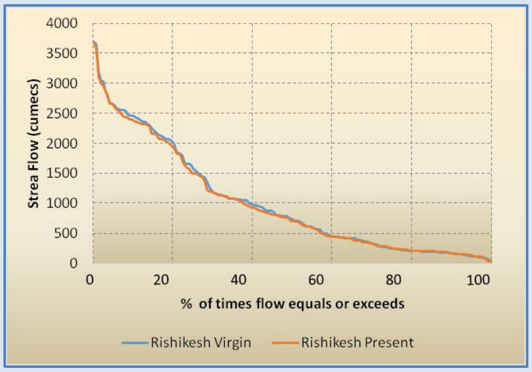
Rudraprayag on Alaknanda (Ganga/Alaknanda)



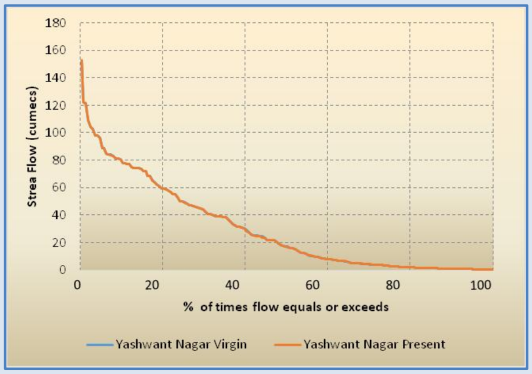
Joshimath on Alaknanda (Ganga/Alaknanda) river



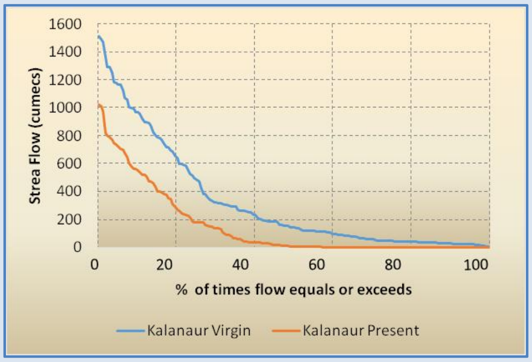
Rishikesh on Ganga river



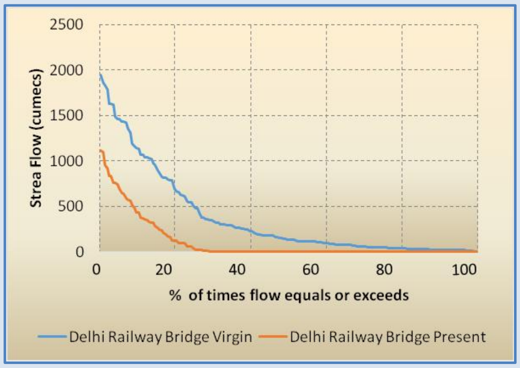
Yashwant Nagar on Giri (Yamuna/Giri) river



Kalanaur on Yamuna (Ganga/Yamuna)river

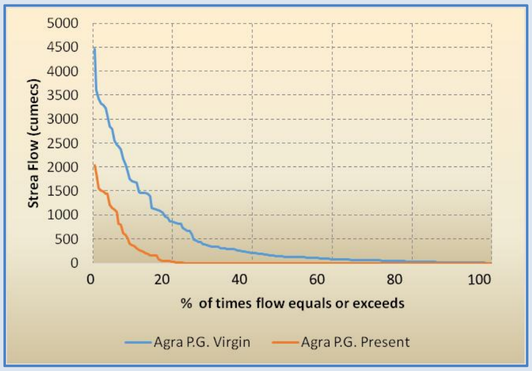


Delhi Rly Bridge on Yamuna (Ganga/Yamuna)



Flow Duration Curve at selected Locations for the Ganga river basin

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



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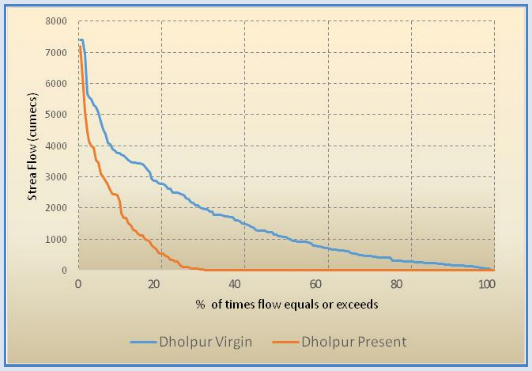
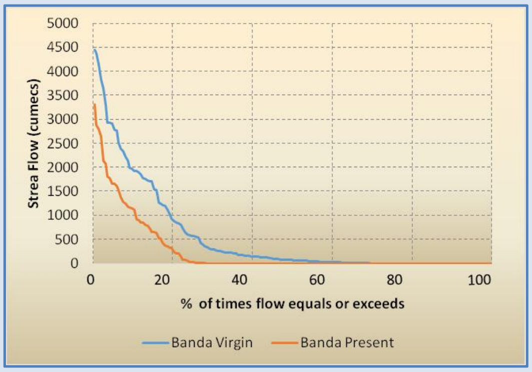
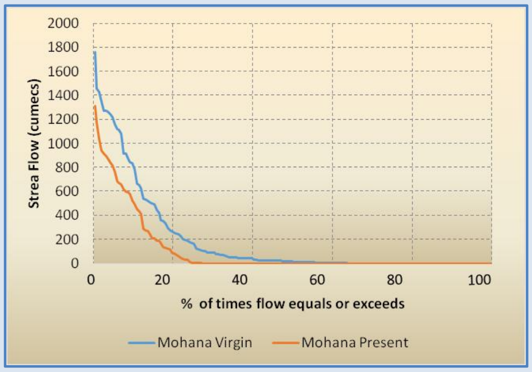


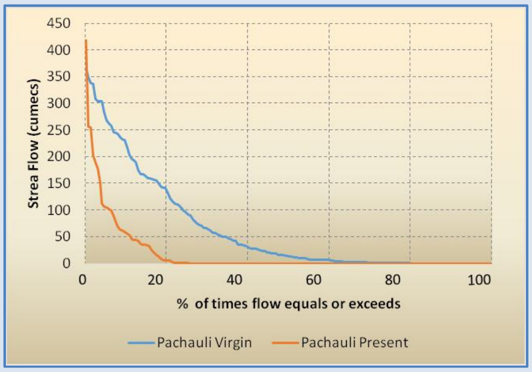
Banda on Ken (Ganga/Yamuna/Ken) river



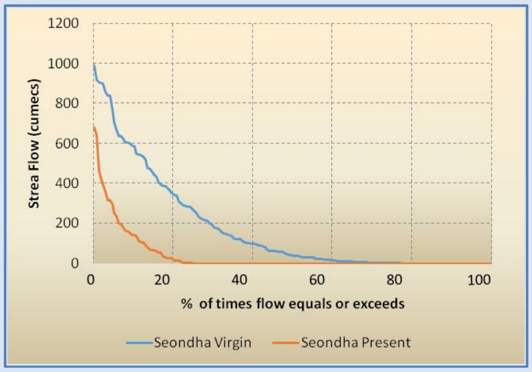
Mohana on Betwa (Ganga/Yamuna/Betwa)



Pachauli on Sind (Ganga/Yamuna/Sind) river

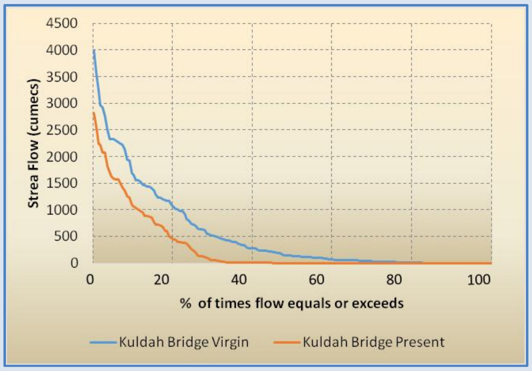


Seondha on Sone (Ganga/Yamuna/Sind) river

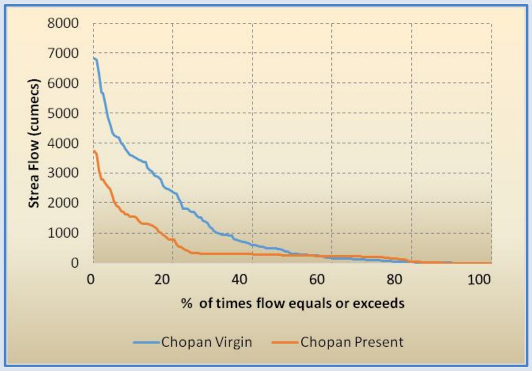


Flow Duration Curve at selected Locations for the Ganga river basin

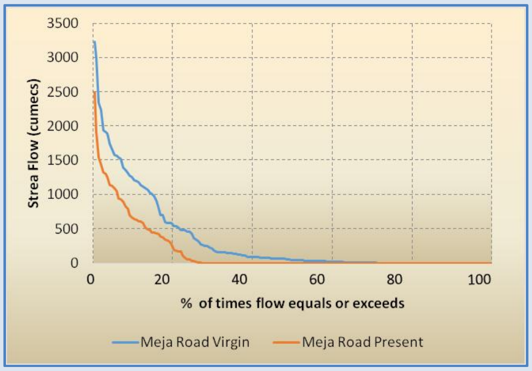
Kuldahbridge on Sind (Ganga/Sone) river



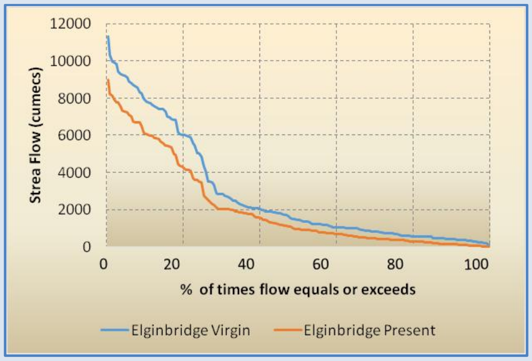
Chopan on Sind (Ganga/Sone) river



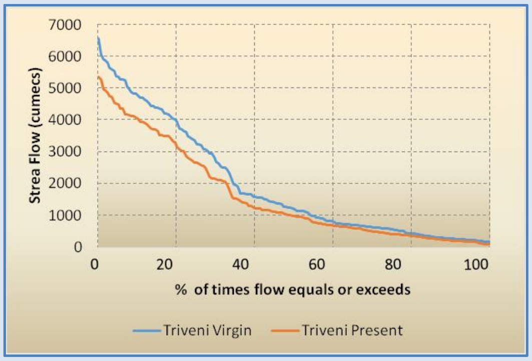
Meja Road on Tons (Ganga/Tons) river



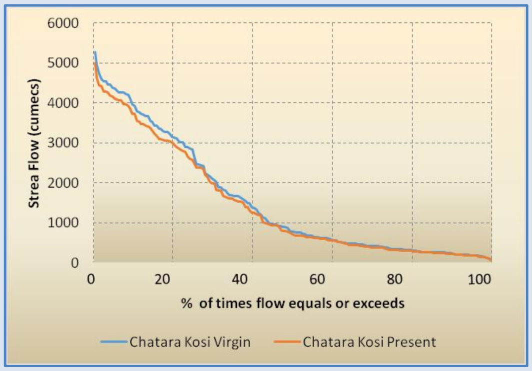
Elginbridge on Ghagra (Ganga/Ghagra) river



Tribeni on Gandak (Ganga/Gandak) river

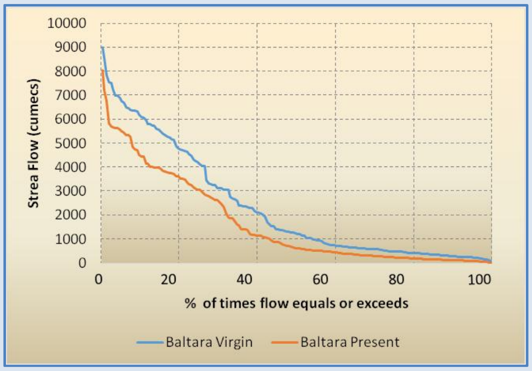


Chatara Kosi on Kosi (Ganga/Kosi) river

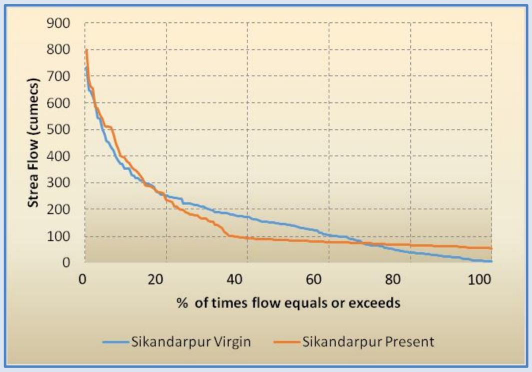


Flow Duration Curve at selected Locations for the Ganga river basin

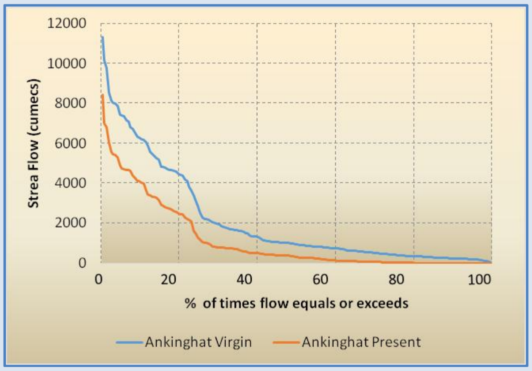
Baltara on Kosi (Ganga/Kosi) river



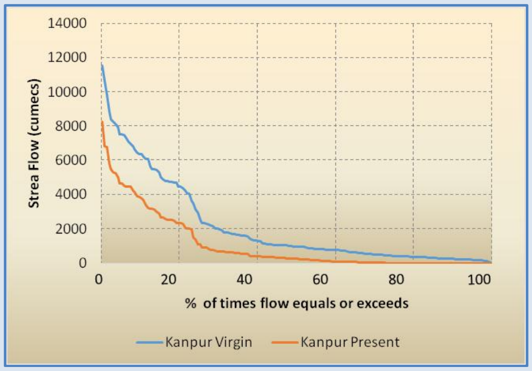
Sikanderpur on Burhi Gandak (Ganga/BurhiG)



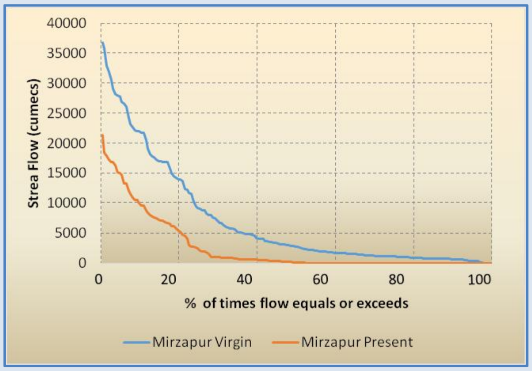
Ankinghat on Ganga river



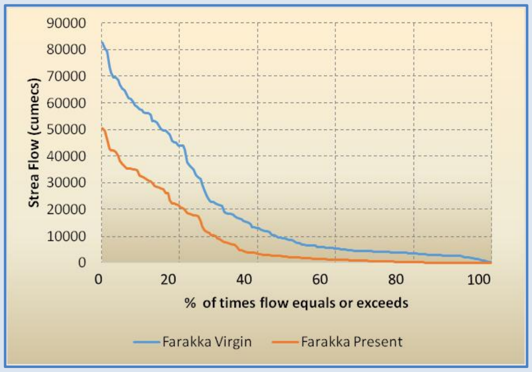
Kanpur on Ganga river



Mirzapur on Ganga river



Farakka on Ganga river



Hydrological Flow Health Assessment of the River Ganga

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 GRBMP 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. A list of persons who have contributed directly and names of those who have taken lead in preparing this report is given on the reverse side.

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Executive Summary

Continuity in flow is a basic concern in Ganga river basin; a number of water resources projects (irrigation and hydropower projects) have rendered the river dry in several stretches. Hence a hydrologic health assessment of the Ganga River basin was undertaken based exclusively on hydrologic flow regime. The scope of this study is limited to assessment of flow health purely based on the hydrologic flow regime. Estimation of flow (E-flow) for different habitat is beyond the scope of this study. Nevertheless, the hydrologic flow health assessment conducted in this study will be an essential precursor for the habitat based assessment of E-flow.

The hydrologic flow regime for the virgin state and the current managed state were obtained through calibrating the hydrologic model Soil and Water Assessment Tool (SWAT) (Refer to the hydrology report for details on hydrologic modelling). The Flow health assessment was made for four scenarios 1) Virgin scenario 2) Currently managed scenario 3) Flow health due to improved irrigation efficiency and 4) Flow health due to implementation of projects such as run of the river hydroelectric projects that are envisaged.

In the first part of the study, a tool called "Flow Health" developed by the International Water Centre was used (Gippel et al, 2012). "Flow Health" is an application to assist in the design and management of river flow regimes thereby providing a “flow health score” assigned for the river based on the magnitude and frequency of the flows. It is based on the concept of comparing the values of hydrological attributes of a river with the values in reference condition. This reference condition is actually a period of time where river was devoid of (or with minimum) human interventions (virgin condition).

In second part, look-up table methods based on low flow indices such as Q_{90}, $Q_{95\ \text{etc.}}$, were applied and checked for their feasibility for Ganga River Basin. Two approaches are used in it viz. Flow Duration Curve analysis and Mean Monthly Flow analysis. Low flow indices e.g. Q_{90}, Q_{95} or their predefined percentage as well as percentages of Mean flows are generally used as indicators of minimum flow requirements. Both of these approaches have been applied for flow health assessment of 146 observation sites.

In general, the study shows that the hydrologic flow health has been considerably affected at several stretches of the River Ganga due to the present state of water management. The impact due to implementation of future projects seems to have only marginal effect over the current state of flow health. However, other aspects of river health such as the functional needs of the ecosystem and habitat should be considered while implementation of future projects. This report could be a first step to start a meaningful and effective dialogue between various stakeholders of the basin and agree upon a desired flow health to achieve in the different stretches of Ganga. This along with a study on the functional needs of the ecosystem along different stretches will help to arrive at an E-flow regime to be maintained along different stretches of Ganga during different times of the year. The hydrologic model in conjunction with the flow health tools could be used to look at the current levels of diversions and the amount of reductions in upstream diversions necessary to achieve the level of desired flow health.

1. Introduction

1.1. Significance of hydrological flow health in the context of the River Ganga

Continuity in flow is a basic concern in Ganga river basin; a number of water resources projects (irrigation and hydropower projects) have rendered the river dry in several stretches and polluted in other stretches. Further, several hydroelectric power projects in Baghirathi and Alaknanda are in various stages of planning and design. Some of the major hydraulic interventions in Ganga include the Upper Ganga Canal near Haridwar, Lower Ganga Canal near Narora, Tehri dam which was constructed on Bhagirathi, a tributary of Ganga, the Bansagar dam and Rihand dam which are built on the Son tributary and the Farrakka barrage on the Hooghly tributary of Ganga and. By the presence of these major interventions as well as due to the large number of minor hydraulic structures, the flow in Ganga has lost continuity and badly fragmented. The wholesomeness of all rivers of the Ganga basin should be ensured for sustaining the population growth, urbanization, industrial and agricultural activities in it. The Water Quality Analysis and Assessment done in 2007 has recommended that the E-flow of Himalayan Rivers should be greater than 2.5% of 75% dependable annual flow *(WQAA, 2007)*. However, a thorough scientific assessment of hydrological flow health and E-flow requirement for the entire Ganga basin has not been done yet. The health of a river could be readily assessed using a set of indicators derived based on hydrology, water quality and biological aspects. In this report, the hydrological river health of different stretches of Ganga would be assessed based on different indicators of flow. This report will serve as a precursor to a detailed assessment of E-flow requirement along different stretches of the River Ganga.

1.2. River Health

River health can be referred to as the degree of similarity in biological diversity and ecological functioning to a river without any interventions (*Schofield, 2007*). Due to the in stream, riparian and catchment modification practices, most rivers will be less biologically functional and of lower ecological value than its original state. Important river stresses include nutrient enrichment, water extraction, flow controls, loss of riparian vegetation and effluent discharge. An ecologically healthy river can sustain a diverse range of habitat and the animals and plants depending on them. That is, by providing sufficient amount of energy and nutrients to sustain the food chain so that the natural interactions between species such as predator – prey, host – parasite and competition relationships are maintained. An ecologically healthy river need not be a pristine river. Deviations from the natural state will be present; but there will be a balance between the human use and the ecology of the river (Fei *et al.,* 2011).

Environmental flows are very important for sustaining the health of the river. A healthy river supports local biota and plays a key role in process such as sediment transport, nutrient cycling and waste assimilation and usually it recovers after short-term natural disturbance.

1.3. Environmental Flows and Flow Health

Rivers and streams have a wide range of functions including irrigation, domestic water supply and biodiversity conservation despite the fact that the flows are varying for different seasons throughout the year. Environmental flows (E-flows) come into picture when the flow volume or natural flow patterns are affected by hydraulic structures like dams, abstractions, diversions or addition of flows (*ACT Government (2006), 2006 Environmental Flow Guidelines*). E-flows are the flows of water in rivers and streams that are necessary to maintain a healthy aquatic ecosystem and life in and out of a river.

The assessment of E-flow is based on the fact that some spare water can be maintained all throughout the year in the river. But it doesn't mean that E-flows are minimum flows; it can be a combination of high flows and low flows maintained at different frequencies. Hence, the E-flows mimic the natural condition in our rivers like transportation of water, self-purification, and sustenance of its cultural and livelihood activities. By providing a range of habitats, including river channels (vegetation cover, flood plains, estuaries, lakes etc.) between aquatic and land ecosystems, it supports an enormous diversity of life (*O'Keeffe and Le Quesne, 2009*).

The requirements for E-flow could be arrived at based on the consideration of hydrology and/or from the consideration of habitat (ecology and geomorphology) of few indicator species. Hydrology affects ecology and geomorphology and vice-versa. The fundamental assumption of the Hydrological Flow Health is that if we strive to maintain a similar hydrological flow regime as that in its virgin state (high and lows and frequency between floods etc.,) then the needs of ecology and geomorphology will be least affected due to development.

In the habitat based assessment we look at only few indicator species and it is possible that we may miss out on the requirements of the functioning of the other species which may not be vulnerable now, but could become vulnerable later. Other than the aquatic species some flora in the flood plain could also become vulnerable as well. E-flow requirements based on Geomorphological requirements could be riddled with large uncertainties.

It is in this regard that the assessment of "hydrological flow health" gains significance. The indicators of hydrological flow health evaluate the frequency and magnitude of high flows and low flows and compare them against flows that occur under a reference (or virgin) condition. This could be one of the important inputs to be used in subsequent studies and will be an essential precursor for the habitat based assessment of E-flow.

2. Hydrological Flow Health Assessment

This study involves two individual exercises undertaken to assess flow health of Ganga river basin. For this assessment, river flow regimes at 146 locations distributed over Ganga basin are used. These flow regimes are obtained from SWAT hydrological modelling under four different scenarios viz. a) in its virgin state (i.e. without any hydraulic structures, diversions or human interventions),b) in its present state of water diversion and management, c) with improved irrigation efficiency and d) due to implementation of future projects. Refer to hydrological modelling report by GRBEMP-WRM (2014) for details on hydrological modelling using SWAT.

In first part of the study, river health was analyzed using 'Flow Health Tool' developed by the International Water Centre. In second part, various hydrological indices like e.g. Q95, Q90, Q75, Q50, Mean Annual Flow, Mean Monthly Flow etc. were calculated for the four different scenarios simulated using SWAT. Worldwide, these indices and/or percentages of them are generally considered as first-cut estimates of minimum in-stream flow requirements in preliminary management decisions.

2.1. Flow Health Tool

Flow Health Tool, developed by the International Water Centre in 2009-2012 for the Australia China Environment Development Program (ACEDP) was used for assessing the River health and environmental flow in China (*Gippel et al, 2012*). It is an application to assist in the design and management of river flow regimes thereby providing a "flow health score" assigned for the river based on the magnitude and frequency of the flows. It is based on the concept of comparing the values of hydrological attributes of a river with the values in reference condition. This reference condition is actually a period of time where river was devoid of (or with minimum) human interventions (virgin condition).

Flow health was used for analysis of river health in different rivers of China by a project undertaken by International water centre. The result obtained from their study on major rivers Taizi and Gui are shown in figure 1 and figure 2. The flow regime was analyzed and the parametric variations contributing to the Flow health score formulation was analyzed in the study. (*Gippel et al, 2012*)

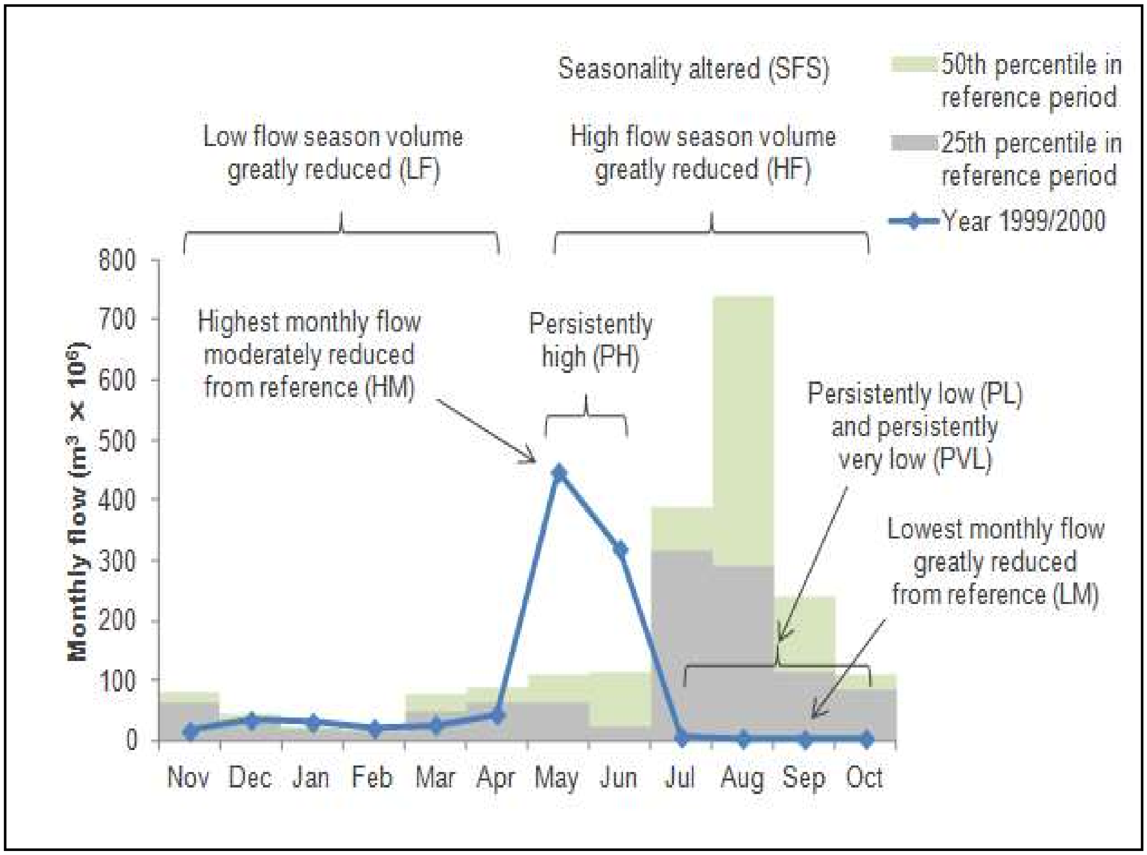

Figure 1: **Illustration of eight of the nine aspects of the flow regime characterized by the Flow Health Tool sub-indicators using a comparison of monthly flows for water year 1999/2000 at Liaoyang on the Taizi River, China with reference period median monthly flows and 25th percentile monthly flows (** ***Flow health User Manual, Gippel et al, 2012*****).**

In the study conducted on Taizi River, it can be seen that eight parameters of the flow health tool are as shown in figure 1. It can be seen that during the period of November to March (low flow season period), flows have been reduced even less than that of 25 percentile flow and during the period of April to July (high flow season period), flows were lesser than the 50 percentile flow of reference period. Persistently very low flow was observed during the period of July to October; during this time, flows were found to be so negligible. Overall the flows were found to be unhealthy during the period 1999 - 2000.

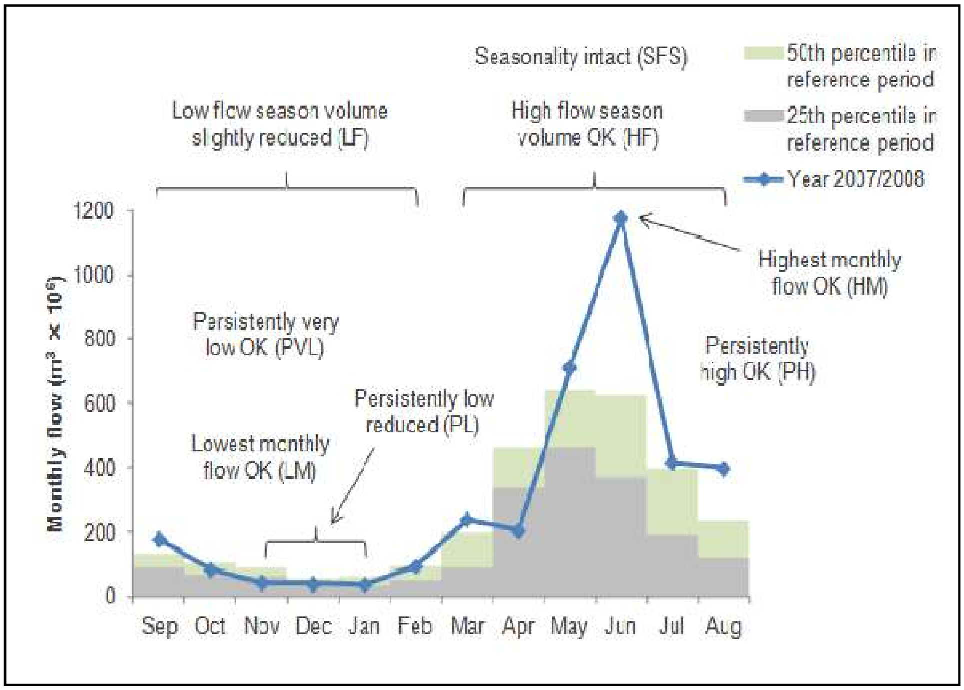

Figure 2: **Illustration of eight of the nine aspects of the flow regime characterized by the flow Health sub-indicators using a comparison of monthly flows for water year 2007/2008 at Guilin on the Gui River, China with reference period median monthly flows and 25th percentile monthly flows (*Flow health User Manual, Gippel et al, 2012*).**

In the study conducted on Gui River in China, the test period for flow was found to be more or less healthy because even during the low flow period, the flows were almost around 25 percentile of flows as that of the reference period. Moreover, in high flow season, flows were higher than 50 percentile of flows mostly touching 75 percentile of flows and hence the flows were found to be healthy during the period 2007 – 2008.

2.2. Look-up Table Methods

Look-up table methods are most simple and quick approach for obtaining the preliminary idea about varying river flow patterns. In this approach, river flow regimes are statistically analyzed to obtain various hydrological indices like e.g. Q_{95}, Q_{90}, Q_{75}, Q_{50}, Mean Annual Flow, Mean Monthly Flow etc. Worldwide, these indices and/or percentages of them are generally considered as minimum flow requirements in preliminary management decisions.

In the present study, four different flow regimes obtained through hydrological modelling are used to obtain these indices. Fate and feasibility of these indices are checked in reference to Ganga River basin. Using these indices, inferences about varying river flow patterns of Ganga can be drawn.

3. Objectives

The objectives of this report are:

1. to assess the hydrological flow health of river Ganga under four scenarios:
    a. in its virgin state (i.e. without any hydraulic structures, diversions or human interventions),
    b. in its present state of water diversion and management,
    c. with improved irrigation efficiency and
    d. due to implementation of future projects
2. to provide information for arriving at policy decisions for regulating current as well as future water diversions from the perspective of hydrologic flow health.

4. Scope

The scope of this study is limited to assessment of flow health purely based on the hydrologic flow regime. Estimation of E-flow or minimum in-stream flow for different habitat is beyond the scope of this study. Nevertheless, the hydrologic assessment conducted in this study will be essential for the habitat based assessment of E-flow. The hydrologic flow regime for the four different scenarios were obtained through calibrating the hydrologic model Soil and Water Assessment Tool (SWAT) (Refer to the hydrology report for details on hydrologic modelling). The hydrologic flow health was assessed using Flow Health, developed by the International Water Centre (*Gippel et al, 2012*) and using look-up table methods separately.

5. Methodology

5.1. Hydrologic Model Simulations for Flow Health Assessment

For hydrologic assessment of flow health, a long record of flow data encompassing both the natural as well as the managed state of the river is essential. As discharge stations having such a long history of flow data are available only at a few locations, a hydrologic model SWAT was used to simulate the long history of hydrology of the basin by calibrating the model with the limited flow data. For the purpose of hydrologic modelling, the entire Ganga river basin was subdivided in to 1045 subbasins, hence flow health could be potentially evaluated with hydrologic simulations made at 1045 locations spread across the basin. The calibrated hydrologic model was then used to simulate a long history of hydrology with hydraulic interventions and diversions (i.e. managed state) and without interventions (i.e. virgin state) for a long history (29 years) of similar weather data (1974 – 2002). Apart from that, long term flows were simulated for future condition where number of consumptive use projects are supposed to start operating. SWAT simulation with increased irrigation efficiency provided an additional scenario.

Among the flow simulations made at 1045 locations, the flow simulations made at 146 critical locations were used to assess the flow health (Fig. 4).Refer to hydrological modelling report by GRBEMP-WRM (2014) for details on hydrological modelling using SWAT.

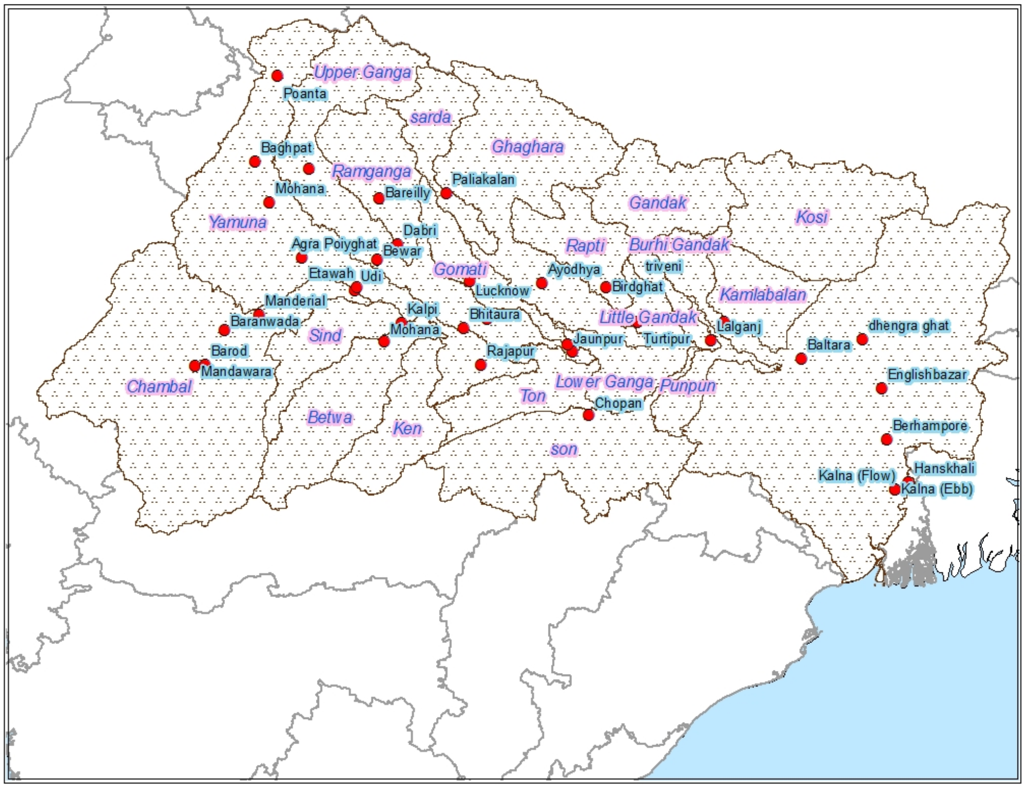

Figure 3: Critical Points along the Flow Network Where the Flow Health was Assessed

5.2. Flow Health Tool

In order to assess the hydrological health of Ganga, a tool called “Flow Health” was used which will help to analyze the flow over a long time period. Flow Health is an application to assist in the assessment, design and management of river flow regimes (*Gippel et al, 2012*). Its main purpose is to provide an annual score for hydrology in river health assessment, but it can also be used as a tool to assist environmental flow assessment. Flow Health Tool was used for this study as it is able to analyze the river flows in a more precise way and suggest flows to improve the hydrological health of the river. Further, the tool can be used to analyze the hydrologic data at different time scales (daily, monthly and yearly).

The major assumption of the flow health tool as with the other tools based on the hydrologic assessment is that the ecosystem will be restored to a greater extent when the flow magnitude and frequencies are made healthy. For that purpose, Flow Health tool was found to be more adaptive. Flow Health has four main functions (*Gippel et al, 2012*):

- To provide an annual score for the hydrology indicator in river health assessment

- To recommend a minimum monthly environmental flow regime
- To test the hydrological health of any monthly environmental flow regime
- To generate a synthetic monthly flow time series based on the designed environmental flow regime

The major inputs required for the Flow health tool is the monthly or daily flow hydrograph (observed or simulated) continuously available for a period of time. The flow health score is derived from nine different hydrological sub indicators: High Flow (HF), Low Flow (LF), Highest Monthly (HM), Lowest Monthly (LM), Persistently Higher (PH), Persistently Lower (PL), Persistently Very Low (PVL), Seasonality Flow Shift (SFS) and Flood Flow Interval (FFI) (*Gippel et al, 2012*). These nine indicators are closely related to the basic flow components of a natural flow regime (Fig. 3) such as ceae-to-flow, low flow period and high period baseflows, high flows and timing (seasonality).

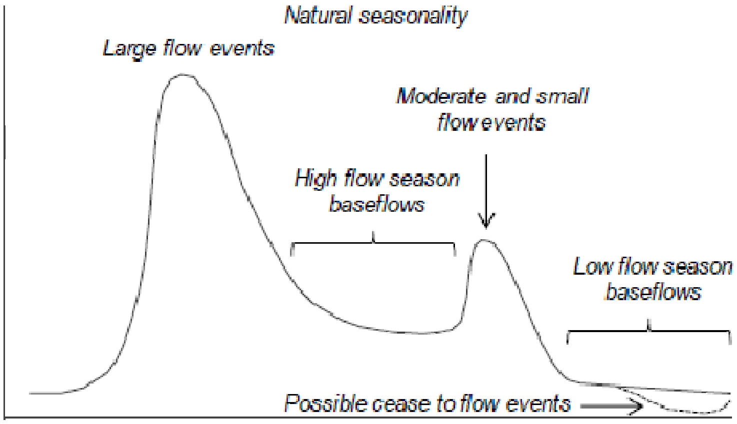

Figure 4: The Main Ecologically Relevant Flow Components (*Flow Health User Manual, Gippel et al, 2012*).

Flow health basically compares the time series data of test year flow data with a reference flow series. For assessing the change in flow health due to diversion, the virgin flow is assumed to be the healthy river flow and hence was taken as the reference flow and the present flow as the test condition flow. The flow health tool compares the monthly flow values, in test period with that of the reference period and assigns a score in such a way that the flow which is more or less the same as that of the virgin condition will have a flow health score close to 1, while the flow which deviate considerably from the virgin condition will be assigned a value close to zero.

The assessment of flow health starts by identifying natural low-flow and natural high-flow periods based on the flows from the reference period. The percentile ranking of different flow metrics were arrived at by comparing the current flow with the reference period to arrive at non-dimensional scoring system of different flow indices. The scoring system assumes that i) flow reductions are more detrimental to river health than flow increases and

ii) occasional increased flows in the high flow season were not detrimental to river health. Flow health adopts the inter-quartile range (25th to 75th percentile) for different flow metrics (hydrological attribute) as the range within which the hydrological health score is 1. Any deviations in an attribute outside this range could potentially affect the flow health and hence assigned a value less than 1.

High Flow (HF): HF is the sum of the monthly flows in the natural high flow period. The flow health score (FHS) is assigned a value of 1 when the cumulative flow during the high flow period is more than 25 percentile of the reference period cumulative flow for high flow period and assigned a value range of 0 to 1 linearly for the flow percentile varying from 0 to 25 percentile.

E.g.: >25%, FHS =1
0% - 25%, FHS = 0 to 1 linearly

Low Flow (LF): LF is the sum of the monthly flows in the natural low flow period. The FHS is assigned a value of 1 if the cumulative flow percentile is between 25 and 75 percentile of cumulative low flow volume during the reference period. The FHS is assigned a value range of 0 to 1 linearly for the flow percentile varying from 0 to 25 percentile. For the flow range above 75 percentile the FHS is linearly reduced in the range of 1 to 0.75 linearly as this higher than expected low flow in the year might negatively impact some biota.
E.g.: 0% - 25%, FHS = 0 to 1 linearly
25% - 75%, FHS =1
75% - 100%, FHS = 1 to 0.75linearly

Highest Monthly (HM): HM is the highest monthly flow in the year. It is assigned a value of 1 if any value in a test year is higher than the 25 percentile value in the reference year and if the max value in the test year is lesser than min value in the reference year, then the value is zero and when the test year maximum value percentile lies in between 0 and 25 percentile, the FHS is assigned a value range of 0 to 1 linearly.
E.g.: > 25%, FHS =1

0% - 25%, FHS = 0 to 1 linearly

Lowest Monthly (LM): LM is the lowest monthly flow in the year. FHS is assigned a value of 1 if any min value in a test year is between 25th and 75th percentile of the lowest flow value in the reference years. The FHS is linearly interpolated between 0 to 1 for percentile values between 0 and 25. For percentile values higher than 75, the FHS is reduced linearly between 1 and 0.75 as this higher than expected brief period of low flow in the year might negatively impact some biota.
E.g.: 0% - 25%, FHS = 0 to 1 linearly

25% - 75%, FHS =1
75% - 100%, FHS = 1 to 0.75 linearly

Persistently Higher (PH): PH is a measure of how many sequential months in the natural low flow season were the flows are higher than expected (95th percentile). The number of consecutive months in the low flow period having a flow lying outside the upper range (95th percentile) of flow in each month in a reference period is counted. If that total is greater than or equal to 6, then it is assigned a FHS of 0 and if that total is less than or equal to 1, it is assigned a FHS of 1.

E.g.: PH Count = 6, FHS = 0

PH Count <= 1, FHS = 1

6 > PH Count > 1, FHS = 0 to 1 linearly

Persistently Lower (PL):_PL is a measure of how many sequential months were lower than expected (25th percentile). It is assigned a FHS of 0 if the number (count) of consecutive months having a flow lower than the lower range of flow is 12 and assigned a FHS of 1 if the count is less than or equal to 1. In the values lying in between, FHS is assigned linearly in the range 0 to 1.

E.g.: PL Count <= 1, FHS = 1
PL Count >= 12, FHS = 0
12 < PL Count < 1, FHS = 0 to 1 linearly

Persistently Very Low (PVL): PVL is a measure of how many sequential months were much lower than expected flow occurs. The number of consecutive months where flow observed is less than 5 percentile of flow is counted in a test year. If that count is greater than or equal to 6, then FHS is assigned a value of 0 and if in any month, flow less than 5 percentile is not observed in the test year, FHS is assigned a value of 1. If the count ranges between 1 and 6, then linear interpolation of FHS from 0 to 1 is required.

E.g.: PVL Count >= 6, FHS = 0

PVL Count = 0, FHS = 1

0< PVL Count < 6, FHS = 0 to 1 linearly

Seasonality Flow Shift (SFS): SFS is a measure of the degree to which the seasonality of the monthly flows has been altered. It is applicable especially in the case of a dam operation. SFS measures the mean deviation in the ranking of the monthly flow values when compared to the deviation in ranks observed in the reference data. If mean monthly deviation of the flow ranking in the test data is lesser than 75 percentile of the deviation observed in the reference data, the FHS is assigned a value of 1 and if it is greater than 75 percentile, it is assigned values linearly from 1 to 0 for 75 percentile to 100 percentile

E.g.: SFS < 75%, FHS =1

SFS > 75%, FHS = 1 to 0 linearly

Flood Flow Interval (FFI): FFI is a measure of the time interval between the last significant flood month. In this a flood of magnitude with five year recurrence interval is considered. If this5 yr flood doesn't occur for continuously 10 years, then FHS is assigned a value of 0 and if it occurs within the 5 years, FHS is assigned a value of 1 and if the flood occurs in between 5 and 10 years, FFI is assigned a FHS value linearly between1 to 0.

E.g.: FFI <60 months, FHS =1

FFI >120 months, FHS = 0

60<Interval between 5-year floods<120, FHS = 1 to 0 linearly

Flow Health Index: Unlike the other metrics, the Persistently High (PH) flow metric rewards the absence of an undesirable condition and hence can technically have a score of 1 with no flow. But in fact the PH sub-indicator loses its meaning when the low flow period flows are depressed. This problem is resolved by using PH as a moderator of the Low Flow (LF) sub-indicator. The LF is multiplied by the PH score to get modified LF score. The overall Flow Health index score is then calculated as the average of this modified LF score and the other 7 individual metric scores. This gives a score within the range 0 – 1, with 1 representing a low degree of deviation from the reference hydrology.

Total Flow Health Score = Average FHS (LF*PH,HF, HM, LM, PL, PVL, SFS, FFI,)

In flow health analysis; two flow metrics, persistently higher (PH) and Seasonality flow shift (SFS) consistently show a very large deviation even during the virgin state itself. This was the case at all the 146 locations. This basically indicates that high flows closer to the upper ranges of monthly flows occur at least more than once within the year during the low flow season and the average deviation in the seasonal ranking of the flows within the year is also quite high. The deviation in the seasonal ranking of the flow is quite high because of the strong monsoonal influence, where the flows during the non-monsoon are more or less similar. Hence, these two flow metrics will not be considered further for health analysis.

5.3. Look-up Table Approach

5.3.1. Flow Duration Curve Analysis

In this method, simple statistical analyses of flow regimes were done to check feasibility of different hydrological indices established and followed worldwide as minimum flow requirements. For four different scenarios, using monthly discharges for 29 years (1975-2003) obtained from SWAT modelling, annual and long term Flow Duration Curves (FDC) are obtained. Different flow percentiles e.g. Q_{95}, Q_{90}, Q_{75} and Q_{50}obtained on long term basis for all four scenarios are tabulated in Table 5 and 6 respectively. Apart from these tables, on a representative basis, variation in Q_{90}over the years for all 146 stations along with long term

Q_{90} are plotted station wise in figures provided in Appendices. These figures show the variation in availability of long term Q_{90} over the years in all four scenarios.

5.3.2. Mean Monthly Flow Analysis

Another look-up table approach used is 'Mean Monthly Flow' (MMF) analysis. Mean monthly flows and long term means were obtained for identified 146 stations for all four scenarios. Generally some predefined percentages of Mean Annual Flow (MAF) are considered as minimum flow requirements e.g. Tennant Method-10% of MAF, 25% of MAF in Canada(Caissie and El-Jabi 1995) etc. In preliminary stage of this study, feasibility of percentages of MAF were checked for Ganga Basin at various stretches and tributaies. From the considerable failures in attaining those percentages of MAF on daily basis, it was observed that '% of MAF' approach does not suit well to Ganga basin. This is on account of high seasonal variability.

From this understanding, Mean Monthly Flow approach has been used in this study. Considering Virgin flow scenario as reference line, long term monthly means of this scenarios are obtained (for 29 years).Availability of different percentages of these long term means (e.g. 10%, 5% and 2%)was checked month wise for 29 year data sets of all four scenarios. Comparisons of these availabilities for four different scenarios are done as shown in figure 7 to figure 10.

6. Result and Discussion

6.1. Preamble

The results from the flow health analysis as well as look-up table analyses at all the 146 locations are presented in the appendices. For the sake of brevity and illustration, the results from only a few locations are discussed here in detail. The Flow health assessment was made for four scenarios

1) Virgin scenario
2) Currently managed scenario
3) Flow health due to improved irrigation efficiency and
4) Flow health due to implementation of projects such as run of the river hydroelectric projects that are envisaged.

In general hydrologic flow health has been considerably affected at several stretches of Ganga due to the present state of water management. The flow health due to improved irrigation efficiency as implemented in the current model run do not seem to have a large impact in improving the hydrologic flow health and needs further investigation. The impact due to implementation of future projects seems to have only marginal effect over the current flow health. However, other aspects of flow health such as the water quality, biological aspects and functional needs of the ecosystem need to be considered while implementation of future projects.

Note: The hydrologic modeling and flow health analysis carried out here are indicative of only the overall flow conditions in stretches. However, there could be some localized conditions such as immediately downstream of the run of the river projects where the flow conditions may not be adequate, however further downstream, it may become normal due to return flows of water used in the power production. Longitudinal and lateral connective of the river along such local stretches should be thoroughly investigated even though the overall flow health in these stretches may appear good.

6.2. Upper Ganga

6.2.1. Rishikesh

As depicted by the long-term monthly flow hydrographs, the mean monthly flows during the managed state as a percentage of mean monthly flows during the virgin state did not deviate considerably. Because of this, small deviation in the managed flows when compared to the virgin flows, the disturbance to the flow health ranged from small to moderate during most of the years. Further, this variation in the flow health score is well within the range of variability in the flow health score during the virgin state itself. Look-up table analyses; Q_{90}as well as % of MMF analyses testimony the results of flow health tool analysis. Yearly Q_{90} and long term FDC are faintly varying from virgin conditions. Hence, the hydrologic flow health at Rishikesh could be considered as good.

6.2.2. Garmukhteshwar and Fatehgarh

Unlike at Rishikesh, the flow at Garmukhteshwar and downstream is considerably affected due to human interventions as reflected by the long-term monthly flow hydrographs. The low flow metrics seem to be reasonable. However, the two high flow metrics that are considerably affected include the High Flow (HF) and the Highest Monthly (HM) flow. This indicates that the total flow volume during the high flow season as well the highest flow within a year have considerably reduced due to human intervention. Further, the metric on flood frequency (FFI) is also very low.

For both Garmukhteshwar as well as Fatehgarh, FDC analysis represents huge alteration in flow regime with high differences in high flows as well as low flows thereby severely affecting total flow volumes. Low flows e.g. Q90 flows are reduced by more than 50%. MMF analysis shows reduction in mean monthly flows from 10% of virgin MMF to less than 2%.

Hence, the overall hydrologic flow health of Upper Ganga downstream of Rishikesh could be considered as poor. The hydrologic flow health is predicted to deteriorate even further if the projects envisaged were implemented above this stretch without adequate provision to maintain a healthy flow regime.

6.2.3. Bewar

The flow at Bewar is that of a different tributary to Upper Ganga. Unlike at Rishikesh, this flow does not include flow from snow melt. The flow health at Bewar is also considerably affected due to human interventions. The low flow metrics seem to be reasonable. However, the two high flow metrics that are considerably affected include the High Flow (HF) and the Highest Monthly (HM) flow, although not to the same degree as that in Garmukteshwar or Fatehgrah. Further, the metric on flood frequency (FFI) is also very low. MMF analysis shows reasonable reduction in total flow volume and MMF analysis shows reduction in mean monthly flows from 5% of virgin MMF to less than 2%. Hence, the overall hydrologic flow health of Upper Ganga at Bewar could be considered as moderate.

6.3. Ramganga

6.3.1. Bareilly and Dabri

As depicted by the long-term monthly flow hydrographs, the flow is considerably affected due to human interventions as reflected by the long-term monthly flow hydrographs. The low flow metrics seem to be reasonable. However, the two high flow metrics that are considerably affected include the High Flow (HF) and the Highest Monthly (HM) flow. This indicates that the total flow volume during the high flow season as well the highest flow within a year have considerably reduced due to human intervention. Further, the metric on flood frequency (FFI) is also very low i.e. the desired 5-yr frequency flood is not occurring at regular intervals. FDC shows that low flows (e.g. long term Q_{90}) are slightly reduced whereas high flows are considerably reduced. Overall, the hydrologic flow health of Ramganga at Bareilly and Dabri could be considered as poor.

6.4. Middle Ganga

6.4.1. Bhitaura

The flow at Bhitaura is contributed from Upper Ganga as well as from Ramgamga and is considerably affected due to human interventions. The low flow metrics seem to be reasonable. However, the two high flow metrics that are considerably affected include the High Flow (HF) and the Highest Monthly (HM) flow. Further, the metric on flood frequency (FFI) is also very low. FDC indicates that reduction in high as well as low flows reflect in high reduction in total flow volume. Mean monthly flows reduced from 5% of virgin MMF to less than 2%. Hence, the overall hydrologic flow health of Middle Ganga at Bhitaura could be considered as Poor.

6.4.2. Allahabad (Chatnag)

This station falls just downstream of confluence of Yamuna with Ganga. As in Bhitaura on Ganga, the flow at Allahabad (Chatnag) is considerably affected due to human interventions. Two high flow metrics that are considerably affected include the High Flow (HF) and the Highest Monthly (HM) flow. Further, the metric on flood frequency (FFI) is also very low. Considerable reduction is observed in Q_{90} flow as well as total flow volume. Hence, the overall hydrologic flow health of Middle Ganga at Allahabad (Chatnag) could be considered as poor.

6.5. Upper Yamuna

6.5.1. Poanta

Poanta is located in the upper reaches of the Yamuna. As depicted by the long-term monthly flow hydrographs, the mean monthly flows during the managed state as a percentage of mean monthly flows during the virgin state did not deviate considerably. The maximum deviation during the month of November is close to 70% of the virgin flow. Because of this small deviation in the managed flows when compared to the virgin flows, the disturbance to the flow health ranged from small to moderate during most of the years. Slight variation in FDCs is observed. Hence, the hydrologic flow health at Poanta could be considered as moderate. Improving the irrigation efficiency seem to improve the hydrologic flow health considerably.

6.6. Middle Yamuna

6.6.1. Baghpat, Mohana, Agra Poiyghat and Etawah

Unlike at Poanta, the flow at Baghpatand downstream is considerably affected due to human interventions as reflected by the long-term monthly flow hydrographs. The low flow metrics seem to be reasonable. However, the two high flow metrics that are considerably affected include the High Flow (HF) and the Highest Monthly (HM) flow. This indicates that the total flow volume during the high flow season as well the highest flow within a year have considerably reduced due to human intervention. FDCs testimony this finding. Mean monthly flows reduced from 5% to 2% of virgin long term mean. Hence, the overall hydrologic flow health of Yamuna downstream ofBaghpat could be considered as poor.

6.7. Chambal

6.7.1. Baranwada

The flow at Baranwada represents the contribution to Chambal from the tributary Banas. The long-term monthly hydrograph indicates that the flow in Banas is only seasonal (June to November) and it is considerably affected due to human interventions. However, the low flow metrics seem to be reasonable. The two high flow metrics that are slightly affected include the High Flow (HF) and the Highest Monthly (HM) flow. In other words, high flows e.g. Q1 to Q25 are reduced considerably. This indicates that the total flow volume during the high flow season as well the highest flow within a year have reasonably reduced due to human intervention. The metric on flood frequency (FFI) is very low indicating reduced frequency of floods. Hence, the overall hydrologic flow health of Chambal at Baranwada could be considered as moderate.

6.7.2. Mandawara

The flow at Mandawara represents the contribution to Chambal from one of the two limbs of Kali Sindh tributary. The long-term monthly hydrograph indicates that the flow in Kali Sindh is only seasonal (July to September) and is considerably affected due to human interventions. The low flow metrics seem to be reasonable and the two high flow metrics High Flow (HF) and the Highest Monthly (HM) flow are only slightly affected. The metric on flood frequency (FFI) although low, it is within the range of variability observed during the virgin condition as well. FDC shows significant reduction in flow volume with major reduction in Q10 to Q40.MMF analysis shows slight variations from virgin condition. Hence, the overall hydrologic flow health of Chambal at Mandawara could be considered to be moderate.

6.7.3. Barod

The flow at Barod represents the contribution from the other limb of Kali Sindh tributary to Chambal. The long-term monthly hydrograph indicates that the flow in Kali Sindh is only seasonal (July to December) and is considerably affected due to human interventions. Long term Q90 reduces from 55 m^3/s to $0m^3/s$. MMF analysis shows marginal reduction in mean monthly flows in comparison to virgin condition. Hence, the overall hydrologic flow health of Chambal at Barodcould be considered as moderate.

6.7.4. Manderial and Udi

The flow at Manderial and Udi represents the contribution from most of Chambal basin. The long-term monthly hydrograph indicates that the seasonal flows in Chambal are considerably affected due to human interventions. Long term Q_{90} reduces from >150 m^3/s to $0m^3/s$. FDCs testimony substantial reduction in flow volume.The overall hydrologic flow health of Chambal at Manderial and Udi could be considered as Moderate.

6.8. Lower Yamuna

6.8.1. Kalpi

The flow at Kalpi represents the contribution to Yamuna from Sind. The long-term monthly hydrograph indicates that the flows in Sind at Kalpi are considerably affected due to human interventions. The low flow metrics seem to be reasonable. However, the two high flow metrics that are considerably affected include the High Flow (HF) and the Highest Monthly (HM) flow. Long term Q_{90} reduces from >250 m^3/s to $0m^3/s$ and high flow e.g. Q_1 reduces from more than 15,000 m^3/s to less than 10,000 m^3/s. This indicates that the total flow volume during the high flow season as well the highest flow within a year have considerably reduced due to human intervention. The metric on flood frequency (FFI) is very low indicating reduction in frequency of floods post development. Hence, the overall hydrologic flow health of Sind at Kalpi could be considered as poor.

6.8.2. Mohana

The flow at Mohana represents the contribution to Yamuna from Betwa. The long-term monthly hydrograph indicates that the flow is only seasonal (July to September) and is considerably affected due to human interventions. Low flows seem to be reasonable but high flows are significantly reduced. Hence, the overall hydrologic flow health of Betwa at Mohana could be considered as poor. Future developments are seem be cascading this situation severely.

6.9. Gomati

6.9.1. Raibareli and Jalalpur

The flows at Raibareli and further downstream at Jalalpurare considerably affected due to human interventions. The flows during the monsoon season have reduced as much as 50% of the virgin condition flows. The low flow metrics seem to be reasonable. $Q_{90}$is consistent. However, the two high flow metrics that are moderately affected include the High Flow (HF) and the Highest Monthly (HM) flow. FDCs witness it reduced flow volumes. The metric on flood frequency (FFI) is also low indicating reduction in the frequency of floods. Hence, the overall hydrologic flow health of Gomati at Raibareli and Jalalpur could be considered as moderate.

6.9.2. Lucknow and Jaunpur

The flows at Lucknow and further downstream at Jaunpur are considerably affected due to human interventions. The flows during the monsoon season have reduced as much as 55% of the virgin condition flows. The low flow metrics seem to be reasonable. However, the two high flow metrics that are moderately affected include the High Flow (HF) and the Highest Monthly (HM) flow. The metric on flood frequency (FFI) is also low indicating reduction in the frequency of floods. Hence, the overall hydrologic flow health of Gomati at Lucknow and Jaunpur could be considered as moderate.

6.10. Sone

6.10.1. Chopan

The long-term monthly hydrograph indicates that the flows in Sone at Chopan are considerably affected due to human interventions. High flows are prominently representation of it. The overall hydrologic flow health of Sone at Chopan could be considered as poor. Additional future developments look to be worsening the situation.

6.11. Gaghra

6.11.1. Paliakalan

The flows at Paliakalan, indicates the most upstream conditions in Gaghra basin. The long-term monthly hydrograph indicates that the flows in Gaghra at Paliakalan are moderately affected due to human interventions. From the hydrological perspective, the low flow metrics and high flow metrics are affected only moderately. Hence, the overall hydrologic flow health of Gaghra at Paliakalan could be considered as moderate. Increased irrigation efficiency scenario shows some betterment in the current situation in FDC.

6.11.2. Ayodhya

Ayodhya is downstream of Paliakalan and the flows indicates the conditions in the middle section of Gaghra basin. The long-term monthly hydrograph indicates that the flows in Gaghra at Ayodhya are only moderately affected due to human interventions. MMF analysis results prove this. From the hydrological perspective, the low flow metrics and high flow metrics are affected only moderately and so the flow volumes. Hence, the overall hydrologic flow health of Gaghra at Ayodhya could be considered as moderate.

6.11.3. Turtipur

The flows at Turtipur is indicative of the most downstream conditions at Gaghra basin. The long-term monthly hydrograph indicates that the flows in Gaghra at Turtipur are moderately affected due to human interventions. The overall hydrologic flow health of Gaghra at Turtipur could be considered as moderate.

6.12. Gandak

6.12.1. Triveni

The flow at Triveni represents the flow conditions in the most upstream reaches of Gandak. The long-term monthly hydrograph indicates that the flows in Gandak at Triveniare only moderately affected due to human interventions. The low flow metrics seem to be reasonable. However, the two high flow metrics that are considerably affected include the High Flow (HF) and the Highest Monthly (HM) flow. This indicates that the total flow volume during the high flow season as well the highest flow within a year have considerably reduced due to human intervention. The metric on flood frequency (FFI) is also very low indicating reduction in frequency of floods post development. Hence, the overall hydrologic flow health of Gandak at Triveni could be considered as moderate.

6.12.2. Lalganj

Lalganj is located in the most downstream portion of Gandak. As at Triveni,the long-term monthly hydrograph indicates that the flows in Gandak at Lalganjare also only moderately affected due to human interventions. FDCs show significant reduction in high as well as low flows. Two high flow metrics that are considerably affected include the High Flow (HF) and the Highest Monthly (HM) flow. This indicates that the total flow volume during the high flow season as well the highest flow within a year have considerably reduced due to human intervention. The metric on flood frequency (FFI) is also very low indicating reduction in frequency of floods post development. MMF analysis also shows the alterations. Hence, the overall hydrologic flow health of Gandak at Lalganjcould be considered as moderate.

6.13. Kosi

6.13.1. Baltara

Baltara is located in the most downstream section of Kosi. The long-term monthly hydrograph indicates that the flows in Kosi at Baltara are marginally affected due to human interventions. From the hydrological perspective, the low flow metrics and high flow metrics are affected moderately. Hence, the overall hydrologic flow health of Kosi at Baltara could be considered as moderate. Increased Irrigation efficiency scenarios seems to add some betterment.

6.14. Lower Ganga

6.14.1. Sikandarpur

The long-term monthly hydrograph indicates that the flows at Sikandarpurare only slightly affected due to human interventions. The low flow metrics seem to be reasonable. The two high flow metrics that are marginally affected include the High Flow (HF) and the Highest Monthly (HM) flow. However, the metric on flood frequency (FFI) is low indicating reduction in frequency of floods post development. Hence, the overall hydrologic flow health at Sikandarpur could be considered as moderate to good.

6.14.2. Sripalpur

The long-term monthly hydrograph indicates that the flows at Sripalpurare considerably affected due to human interventions. The low flow metrics seem to be reasonable. However, the two high flow metrics that are considerably affected include the High Flow (HF) and the Highest Monthly (HM) flow. This indicates that the total flow volume during the high flow season as well the highest flow within a year have considerably reduced due to human intervention. The metric on flood frequency (FFI) is also very low indicating reduction in frequency of floods post development. Hence, the overall hydrologic flow health of Sripalpur could be considered as moderate.

6.14.3. Dhengra Ghat, Patna and Farakka

The long-term monthly hydrograph indicates that the flows at Dhengra Ghat all the way to Patna, Farakka are considerably affected due to human interventions. The low flow metrics seem to be reasonable. However, the two high flow metrics that are considerably affected include the High Flow (HF) and the Highest Monthly (HM) flow. This indicates that the total flow volume during the high flow season as well the highest flow within a year have considerably reduced due to human intervention. The metric on flood frequency (FFI) is very low indicating reduction in frequency of floods post development. Hence, the overall hydrologic flow health downstream of Dhengra Ghat all the way to Farakka could be considered as poor. From FDCs it can be seen that, increased irrigation efficiency scenario can help in improvement of the situation.

Table 1: **Median flow Health scores based on 29 years of simulation assuming virgin flow conditions**

Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Very Good	**Good**		**Moderate**		**Poor**		**Worst**	
				Upper Ganga Basin				
Badrinath	1	1	0.75	0.75	1	1	0.89	0.7
Joshimath	1	1	0.75	0.75	1	1	0.88	0.69
Nandkeshri	1	1	0.75	0.75	1	1	0.5	0.62
Karanprayag	1	1	0.75	0.75	1	1	0.89	0.7
Chandrapuri	1	1	0.75	0.75	1	1	0.89	0.7
Rudraprayag Below Confluence	1	1	0.75	0.75	1	1	0.89	0.69
Uttarkashi	1	1	0.75	0.75	1	1	0.88	0.69
Tehri (Zero Point)	1	1	0.75	0.75	1	1	0.75	0.66
Deoprayag A-1	1	1	0.75	0.75	1	1	0.75	0.66
Deoprayag Z-9	1	1	0.75	0.75	1	1	0.89	0.69
Marora	1	1	0.75	0.75	1	1	0.88	0.67
Rishikesh	1	1	0.75	0.75	1	1	0.89	0.69
Garmukhteshwar	1	1	0.75	0.75	1	1	0.88	0.69
Kachlabridge	1	1	0.75	0.75	1	1	0.88	0.69
Fatehgarh	1	1	0.75	0.75	1	1	0.89	0.69
Bewar	1	1	0.75	0.75	1	1	0.88	0.69
				Ramganga Basin				
Moradabad	1	1	0.75	0.75	1	1	0.89	0.69
Rampur	1	1	0.75	0.75	1	1	0.89	0.69
Gangan	1	1	0.75	0.75	1	1	0.88	0.67
Bareilly	1	1	0.75	0.75	1	1	0.89	0.68
Dabri	1	1	0.75	0.75	1	1	0.89	0.69
				Middle Ganga Basin				
Ankinghat	1	1	0.75	0.75	1	1	0.89	0.68
Kanpur	1	1	0.75	0.75	1	1	0.89	0.68
Bhitaura	1	1	0.75	0.75	1	1	0.89	0.68
allahabad (chatnag)	1	1	0.75	0.75	1	1	0.88	0.69
Pratappur	1	1	0.75	0.75	1	1	0.88	0.68
				Upper Yamuna basin				
Tuini (P)	1	1	0.75	0.75	1	1	0.88	0.69
Tuini (T)	1	1	0.75	0.75	1	1	0.88	0.69
Yashwant Nagar	1	1	0.75	0.75	1	1	0.88	0.67
Naugaon	1	1	0.75	0.75	1	1	0.89	0.7
Bausan	1	1	0.75	0.75	1	1	0.88	0.69
Haripur	1	1	0.75	0.75	1	1	0.88	0.68
Poanta	1	1	0.75	0.75	1	1	0.88	0.69
Kalanaur	1	1	0.75	0.75	1	1	0.88	0.69
Karnal	1	1	0.75	0.75	1	1	0.88	0.69
Mawi	1	1	0.75	0.75	1	1	0.88	0.69
Baghpat	1	1	0.75	0.75	1	1	0.88	0.69
Galeta	1	1	0.75	0.75	1	1	0.88	0.69

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Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Very Good		**Good**		**Moderate**		**Poor**		**Worst**
				Middle Yamuna basin				
Delhi Rly. Bridge	1	1	0.75	0.75	1	1	0.88	0.69
Mohana_UY	1	1	0.75	0.75	1	1	0.88	0.67
Mathura	1	1	0.75	0.75	1	1	0.88	0.67
Agra Poiyghat	1	1	0.75	0.75	1	1	0.88	0.67
				Banas				
Chittorgarh	1	1	0.75	0.75	1	1	0.88	0.69
Bigod	1	1	0.75	0.75	1	1	0.88	0.68
Tonk	1	1	0.75	0.75	1	1	0.88	0.67
				Kali sindh				
Salavad	1	1	0.75	0.75	1	1	0.88	0.69
Sarangpur	1	1	0.75	0.75	1	1	0.75	0.69
Aklera	1	1	0.75	0.75	1	1	0.88	0.69
Sangod	1	1	0.75	0.75	1	1	0.88	0.7
				Chambal Upper				
Dhareri	1	1	0.75	0.75	1	1	0.76	0.67
tal	1	1	0.75	0.75	1	1	0.62	0.64
Ujjain	1	1	0.75	0.75	1	1	0.75	0.69
Mahidpur	1	1	0.75	0.75	1	1	0.75	0.66
Mandawara	1	1	0.75	0.75	1	1	0.75	0.66
Barod	1	1	0.75	0.75	1	1	0.88	0.69
Khatoli	1	1	0.75	0.75	1	1	0.89	0.69
Pali	1	1	0.75	0.75	1	1	0.88	0.67
				Chambal Lower				
A. B. Road X-ing	1	1	0.75	0.75	1	1	0.88	0.69
Baranwada	1	1	0.75	0.75	1	1	0.75	0.67
Manderial	1	1	0.75	0.75	1	1	0.75	0.67
Dholpur	1	1	0.75	0.75	1	1	0.75	0.66
				Lower Yamuna				
Pachauli	1	1	0.75	0.75	1	1	0.88	0.67
Seonda	1	1	0.75	0.75	1	1	0.88	0.69
Bhind	1	1	0.75	0.75	1	1	0.89	0.69
Udi	1	1	0.75	0.75	1	1	0.75	0.66
Etawah	1	1	0.75	0.75	1	1	0.88	0.67
Auraiya	1	1	0.75	0.75	1	1	0.75	0.67
Kalpi	1	1	0.75	0.75	1	1	0.75	0.67
Lalpur	1	1	0.75	0.75	1	1	0.89	0.7
Hamirpur	1	1	0.75	0.75	1	1	0.75	0.67
Shahjina	1	1	0.75	0.75	1	1	0.88	0.69
Basoda	1	1	0.75	0.75	1	1	0.88	0.68
Mohana_LY	1	1	0.75	0.75	1	1	0.88	0.69

Table1 continued to next page … … …

… … … Table 1 continued from previous page

Very Good | Good | Moderate | Poor | Worst

Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Garrauli	1	1	0.75	0.75	1	1	0.88	0.69
Garhakota	1	1	0.75	0.75	1	1	0.88	0.7
Gaisabad	1	1	0.75	0.75	1	1	0.88	0.69
Madla	1	1	0.75	0.75	1	1	0.88	0.69
Banda	1	1	0.75	0.75	1	1	0.88	0.69
Rajapur	1	1	0.75	0.75	1	1	0.88	0.68
Gomati								
Neemsar	1	1	0.75	0.75	1	1	0.89	0.69
Lucknow	1	1	0.75	0.75	1	1	0.89	0.7
Jaunpur	1	1	0.75	0.75	1	1	0.88	0.69
Raibareli	1	1	0.75	0.75	1	1	0.89	0.66
Jalalpur	1	1	0.75	0.75	1	1	0.88	0.67
Sone								
Goverdheghat	1	1	0.75	0.75	1	1	0.88	0.69
Chopan	1	1	0.75	0.75	1	1	0.89	0.68
Duddhi	1	1	0.75	0.75	1	1	0.89	0.7
Ghaghra								
Tawaghat	1	1	0.75	0.75	1	1	0.75	0.67
Jauljibi	1	1	0.75	0.75	1	1	0.5	0.66
Ghat	1	1	0.75	0.75	1	1	0.5	0.62
Paliakalan	1	1	0.75	0.75	1	1	0.5	0.65
Elginbridge	1	1	0.75	0.75	1	1	0.89	0.69
Ayodhya	1	1	0.75	0.75	1	1	0.89	0.69
Bijalpur								
Gandak								
Basti	1	1	0.75	0.75	1	1	0.88	0.69
Bhinga	1	1	0.75	0.75	1	1	0.89	0.69
Balrampur	1	1	0.75	0.75	1	1	0.89	0.69
Kakrahi	1	1	0.75	0.75	1	1	0.88	0.69
Regauli	1	1	0.75	0.75	1	1	0.88	0.69
Birdghat	1	1	0.75	0.75	1	1	0.88	0.68
Turtipur	1	1	0.75	0.75	1	1	0.88	0.69
triveni	1	1	0.75	0.75	1	1	0.76	0.67
Dumariaghat	1	1	0.75	0.75	1	1	0.75	0.67
Lalganj	1	1	0.75	0.75	1	1	0.75	0.67
Gangajal								
Kosi								
Jainagar	1	1	0.75	0.75	1	1	0.88	0.68
Jhanjharpur	1	1	0.75	0.75	1	1	0.88	0.67

Table1 continued to next page … … …

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Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Very Good		**Good**		**Moderate**	**Poor**		**Worst**	
Lower Ganga								
Jamalpur	1	1	0.75	0.75	1	1	0.88	0.68
Ramchandipur	1	1	0.75	0.75	1	1	0.88	0.68
Ithara	1	1	0.75	0.75	1	1	0.88	0.69
Katesar	1	1	0.75	0.75	1	1	0.88	0.69
lalbegiaGhat	1	1	0.75	0.75	1	1	0.75	0.67
Sikandarpur	1	1	0.75	0.75	1	1	0.75	0.66
Sripalpur	1	1	0.75	0.75	1	1	0.88	0.7
Dheng Bridge	1	1	0.75	0.75	1	1	0.88	0.67
Benibad	1	1	0.75	0.75	1	1	0.75	0.67
Ekmighat	1	1	0.75	0.75	1	1	0.75	0.68
Hayaghat	1	1	0.75	0.75	1	1	0.88	0.67
Saulighat	1	1	0.75	0.75	1	1	0.75	0.66
Baltara	1	1	0.75	0.75	1	1	0.88	0.68
dhengraghat	1	1	0.75	0.75	1	1	0.88	0.68
Labha	1	1	0.75	0.75	1	1	0.88	0.69
Hanskhali	1	1	0.75	0.75	1	1	0.88	0.67
Kalna (Ebb)	1	1	0.75	0.75	1	1	0.88	0.69
Kalna (Flow)	1	1	0.75	0.75	1	1	0.88	0.69
Islampur	1	1	0.75	0.75	1	1	0.75	0.65
Palasipara	1	1	0.75	0.75	1	1	0.88	0.69
Chapra	1	1	0.75	0.75	1	1	0.88	0.69
Katwa	1	1	0.75	0.75	1	1	0.75	0.66
Bazarsau	1	1	0.75	0.75	1	1	0.5	0.62
Berhampore	1	1	0.75	0.75	1	1	0.64	0.65
GangbararJivpur	1	1	0.75	0.75	1	1	1	0.7
Birpur	1	1	0.75	0.75	1	1	0.89	0.7
Narainpur	1	1	0.75	0.75	1	1	0.88	0.67
Rudrapur	1	1	0.75	0.75	1	1	0.89	0.7
TolaBalaRai	1	1	0.75	0.75	1	1	0.89	0.68
Patna	1	1	0.75	0.75	1	1	0.89	0.69
HathidahBuzurg	1	1	0.75	0.75	1	1	1	0.7
Padma, Teesta and Jamuna								
Englishbazar	1	1	0.75	0.75	1	1	0.75	0.65
Rasalpur	1	1	0.75	0.75	1	1	1	0.7
Gangania	1	1	0.75	0.75	1	1	1	0.7
Bariarpur	1	1	0.75	0.75	1	1	1	0.7
Kamlakund	1	1	0.75	0.75	1	1	1	0.7
Mahespur	1	1	0.75	0.75	1	1	0.88	0.68
HR Farakka	1	1	0.75	0.75	1	1	0.88	0.68
Mirzapur	1	1	0.75	0.75	1	1	0.88	0.69

Table 2: **Median flow Health scores based on 29 years of simulation with the current state of management**

Very Good | Good | Moderate | Poor | Worst

Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Upper Ganga basin								
Badrinath	1	1	0.75	0.75	1	1	0.89	0.7
Joshimath	1	1	0.75	0.75	1	1	0.88	0.69
Nandkeshri	1	1	0.75	0.75	1	1	0.88	0.68
Karanprayag	1	1	0.75	0.75	1	1	0.75	0.66
Chandrapuri	1	1	0.75	0.75	1	1	0.89	0.7
Rudraprayag_Below Confluence	1	1	0.75	0.75	1	1	0.89	0.68
Uttarkashi	1	1	0.75	0.75	1	1	0.88	0.69
Tehri (Zero Point)	1	1	0.75	0.75	1	1	0.75	0.66
Deoprayag A-1	1	1	0.75	0.75	1	1	0.75	0.66
Deoprayag Z-9	1	1	0.75	0.75	1	1	0.75	0.64
Marora	1	1	0.75	0.75	1	1	0.75	0.66
Rishikesh	1	1	0.75	0.75	1	1	0.62	0.64
Garmukhteshwar	0	0	0.75	0.75	1	1	0	0.47
Kachlabridge	0	0	0.75	0.75	1	1	0	0.41
Fatehgarh	0	0	0.75	0.75	1	1	0	0.38
Bewar	0.27	0.27	0.75	0.75	1	1	0	0.48
Ramganga basin								
Moradabad	0	0	0.75	0.75	1	1	0	0.34
Rampur	0.19	0.19	0.75	0.75	1	1	0	0.41
Gangan	0.81	0.81	0.75	0.75	1	1	0.5	0.59
Bareilly	0.04	0.04	0.75	0.75	1	1	0	0.41
Dabri	0.06	0.06	0.75	0.75	1	1	0	0.4
Middle Ganga basin								
Ankinghat	0	0	0.75	0.75	1	1	0	0.36
Kanpur	0	0	0.75	0.75	1	1	0	0.36
Bhitaura	0	0	0.75	0.75	1	1	0	0.36
allahabad (chatnag)	0	0	0.75	0.75	1	1	0	0.34
Pratappur	0	0	0.75	0.75	1	1	0	0.34
Upper Yamuna basin								
Tuini (P)	1	1	0.75	0.75	1	1	0.88	0.69
Tuini (T)	1	1	0.75	0.75	1	1	0.88	0.69
Yashwant Nagar	1	1	0.75	0.75	1	1	0.88	0.67
Naugaon	1	1	0.75	0.75	1	1	0.89	0.7
Bausan	1	1	0.75	0.75	1	1	0.88	0.69
Haripur	1	1	0.75	0.75	1	1	0.88	0.68
Poanta	1	1	0.75	0.75	1	1	0	0.59
Kalanaur	0	0	0.75	0.75	1	1	0	0.34
Karnal	0	0	0.75	0.75	1	1	0	0.34
Mawi	0	0	0.75	0.75	1	1	0	0.34
Baghpat	0	0	0.75	0.75	1	1	0	0.34
Galeta	1	1	0.75	0.75	1	1	0.88	0.67

Table2 continued to next page … … …

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Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Very Good	Good	Moderate	Poor	Worst				
Middle Yamuna basin								
Delhi Rly. Bridge	0	0	0.75	0.75	1	1	0	0.34
Mohana_UY	0	0	0.75	0.75	1	1	0	0.34
Mathura	0	0	0.75	0.75	1	1	0	0.34
Agra Poiyghat	0	0	0.75	0.75	1	1	0	0.34
Banas								
Chittorgarh	0	0	0.75	0.75	1	1	0	0.43
Bigod	0.22	0.22	0.75	0.75	1	1	0	0.44
Tonk	0.2	0.2	0.75	0.75	1	1	0	0.43
Kali sindh								
Salavad	0.26	0.26	0.75	0.75	1	1	0.25	0.45
Sarangpur	0	0	0.75	0.75	1	1	0	0.39
Aklera	0	0	0.75	0.75	1	1	0	0.34
Sangod	0	0	0.75	0.75	1	1	0	0.34
Chambal Upper								
Dhareri	0.34	0.34	0.75	0.75	1	1	0	0.47
tal	0.65	0.65	0.75	0.75	1	1	0	0.51
Ujjain	0	0	0.75	0.75	1	1	0	0.41
Mahidpur	0.12	0.12	0.75	0.75	1	1	0	0.41
Mandawara	0	0	0.75	0.75	1	1	0	0.38
Barod	0	0	0.75	0.75	1	1	0	0.38
Khatoli	0	0	0.75	0.75	1	1	0	0.34
Pali	0	0	0.75	0.75	1	1	0	0.34
Chambal Lower								
A. B. Road X-ing	0	0	0.75	0.75	1	1	0	0.34
Baranwada	0.24	0.24	0.75	0.75	1	1	0	0.42
Manderial	0	0	0.75	0.75	1	1	0	0.35
Dholpur	0	0	0.75	0.75	1	1	0	0.35
Lower Yamuna								
Pachauli	0.09	0.09	0.75	0.75	1	1	0	0.39
Seonda	0	0	0.75	0.75	1	1	0	0.39
Bhind	0	0	0.75	0.75	1	1	0	0.34
Udi	0	0	0.75	0.75	1	1	0	0.35
Etawah	0	0	0.75	0.75	1	1	0	0.36
Auraiya	0	0	0.75	0.75	1	1	0	0.34
Kalpi	0	0	0.75	0.75	1	1	0	0.34
Lalpur	0.29	0.29	0.75	0.75	1	1	0	0.44
Hamirpur	0	0	0.75	0.75	1	1	0	0.34
Shahjina	0.03	0.03	0.75	0.75	1	1	0	0.38
Basoda	0.04	0.04	0.75	0.75	1	1	0	0.37
Mohana_LY	0.05	0.05	0.75	0.75	1	1	0	0.38
Garrauli	0.31	0.31	0.75	0.75	1	1	0.62	0.53
Garhakota	0.14	0.14	0.75	0.75	1	1	0.62	0.45

Table2 continued to next page … … …

… … … Table 2 continued form previous page

Stream flow station	**High flow (HF)**	**Highest monthly (HM)**	**Low flow (LF)**	**Lowest monthly (LM)**	**Persistently lower (PL)**	**Persistently very low (PVL)**	**Flood flow interval (FFI)**	**Flow health score (FH)**
Very Good	**Good**		**Moderate**		**Poor**		**Worst**	
Gaisabad	0.11	0.11	0.75	0.75	1	1	0	0.44
Madla	0.11	0.11	0.75	0.75	1	1	0	0.41
Banda	0.11	0.11	0.75	0.75	1	1	0	0.41
Rajapur	0	0	0.75	0.75	1	1	0	0.34
Gomati								
Neemsar	0.24	0.24	0.75	0.75	1	1	0	0.48
Lucknow	0.59	0.59	0.75	0.75	1	1	0.12	0.54
Jaunpur	0.21	0.21	0.75	0.75	1	1	0	0.44
Raibareli	0.3	0.3	0.75	0.75	1	1	0	0.46
Jalalpur	0.24	0.24	0.75	0.75	1	1	0.62	0.49
Sone								
Goverdheghat	0	0	0.75	0.75	1	1	0	0.34
Chopan	0.03	0.03	0.75	0.75	1	1	0	0.36
Duddhi	0	0	0.75	0.75	1	1	0	0.38
Ghaghra								
Tawaghat	1	1	0.75	0.75	1	1	0.75	0.67
Jauljibi	1	1	0.75	0.75	1	1	0.5	0.64
Ghat	0.47	0.47	0.75	0.75	1	1	0	0.47
Paliakalan	0	0	0.75	0.75	1	1	0	0.46
Elginbridge	0.09	0.09	0.75	0.75	1	1	0	0.44
Ayodhya	0	0	0.75	0.75	1	1	0	0.41
Bijalpur								
Gandak								
Basti	0.24	0.24	0.75	0.75	1	1	0	0.49
Bhinga	0	0	0.75	0.75	1	1	0	0.36
Balrampur	0	0	0.75	0.75	1	1	0	0.35
Kakrahi	0.25	0.25	0.75	0.75	1	1	0	0.46
Regauli	0.09	0.09	0.75	0.75	1	1	0	0.41
Birdghat	0.1	0.1	0.75	0.75	1	1	0	0.41
Turtipur	0	0	0.75	0.75	1	1	0	0.37
triveni	0.22	0.22	0.75	0.75	1	1	0	0.41
Dumariaghat	0.08	0.08	0.75	0.75	1	1	0	0.38
Lalganj	0.05	0.05	0.75	0.75	1	1	0	0.37
Gangajal								
Kosi								
Jainagar	0	0	0.75	0.75	1	1	0	0.39
Jhanjharpur	0	0	0.75	0.75	1	1	0	0.36

Table2 continued to next page … … …

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Very Good | **Good** | **Moderate** | **Poor** | **Worst**

Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Lower Ganga								
Jamalpur	0	0	0.75	0.75	1	1	0	0.34
Ramchandipur	0	0	0.75	0.75	1	1	0	0.34
Ithara	0	0	0.75	0.75	1	1	0	0.34
Katesar	0	0	0.75	0.75	1	1	0	0.34
lalbegiaGhat	0.81	0.81	0.75	0.75	1	1	0	0.56
Sikandarpur	1	1	0.75	0.75	1	1	0.38	0.64
Sripalpur	0.02	0.02	0.75	0.75	1	1	0	0.39
Dheng Bridge	0	0	0.75	0.75	1	1	0	0.34
Benibad	0.14	0.14	0.75	0.75	1	1	0	0.41
Ekmighat	0.44	0.44	0.75	0.75	1	1	0	0.49
Hayaghat	0	0	0.75	0.75	1	1	0	0.34
Saulighat	0.03	0.03	0.75	0.75	1	1	0	0.39
Baltara	0.1	0.1	0.75	0.75	1	1	0	0.4
dhengraghat	0	0	0.75	0.75	1	1	0	0.34
Labha	0	0	0.75	0.75	1	1	0	0.34
Hanskhali	0	0	0.75	0.75	1	1	0	0.34
Kalna (Ebb)	0	0	0.75	0.75	1	1	0	0.36
Kalna (Flow)	0	0	0.75	0.75	1	1	0	0.36
Islampur	0.06	0.06	0.75	0.75	1	1	0	0.38
Palasipara	0.01	0.01	0.75	0.75	1	1	0	0.38
Chapra	0	0	0.75	0.75	1	1	0	0.36
Katwa	0.09	0.09	0.75	0.75	1	1	0	0.41
Bazarsau	0.71	0.71	0.75	0.75	1	1	0	0.52
Berhampore	0.43	0.43	0.75	0.75	1	1	0	0.46
GangbararJivpur	0	0	0.75	0.75	1	1	0	0.34
Birpur	0	0	0.75	0.75	1	1	0	0.34
Narainpur	0	0	0.75	0.75	1	1	0	0.34
Rudrapur	0	0	0.75	0.75	1	1	0	0.34
TolaBalaRai	0	0	0.75	0.75	1	1	0	0.34
Patna	0	0	0.75	0.75	1	1	0	0.34
HathidahBuzurg	0	0	0.75	0.75	1	1	0	0.34
Padma, Teesta and Jamuna								
Englishbazar	0	0	0.75	0.75	1	1	0	0.34
Rasalpur	0	0	0.75	0.75	1	1	0	0.34
Gangania	0	0	0.75	0.75	1	1	0	0.34
Bariarpur	0	0	0.75	0.75	1	1	0	0.34
Kamlakund	0	0	0.75	0.75	1	1	0	0.34
Mahespur	0	0	0.75	0.75	1	1	0	0.34
HR Farakka	0	0	0.75	0.75	1	1	0	0.34
Mirzapur	0	0	0.75	0.75	1	1	0	0.34

Table 3: Median flow Health scores based on 29 years of simulation with the current state of management but with increased irrigation efficiency

Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Very Good	**Good**		**Moderate**		**Poor**		**Worst**	
				Upper Ganga basin				
Badrinath	1	1	0.75	0.75	1	1	0.89	0.7
Joshimath	1	1	0.75	0.75	1	1	0.88	0.69
Nandkeshri	1	1	0.75	0.75	1	1	0.88	0.68
Karanprayag	1	1	0.75	0.75	1	1	0.75	0.67
Chandrapuri	1	1	0.75	0.75	1	1	0.89	0.7
Rudraprayag_Below Confluence	1	1	0.75	0.75	1	1	0.89	0.69
Uttarkashi	1	1	0.75	0.75	1	1	0.88	0.69
Tehri (Zero Point)	1	1	0.75	0.75	1	1	0.75	0.66
Deoprayag A-1	1	1	0.75	0.75	1	1	0.75	0.66
Deoprayag Z-9	1	1	0.75	0.75	1	1	0.88	0.67
Marora	1	1	0.75	0.75	1	1	0.75	0.66
Rishikesh	1	1	0.75	0.75	1	1	0.88	0.67
Garmukhteshwar	0	0	0.75	0.75	1	1	0	0.47
Kachlabridge	0	0	0.75	0.75	1	1	0	0.47
Fatehgarh	0	0	0.75	0.75	1	1	0	0.41
Bewar	0.31	0.31	0.75	0.75	1	1	0.5	0.51
				Ramganga basin				
Moradabad	0	0	0.75	0.75	1	1	0	0.34
Rampur	0.47	0.47	0.75	0.75	1	1	0	0.46
Gangan	0.83	0.83	0.75	0.75	1	1	0.5	0.59
Bareilly	0.06	0.06	0.75	0.75	1	1	0	0.41
Dabri	0.09	0.09	0.75	0.75	1	1	0	0.41
				Middle Ganga basin				
Ankinghat	0	0	0.75	0.75	1	1	0	0.38
Kanpur	0	0	0.75	0.75	1	1	0	0.36
Bhitaura	0	0	0.75	0.75	1	1	0	0.36
allahabad (chatnag)	0	0	0.75	0.75	1	1	0	0.34
Pratappur	0	0	0.75	0.75	1	1	0	0.34
				Upper Yamuna basin				
Tuini (P)	1	1	0.75	0.75	1	1	0.88	0.69
Tuini (T)	1	1	0.75	0.75	1	1	0.88	0.69
Yashwant Nagar	1	1	0.75	0.75	1	1	0.88	0.67
Naugaon	1	1	0.75	0.75	1	1	0.89	0.7
Bausan	1	1	0.75	0.75	1	1	0.88	0.69
Haripur	1	1	0.75	0.75	1	1	0.88	0.68
Poanta	1	1	0.75	0.75	1	1	0.88	0.69
Kalanaur	0	0	0.75	0.75	1	1	0	0.34
Karnal	0	0	0.75	0.75	1	1	0	0.34
Mawi	0	0	0.75	0.75	1	1	0	0.34
Baghpat	0	0	0.75	0.75	1	1	0	0.34
Galeta	1	1	0.75	0.75	1	1	0.88	0.67

Table3 continued to next page … … …

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Very Good | Good | Moderate | Poor | Worst

Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Middle Yamuna basin								
Delhi Rly. Bridge	0	0	0.75	0.75	1	1	0	0.34
Mohana_UY	0	0	0.75	0.75	1	1	0	0.34
Mathura	0	0	0.75	0.75	1	1	0	0.34
Agra Poiyghat	0	0	0.75	0.75	1	1	0	0.34
Banas								
Chittorgarh	0.02	0.02	0.75	0.75	1	1	0	0.44
Bigod	0.22	0.22	0.75	0.75	1	1	0	0.45
Tonk	0.24	0.24	0.75	0.75	1	1	0	0.43
Kali sindh								
Salavad	0.21	0.21	0.75	0.75	1	1	0.25	0.45
Sarangpur	0	0	0.75	0.75	1	1	0	0.39
Aklera	0	0	0.75	0.75	1	1	0.25	0.41
Sangod	0	0	0.75	0.75	1	1	0	0.34
Chambal Upper								
Dhareri	0.35	0.35	0.75	0.75	1	1	0	0.48
tal	0.67	0.67	0.75	0.75	1	1	0	0.52
Ujjain	0	0	0.75	0.75	1	1	0	0.41
Mahidpur	0.16	0.16	0.75	0.75	1	1	0	0.42
Mandawara	0	0	0.75	0.75	1	1	0	0.39
Barod	0	0	0.75	0.75	1	1	0	0.38
Khatoli	0	0	0.75	0.75	1	1	0	0.34
Pali	0	0	0.75	0.75	1	1	0	0.34
Chambal Lower								
A. B. Road X-ing	0	0	0.75	0.75	1	1	0	0.34
Baranwada	0.24	0.24	0.75	0.75	1	1	0	0.42
Manderial	0	0	0.75	0.75	1	1	0	0.35
Dholpur	0	0	0.75	0.75	1	1	0	0.35
Lower Yamuna								
Pachauli	0.1	0.1	0.75	0.75	1	1	0	0.39
Seonda	0	0	0.75	0.75	1	1	0	0.39
Bhind	0	0	0.75	0.75	1	1	0	0.34
Udi	0	0	0.75	0.75	1	1	0	0.35
Etawah	0	0	0.75	0.75	1	1	0	0.36
Auraiya	0	0	0.75	0.75	1	1	0	0.34
Kalpi	0	0	0.75	0.75	1	1	0	0.34
Lalpur	0.32	0.32	0.75	0.75	1	1	0	0.45
Hamirpur	0	0	0.75	0.75	1	1	0	0.34
Shahjina	0.06	0.06	0.75	0.75	1	1	0	0.38
Basoda	0.04	0.04	0.75	0.75	1	1	0	0.37
Mohana_LY	0.07	0.07	0.75	0.75	1	1	0	0.39
Garrauli	0.41	0.41	0.75	0.75	1	1	0.62	0.53
Garhakota	0.15	0.15	0.75	0.75	1	1	0.62	0.45

Table3 continued to next page … … …

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Very Good | **Good** | **Moderate** | **Poor** | **Worst**

Stream flow station	**High flow (HF)**	**Highest monthly (HM)**	**Low flow (LF)**	**Lowest monthly (LM)**	**Persistently lower (PL)**	**Persistently very low (PVL)**	**Flood flow interval (FFI)**	**Flow health score (FH)**
Gaisabad	0.12	0.12	0.75	0.75	1	1	0	0.44
Madla	0.12	0.12	0.75	0.75	1	1	0	0.41
Banda	0.13	0.13	0.75	0.75	1	1	0	0.41
Rajapur	0	0	0.75	0.75	1	1	0	0.34
Gomati								
Neemsar	0.26	0.26	0.75	0.75	1	1	0	0.51
Lucknow	0.61	0.61	0.75	0.75	1	1	0.12	0.55
Jaunpur	0.24	0.24	0.75	0.75	1	1	0	0.44
Raibareli	0.38	0.38	0.75	0.75	1	1	0	0.47
Jalalpur	0.57	0.57	0.75	0.75	1	1	0.62	0.5
Sone								
Goverdheghat	0	0	0.75	0.75	1	1	0	0.34
Chopan	0.05	0.05	0.75	0.75	1	1	0	0.36
Duddhi	0.02	0.02	0.75	0.75	1	1	0	0.41
Ghaghra								
Tawaghat	1	1	0.75	0.75	1	1	0.75	0.67
Jauljibi	1	1	0.75	0.75	1	1	0.5	0.65
Ghat	1	1	0.75	0.75	1	1	0	0.59
Paliakalan	0.45	0.45	0.75	0.75	1	1	0	0.47
Elginbridge	0.37	0.37	0.75	0.75	1	1	0	0.46
Ayodhya	0.25	0.25	0.75	0.75	1	1	0	0.47
Bijalpur								
Gandak								
Basti	0.26	0.26	0.75	0.75	1	1	0	0.49
Bhinga	0	0	0.75	0.75	1	1	0	0.36
Balrampur	0	0	0.75	0.75	1	1	0	0.36
Kakrahi	0.31	0.31	0.75	0.75	1	1	0	0.47
Regauli	0.11	0.11	0.75	0.75	1	1	0	0.42
Birdghat	0.12	0.12	0.75	0.75	1	1	0	0.42
Turtipur	0	0	0.75	0.75	1	1	0	0.44
triveni	0.23	0.23	0.75	0.75	1	1	0	0.41
Dumariaghat	0.12	0.12	0.75	0.75	1	1	0	0.39
Lalganj	0.1	0.1	0.75	0.75	1	1	0	0.38
Gangajal								
Kosi								
Jainagar	0.03	0.03	0.75	0.75	1	1	0	0.4
Jhanjharpur	0	0	0.75	0.75	1	1	0	0.36

Table3 continued to next page … … …

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Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Very Good	**Good**	**Moderate**	**Poor**	**Worst**				
Lower Ganga								
Jamalpur	0	0	0.75	0.75	1	1	0	0.34
Ramchandipur	0	0	0.75	0.75	1	1	0	0.34
Ithara	0	0	0.75	0.75	1	1	0	0.34
Katesar	0	0	0.75	0.75	1	1	0	0.34
lalbegiaGhat	0.82	0.82	0.75	0.75	1	1	0	0.58
Sikandarpur	1	1	0.75	0.75	1	1	0.38	0.64
Sripalpur	0.04	0.04	0.75	0.75	1	1	0	0.39
Dheng Bridge	0	0	0.75	0.75	1	1	0	0.34
Benibad	0.16	0.16	0.75	0.75	1	1	0	0.42
Ekmighat	0.47	0.47	0.75	0.75	1	1	0	0.49
Hayaghat	0	0	0.75	0.75	1	1	0	0.34
Saulighat	0.05	0.05	0.75	0.75	1	1	0	0.41
Baltara	0.14	0.14	0.75	0.75	1	1	0	0.42
dhengraghat	0	0	0.75	0.75	1	1	0	0.34
Labha	0	0	0.75	0.75	1	1	0	0.34
Hanskhali	0	0	0.75	0.75	1	1	0	0.34
Kalna (Ebb)	0.01	0.01	0.75	0.75	1	1	0	0.37
Kalna (Flow)	0.01	0.01	0.75	0.75	1	1	0	0.37
Islampur	0.09	0.09	0.75	0.75	1	1	0	0.42
Palasipara	0.03	0.03	0.75	0.75	1	1	0	0.38
Chapra	0	0	0.75	0.75	1	1	0	0.36
Katwa	0.13	0.13	0.75	0.75	1	1	0	0.41
Bazarsau	0.71	0.71	0.75	0.75	1	1	0	0.54
Berhampore	0.44	0.44	0.75	0.75	1	1	0	0.47
GangbararJivpur	0	0	0.75	0.75	1	1	0	0.34
Birpur	0	0	0.75	0.75	1	1	0	0.34
Narainpur	0	0	0.75	0.75	1	1	0	0.34
Rudrapur	0	0	0.75	0.75	1	1	0	0.34
TolaBalaRai	0	0	0.75	0.75	1	1	0	0.34
Patna	0	0	0.75	0.75	1	1	0	0.34
HathidahBuzurg	0	0	0.75	0.75	1	1	0	0.34
Padma, Teesta and Jamuna								
Englishbazar	0	0	0.75	0.75	1	1	0	0.34
Rasalpur	0	0	0.75	0.75	1	1	0	0.34
Gangania	0	0	0.75	0.75	1	1	0	0.34
Bariarpur	0	0	0.75	0.75	1	1	0	0.34
Kamlakund	0	0	0.75	0.75	1	1	0	0.34
Mahespur	0	0	0.75	0.75	1	1	0	0.34
HR Farakka	0	0	0.75	0.75	1	1	0	0.34
Mirzapur	0	0	0.75	0.75	1	1	0	0.34

Table 4: **Median flow Health scores based on 29 years of simulation with the implementation of future projects**

Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)

Very Good	Good	Moderate	Poor	Worst

Stream flow station	HF	HM	LF	LM	PL	PVL	FFI	FH
Upper Ganga basin								
Badrinath	1	1	0.75	0.75	1	1	0.89	0.7
Joshimath	1	1	0.75	0.75	1	1	0.88	0.69
Nandkeshri	1	1	0.75	0.75	1	1	0.88	0.68
Karanprayag	1	1	0.75	0.75	1	1	0.75	0.66
Chandrapuri	1	1	0.75	0.75	1	1	0.89	0.7
Rudraprayag_Below Confluence	1	1	0.75	0.75	1	1	0.89	0.68
Uttarkashi	1	1	0.75	0.75	1	1	0.88	0.69
Tehri (Zero Point)	1	1	0.75	0.75	1	1	0.75	0.66
Deoprayag A-1	1	1	0.75	0.75	1	1	0.75	0.66
Deoprayag Z-9	1	1	0.75	0.75	1	1	0.75	0.64
Marora	1	1	0.75	0.75	1	1	0.75	0.66
Rishikesh	1	1	0.75	0.75	1	1	0.62	0.64
Garmukhteshwar	0.04	0.04	0.75	0.75	1	1	0	0.47
Kachlabridge	0	0	0.75	0.75	1	1	0	0.47
Fatehgarh	0	0	0.75	0.75	1	1	0	0.42
Bewar	0.27	0.27	0.75	0.75	1	1	0	0.48
Ramganga basin								
Moradabad	0	0	0.75	0.75	1	1	0	0.34
Rampur	0.19	0.19	0.75	0.75	1	1	0	0.41
Gangan	0.81	0.81	0.75	0.75	1	1	0.5	0.59
Bareilly	0.04	0.04	0.75	0.75	1	1	0	0.41
Dabri	0.06	0.06	0.75	0.75	1	1	0	0.4
Middle Ganga basin								
Ankinghat	0	0	0.75	0.75	1	1	0	0.39
Kanpur	0	0	0.75	0.75	1	1	0	0.37
Bhitaura	0	0	0.75	0.75	1	1	0	0.37
allahabad (chatnag)	0	0	0.75	0.75	1	1	0	0.34
Pratappur	0	0	0.75	0.75	1	1	0	0.34
Upper Yamuna basin								
Tuini (P)	1	1	0.75	0.75	1	1	0.88	0.69
Tuini (T)	1	1	0.75	0.75	1	1	0.88	0.69
Yashwant Nagar	1	1	0.75	0.75	1	1	0.88	0.67
Naugaon	1	1	0.75	0.75	1	1	0.89	0.7
Bausan	1	1	0.75	0.75	1	1	0.88	0.69
Haripur	1	1	0.75	0.75	1	1	0.88	0.68
Poanta	1	1	0.75	0.75	1	1	0	0.59
Kalanaur	0	0	0.75	0.75	1	1	0	0.34
Karnal	0	0	0.75	0.75	1	1	0	0.34
Mawi	0	0	0.75	0.75	1	1	0	0.34
Baghpat	0	0	0.75	0.75	1	1	0	0.34
Galeta	1	1	0.75	0.75	1	1	0.88	0.67

Table 4 continued to next page … … …

… … … *Table 4 continued form previous page*

Very Good | Good | Moderate | Poor | Worst

Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Middle Yamuna basin								
Delhi Rly. Bridge	0	0	0.75	0.75	1	1	0	0.34
Mohana_UY	0	0	0.75	0.75	1	1	0	0.34
Mathura	0	0	0.75	0.75	1	1	0	0.34
Agra Poiyghat	0	0	0.75	0.75	1	1	0	0.34
Banas								
Chittorgarh	0	0	0.75	0.75	1	1	0	0.43
Bigod	0.22	0.22	0.75	0.75	1	1	0	0.44
Tonk	0.2	0.2	0.75	0.75	1	1	0	0.43
Kali sindh								
Salavad	0.26	0.26	0.75	0.75	1	1	0.25	0.45
Sarangpur	0	0	0.75	0.75	1	1	0	0.39
Aklera	0	0	0.75	0.75	1	1	0	0.34
Sangod	0	0	0.75	0.75	1	1	0	0.34
Chambal Upper								
Dhareri	0.34	0.34	0.75	0.75	1	1	0	0.47
tal	0.65	0.65	0.75	0.75	1	1	0	0.51
Ujjain	0	0	0.75	0.75	1	1	0	0.41
Mahidpur	0.12	0.12	0.75	0.75	1	1	0	0.41
Mandawara	0	0	0.75	0.75	1	1	0	0.38
Barod	0	0	0.75	0.75	1	1	0	0.38
Khatoli	0	0	0.75	0.75	1	1	0	0.34
Pali	0	0	0.75	0.75	1	1	0	0.34
Chambal Lower								
A. B. Road X-ing	0	0	0.75	0.75	1	1	0	0.34
Baranwada	0.24	0.24	0.75	0.75	1	1	0	0.42
Manderial	0	0	0.75	0.75	1	1	0	0.35
Dholpur	0	0	0.75	0.75	1	1	0	0.35
Lower Yamuna								
Pachauli	0.09	0.09	0.75	0.75	1	1	0	0.39
Seonda	0	0	0.75	0.75	1	1	0	0.39
Bhind	0	0	0.75	0.75	1	1	0	0.34
Udi	0	0	0.75	0.75	1	1	0	0.35
Etawah	0	0	0.75	0.75	1	1	0	0.36
Auraiya	0	0	0.75	0.75	1	1	0	0.34
Kalpi	0	0	0.75	0.75	1	1	0	0.34
Lalpur	0.29	0.29	0.75	0.75	1	1	0	0.44
Hamirpur	0	0	0.75	0.75	1	1	0	0.34
Shahjina	0	0	0.75	0.75	1	1	0	0.34
Basoda	0.04	0.04	0.75	0.75	1	1	0	0.37
Mohana_LY	0	0	0.75	0.75	1	1	0	0.35
Garrauli	0.22	0.22	0.75	0.75	1	1	0.25	0.46
Garhakota	0.14	0.14	0.75	0.75	1	1	0.62	0.45

Table 4 continued to next page … … …

… … … Table 4 continued form previous page

Very Good	**Good**	**Moderate**	**Poor**	**Worst**

Stream flow station	**High flow (HF)**	**Highest monthly (HM)**	**Low flow (LF)**	**Lowest monthly (LM)**	**Persistently lower (PL)**	**Persistently very low (PVL)**	**Flood flow interval (FFI)**	**Flow health score (FH)**
Gaisabad	0.11	0.11	0.75	0.75	1	1	0	0.44
Madla	0.09	0.09	0.75	0.75	1	1	0	0.41
Banda	0.08	0.08	0.75	0.75	1	1	0	0.4
Rajapur	0	0	0.75	0.75	1	1	0	0.34
Gomati								
Neemsar	0.24	0.24	0.75	0.75	1	1	0	0.48
Lucknow	0.59	0.59	0.75	0.75	1	1	0.12	0.54
Jaunpur	0.21	0.21	0.75	0.75	1	1	0	0.44
Raibareli	0.3	0.3	0.75	0.75	1	1	0	0.46
Jalalpur	0.24	0.24	0.75	0.75	1	1	0.62	0.49
Sone								
Goverdheghat	0	0	0.75	0.75	1	1	0	0.34
Chopan	0.01	0.01	0.75	0.75	1	1	0	0.35
Duddhi	0	0	0.75	0.75	1	1	0	0.38
Ghaghra								
Tawaghat	1	1	0.75	0.75	1	1	0.75	0.67
Jauljibi	1	1	0.75	0.75	1	1	0.5	0.64
Ghat	0.47	0.47	0.75	0.75	1	1	0	0.47
Paliakalan	0	0	0.75	0.75	1	1	0	0.43
Elginbridge	0.04	0.04	0.75	0.75	1	1	0	0.44
Ayodhya	0	0	0.75	0.75	1	1	0	0.4
Bijalpur								
Gandak								
Basti	0.24	0.24	0.75	0.75	1	1	0	0.49
Bhinga	0	0	0.75	0.75	1	1	0	0.36
Balrampur	0	0	0.75	0.75	1	1	0	0.35
Kakrahi	0.25	0.25	0.75	0.75	1	1	0	0.46
Regauli	0.09	0.09	0.75	0.75	1	1	0	0.41
Birdghat	0.1	0.1	0.75	0.75	1	1	0	0.41
Turtipur	0	0	0.75	0.75	1	1	0	0.36
triveni	0.22	0.22	0.75	0.75	1	1	0	0.41
Dumariaghat	0.08	0.08	0.75	0.75	1	1	0	0.38
Lalganj	0.06	0.06	0.75	0.75	1	1	0	0.37
Gangajal								
Kosi								
Jainagar	0	0	0.75	0.75	1	1	0	0.34
Jhanjharpur	0	0	0.75	0.75	1	1	0	0.34

Table 4 continued to next page … … …

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Very Good | Good | Moderate | Poor | Worst

Stream flow station	High flow (HF)	Highest monthly (HM)	Low flow (LF)	Lowest monthly (LM)	Persistently lower (PL)	Persistently very low (PVL)	Flood flow interval (FFI)	Flow health score (FH)
Lower Ganga								
Jamalpur	0	0	0.75	0.75	1	1	0	0.34
Ramchandipur	0	0	0.75	0.75	1	1	0	0.34
Ithara	0	0	0.75	0.75	1	1	0	0.34
Katesar	0	0	0.75	0.75	1	1	0	0.34
lalbegiaGhat	0.81	0.81	0.75	0.75	1	1	0	0.56
Sikandarpur	1	1	0.75	0.75	1	1	0.38	0.64
Sripalpur	0.02	0.02	0.75	0.75	1	1	0	0.39
Dheng Bridge	0	0	0.75	0.75	1	1	0	0.34
Benibad	0.14	0.14	0.75	0.75	1	1	0	0.41
Ekmighat	0.44	0.44	0.75	0.75	1	1	0	0.49
Hayaghat	0	0	0.75	0.75	1	1	0	0.34
Saulighat	0.03	0.03	0.75	0.75	1	1	0	0.39
Baltara	0.08	0.08	0.75	0.75	1	1	0	0.4
dhengraghat	0	0	0.75	0.75	1	1	0	0.34
Labha	0	0	0.75	0.75	1	1	0	0.34
Hanskhali	0	0	0.75	0.75	1	1	0	0.34
Kalna (Ebb)	0	0	0.75	0.75	1	1	0	0.36
Kalna (Flow)	0	0	0.75	0.75	1	1	0	0.36
Islampur	0.06	0.06	0.75	0.75	1	1	0	0.38
Palasipara	0.01	0.01	0.75	0.75	1	1	0	0.38
Chapra	0	0	0.75	0.75	1	1	0	0.36
Katwa	0.09	0.09	0.75	0.75	1	1	0	0.41
Bazarsau	0.71	0.71	0.75	0.75	1	1	0	0.52
Berhampore	0.43	0.43	0.75	0.75	1	1	0	0.46
GangbararJivpur	0	0	0.75	0.75	1	1	0	0.34
Birpur	0	0	0.75	0.75	1	1	0	0.34
Narainpur	0	0	0.75	0.75	1	1	0	0.34
Rudrapur	0	0	0.75	0.75	1	1	0	0.34
TolaBalaRai	0	0	0.75	0.75	1	1	0	0.34
Patna	0	0	0.75	0.75	1	1	0	0.34
HathidahBuzurg	0	0	0.75	0.75	1	1	0	0.34
Padma, Teesta and Jamuna								
Englishbazar	0	0	0.75	0.75	1	1	0	0.34
Rasalpur	0	0	0.75	0.75	1	1	0	0.34
Gangania	0	0	0.75	0.75	1	1	0	0.34
Bariarpur	0	0	0.75	0.75	1	1	0	0.34
Kamlakund	0	0	0.75	0.75	1	1	0	0.34
Mahespur	0	0	0.75	0.75	1	1	0	0.34
HR Farakka	0	0	0.75	0.75	1	1	0	0.34
Mirzapur	0	0	0.75	0.75	1	1	0	0.34

Table 5: Q_{95} and Q_{90} flows for four scenarios for 146 stations in Ganga Basin

Stream flow station	Q95				Q90			
	Virgin	Present	Future	Increased. Eff.	Virgin	Present	Future	Increased. Eff.
'Tuini (P)'	1.77	1.76	1.76	1.76	2.34	2.34	2.34	2.34
'Tuini (T)'	10.05	9.86	9.86	9.95	13.52	13.56	13.56	13.56
'Yashwant Nagar'	0.81	0.80	0.80	0.80	1.17	1.12	1.12	1.12
'Naugaon'	0.60	0.61	0.61	0.61	0.77	0.77	0.77	0.77
'Badrinath'	0.50	0.49	0.49	0.49	0.60	0.58	0.58	0.58
'Uttarkashi'	16.37	16.32	16.46	16.32	23.16	23.13	23.18	23.13
'Haripur'	0.11	0.08	0.08	0.08	0.16	0.12	0.12	0.12
'Bausan'	2.80	2.76	2.76	2.76	3.66	3.63	3.63	3.63
'Chandrapuri'	9.39	9.34	9.34	9.34	12.49	12.48	12.48	12.48
'Poanta'	22.50	20.50	18.41	20.74	28.13	26.77	24.94	27.01
'Joshimath'	15.69	15.70	15.70	15.70	19.85	19.68	19.68	19.68
'Tehri (Zero Point)'	27.58	27.52	27.69	27.52	35.80	35.74	35.63	35.74
'Rudraprayag_ Below Confluence'	67.50	69.62	69.53	71.65	90.03	92.68	92.67	92.67
'Karanprayag'	19.66	22.21	22.21	22.52	29.38	29.44	29.44	30.52
'Deoprayag A-1-Bhagirathi'	32.26	32.30	33.02	32.30	41.98	41.92	41.87	41.92
'Deoprayag Z-9-Ganga'	115.30	118.70	118.10	118.70	137.80	140.50	140.70	140.60
'Kalanaur'	21.51	0.00	0.00	0.00	26.81	0.00	0.00	0.00
'Rishikesh'	125.70	124.60	121.70	124.60	149.30	152.20	153.20	153.00
'Nandkeshri'	12.89	12.92	12.92	12.92	16.32	16.36	16.36	16.36
'Marora'	2.38	2.39	2.39	2.39	3.16	3.23	3.23	3.23
'Tawaghat'	14.88	14.86	14.86	14.86	18.88	18.84	18.84	18.84
'Karnal'	20.91	0.00	0.00	0.00	26.15	0.00	0.00	0.00
'Jauljibi'	28.36	26.86	26.86	27.61	36.80	37.01	37.01	38.29
'Ghat'	8.51	0.00	0.00	1.28	13.72	1.69	1.69	6.37
'Mawi'	20.38	0.00	0.00	0.00	25.82	0.00	0.00	0.00
'Galeta'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Baghpat'	19.39	0.00	0.00	0.00	25.61	0.00	0.00	0.00
'Moradabad'	3.25	0.00	0.00	0.00	7.18	0.00	0.00	0.00
‘Garmukhteswar	124.50	21.42	33.21	20.14	166.00	47.17	63.53	50.73
'Gangan'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Rampur'	0.00	0.00	0.00	0.00	0.56	0.00	0.00	0.00
'Delhi Rly. Bridge'	18.76	0.00	0.00	0.00	27.06	0.00	0.00	0.00
'Paliakalan'	63.69	1.84	0.23	8.04	87.58	17.61	2.03	45.87
'Bareilly'	4.85	0.00	0.00	0.00	12.55	0.00	0.00	0.00
'Mohana_UY'	16.97	0.00	0.00	0.00	25.27	0.00	0.00	0.00

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Stream flow station	Q95				Q90			
	Virgin	Present	Future	Increased. Eff.	Virgin	Present	Future	Increased. Eff.
'Kachlabridge'	117.60	4.29	3.87	6.65	161.10	21.50	29.20	27.32
'Bhinga'	6.81	0.00	0.00	0.00	12.17	0.00	0.00	0.00
'Mathura'	13.25	0.00	0.00	0.00	20.03	0.00	0.00	0.00
'Dabri'	4.09	0.00	0.00	0.00	10.51	0.00	0.00	0.00
'Balrampur'	6.42	0.00	0.00	0.00	11.22	0.00	0.00	0.00
'Fatehgarh'	115.80	0.00	0.00	0.00	171.30	0.00	2.73	2.30
'Triveni'	250.80	213.80	209.60	220.20	329.70	282.10	278.70	289.90
'Neemsar'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Agra Poiyghat'	10.84	0.00	0.00	0.00	18.00	0.00	0.00	0.00
'Bewar'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Kakrahi'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Elginbridge'	356.60	72.46	66.30	131.90	444.70	152.60	137.10	213.40
'Ankinghat'	171.90	0.00	0.00	0.00	230.10	0.00	0.01	0.10
'Lucknow'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Ayodhya'	359.50	44.64	38.72	80.90	438.80	108.90	89.15	176.10
'Etawah'	6.78	0.00	0.00	0.00	13.68	0.00	0.00	0.00
'Basti'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Dheng Bridge'	10.82	0.05	0.05	0.24	16.39	0.20	0.20	0.79
'Regauli'	5.35	0.00	0.00	0.00	12.46	0.00	0.00	0.00
'Birdghat'	6.37	0.00	0.00	0.00	12.79	0.00	0.00	0.00
'Lalbegia Ghat'	11.63	6.04	6.04	8.86	17.82	9.50	9.50	11.26
'Udi'	102.50	0.00	0.00	0.00	156.90	0.00	0.00	0.00
'Bhind'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Jainagar'	0.93	0.00	0.00	0.00	2.13	0.00	0.00	0.00
'Kanpur'	176.30	0.00	0.00	0.00	233.90	0.00	0.00	0.00
'Dholpur'	119.80	0.00	0.00	0.00	170.40	0.00	0.00	0.00
'Saulighat'	1.76	0.00	0.00	0.00	2.80	0.00	0.00	0.00
'Auraiya'	207.70	0.00	0.00	0.00	285.20	0.00	0.00	0.00
'Manderial'	125.40	0.00	0.00	0.00	179.40	0.00	0.00	0.00
'Tonk'	0.74	0.00	0.00	0.00	8.52	0.00	0.00	0.00
'Jhanjharpur'	3.28	0.00	0.00	0.00	5.61	0.00	0.00	0.00
'Lalpur'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Benibad'	0.59	0.00	0.00	0.00	1.12	0.00	0.00	0.00
'Raibareli'	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
'Sikandarpur'	12.57	58.82	58.82	58.91	22.41	61.48	61.48	61.57
'Ekmighat'	0.01	0.00	0.00	0.00	0.07	0.00	0.00	0.00
'Turtipur'	352.90	0.00	0.00	0.00	511.80	0.00	0.00	0.00

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Stream flow station	Q95				Q90			
	Virgin	Present	Future	Increased. Eff.	Virgin	Present	Future	Increased. Eff.
'Kalpi'	192.60	0.00	0.00	0.00	270.00	0.00	0.00	0.00
'Baranwada'	2.37	0.00	0.00	0.00	12.84	0.00	0.00	0.00
'Seonda'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Hayaghat'	19.51	0.00	0.00	0.00	25.79	0.00	0.00	0.00
'Bhitaura'	183.70	0.00	0.00	0.00	242.00	0.00	0.00	0.00
'Dumariaghat'	272.00	72.70	68.16	98.73	359.50	117.40	117.80	154.50
'Hamirpur'	182.90	0.00	0.00	0.00	262.60	0.00	0.00	0.00
'dhengra ghat'	24.98	0.00	0.00	0.00	33.51	0.00	0.00	0.00
'Shahjina'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Pali'	105.60	0.00	0.00	0.00	144.20	0.00	0.00	0.00
'Lalganj'	272.40	55.62	49.83	81.53	360.50	101.70	94.78	135.20
'Mohana_LY'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Rudrapur'	0.00	0.00	0.00	0.00	622.00	0.00	0.00	0.00
'Tola Bala Rai '	852.20	0.00	0.00	0.00	1504.00	0.00	0.00	0.00
'Khatoli'	19.85	0.00	0.00	0.00	27.65	0.00	0.00	0.00
'Jaunpur'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Gangajal'	876.60	0.00	0.00	0.00	1522.0	0.00	0.00	3.49
'Bijalpur'	172.00	0.00	0.00	0.00	626.70	0.00	0.00	0.00
'Patna '	1512.0	43.47	44.19	89.41	2254.0	97.10	88.75	167.90
'Jalalpur'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Baltara'	236.00	94.01	79.38	111.20	296.00	124.40	119.30	146.70
'Narainpur'	160.80	0.00	0.00	0.00	626.90	0.00	0.00	0.00
'Labha'	54.29	0.00	0.00	0.00	61.72	0.00	0.00	0.00
'Birpur'	148.60	0.00	0.00	0.00	627.00	0.00	0.00	0.00
'Jamalpur'	328.00	0.00	0.00	0.00	669.00	0.00	0.00	0.00
'Barod'	38.91	0.00	0.00	0.00	55.25	0.00	0.00	0.00
'Gangbarar Jivpur'	323.00	0.00	0.00	0.00	668.40	0.00	0.00	0.00
'Mandawara'	42.03	0.02	0.02	0.11	57.94	0.12	0.12	0.27
'Hathidah Buzurg'	1480.0	22.74	24.64	66.57	2225.0	71.41	57.97	145.10
'Sripalpur'	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00
'Bigod'	5.11	0.00	0.00	0.00	9.08	0.00	0.00	0.00
'Mahespur'	1811.0	100.50	71.93	187.20	2574.0	187.70	174.70	305.50
'Rajapur'	127.00	0.00	0.00	0.00	237.40	0.00	0.00	0.00
'Rasalpur'	1485.0	6.87	7.73	44.31	2209.0	37.17	31.48	115.70
'Allahabad (Chatnag)'	507.10	0.00	0.00	0.00	708.40	0.00	0.00	0.00
'Bariarpur'	1568.0	2.78	2.11	25.93	2220.0	19.42	14.05	100.60
'Pratappur'	67.17	0.00	0.00	0.00	181.50	0.00	0.00	0.00

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Stream flow station	Q95				Q90			
	Virgin	Present	Future	Increased. Eff.	Virgin	Present	Future	Increased. Eff.
'Kamlakund'	1560.0	0.00	0.00	15.95	2215.0	10.55	7.40	85.05
'Gangania'	1572.0	1.62	1.14	24.96	2223.0	16.41	13.31	100.80
'Ramchandipur'	447.90	0.00	0.00	0.00	643.80	0.00	0.00	0.00
'Banda'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Katesar'	450.60	0.00	0.00	0.00	644.00	0.00	0.00	0.00
'Pachauli'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'HR Farakka'	1920.0	53.34	44.23	135.40	2719.0	133.70	118.20	251.40
'Ithara'	455.60	0.00	0.00	0.00	651.30	0.00	0.00	0.00
'Mirzapur'	456.10	0.00	0.00	0.00	646.10	0.00	0.00	0.00
'Englishbazar'	0.44	0.00	0.00	0.00	1.25	0.00	0.00	0.00
'Sangod'	14.66	0.00	0.00	0.00	20.02	0.00	0.00	0.00
'Chittorgarh'	1.16	0.00	0.00	0.00	1.88	0.00	0.00	0.00
'Garrauli'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Madla'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Chopan'	0.11	0.00	0.00	0.00	4.19	0.00	0.00	1.28
'Aklera'	10.44	0.00	0.00	0.00	14.59	0.00	0.00	0.00
'Salavad'	9.82	0.00	0.00	0.00	15.05	0.13	0.13	0.03
'A. B. Road X-ing'	7.82	0.00	0.00	0.00	12.73	0.00	0.00	0.00
'Islampur'	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00
'Gaisabad'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Berhampore'	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00
'Duddhi'	0.00	0.30	0.30	0.31	0.00	0.35	0.35	0.35
'Bazarsau'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Palasipara'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Basoda'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Garhakota'	0.03	0.00	0.00	0.00	0.12	0.00	0.00	0.00
'Katwa'	0.54	0.00	0.00	0.00	2.26	0.00	0.00	0.00
'Goverdheghat'	0.54	0.00	0.00	0.00	2.79	0.00	0.00	0.00
'Chapra'	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
'Sarangpur'	2.49	0.00	0.00	0.00	3.96	0.00	0.00	0.00
'Tal'	5.93	0.00	0.00	0.00	8.43	0.00	0.00	0.00
'Mahidpur'	8.04	0.00	0.00	0.00	10.13	0.00	0.00	0.00
'Hanskhali'	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
'Kalna (Ebb)'	0.27	0.00	0.00	0.00	1.94	0.00	0.00	0.00
'Kalna (Flow)'	0.27	0.00	0.00	0.00	1.94	0.00	0.00	0.00
'Ujjain'	3.80	0.00	0.00	0.00	5.38	0.00	0.00	0.00
'Dhareri'	1.43	0.00	0.00	0.00	2.38	0.00	0.00	0.00

Table 6: Q_{75} and Q_{50} flows for four scenarios for 146 stations in Ganga Basin

Stream flow station	Q_{75}				Q_{50}			
	Virgin	Present	Future	Increased. Eff.	Virgin	Present	Future	Increased. Eff.
'Tuini (P)'	5.90	5.91	5.91	5.91	22.49	22.80	22.80	22.80
'Tuini (T)'	23.74	23.98	23.98	23.98	57.59	57.55	57.55	57.55
'Yashwant Nagar'	3.00	3.05	3.05	3.05	18.12	17.68	17.68	17.68
'Naugaon'	2.09	2.09	2.09	2.09	7.91	7.91	7.91	7.91
'Badrinath'	1.23	1.21	1.21	1.21	8.30	8.28	8.28	8.28
'Uttarkashi'	44.80	44.86	44.90	44.86	158.60	157.40	157.00	157.90
'Haripur'	0.32	0.29	0.29	0.29	1.55	1.51	1.51	1.51
'Bausan'	9.22	9.20	9.20	9.20	34.01	34.16	34.16	34.16
'Chandrapuri'	21.08	21.06	21.06	21.06	46.08	46.03	46.03	46.03
'Poanta'	51.00	46.90	45.20	47.73	158.20	138.60	135.80	141.50
'Joshimath'	40.70	41.16	41.16	41.16	119.50	119.40	119.40	119.40
'Tehri (Zero Point)'	81.26	81.26	81.24	81.26	263.60	263.50	263.50	263.50
'Rudraprayag_Below Confluence'	152.00	147.50	147.40	151.50	347.50	341.80	341.80	344.50
'Karanprayag'	43.59	43.91	43.91	44.52	96.06	91.28	91.28	95.34
'Deoprayag A-1-Bhagirathi'	90.40	90.41	90.48	90.41	274.30	274.20	273.90	274.30
'Deoprayag Z-9-Ganga'	235.70	233.70	237.30	235.90	642.40	621.50	622.90	630.20
'Kalanaur'	50.35	0.00	0.00	0.00	154.50	18.71	16.39	19.47
'Rishikesh'	246.50	247.50	248.40	250.40	697.50	673.20	673.50	680.20
'Nandkeshri'	26.02	26.11	26.11	26.11	64.15	64.15	64.15	64.15
'Marora'	6.83	6.88	6.88	6.88	26.47	26.28	26.28	26.27
'Tawaghat'	33.42	33.39	33.39	33.39	70.15	70.16	70.16	70.16
'Karnal'	50.76	0.00	0.00	0.00	153.00	6.39	6.38	8.01
'Jauljibi'	68.47	63.02	63.02	66.63	135.20	128.40	128.40	132.70
'Ghat'	29.40	15.12	15.12	23.75	66.79	41.10	41.10	53.70
'Mawi'	50.73	0.00	0.00	0.00	152.50	4.27	4.27	6.95
'Galeta'	0.01	0.00	0.00	0.00	0.79	0.00	0.00	0.00
'Baghpat'	51.13	0.00	0.00	0.00	151.80	0.00	0.00	0.00
'Moradabad'	13.98	0.00	0.00	0.00	35.51	0.21	0.21	0.28
‘Garmukhteswar	271.10	134.60	165.20	137.50	735.50	427.80	494.50	463.50

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Stream flow station	Q_{75}				Q_{50}			
	Virgin	**Present**	**Future**	**Increased. Eff.**	**Virgin**	**Present**	**Future**	**Increased. Eff.**
'Gangan'	0.21	0.00	0.00	0.00	2.15	0.00	0.00	0.00
'Rampur'	5.48	0.00	0.00	0.00	22.73	0.00	0.00	6.22
'Delhi Rly. Bridge'	53.25	0.00	0.00	0.00	150.80	0.00	0.00	0.00
'Paliakalan'	144.20	64.54	38.44	95.46	305.30	159.30	141.20	184.30
'Bareilly'	33.78	0.00	0.00	0.00	90.19	0.69	0.69	3.42
'Mohana_UY'	52.72	0.00	0.00	0.00	147.10	0.00	0.00	0.00
'Kachlabridge'	272.20	103.50	120.20	113.20	679.60	413.50	479.20	431.90
'Bhinga'	23.39	0.00	0.00	0.52	67.68	12.17	12.17	15.17
'Mathura'	48.52	0.00	0.00	0.00	139.20	0.00	0.00	0.00
'Dabri'	33.41	0.00	0.00	0.00	94.86	0.00	0.00	0.00
'Balrampur'	23.15	0.00	0.00	0.00	68.34	3.73	3.73	7.22
'Fatehgarh'	287.60	42.11	69.57	56.47	703.60	303.00	411.50	345.40
'Triveni'	607.10	498.70	494.20	522.30	1230.0	1046.0	1043.0	1051.00
'Neemsar'	0.00	0.00	0.00	0.00	0.61	0.00	0.00	0.00
'Agra Poiyghat'	46.22	0.00	0.00	0.00	133.70	0.00	0.00	0.00
'Bewar'	0.04	0.00	0.00	0.00	13.85	0.00	0.00	0.00
'Kakrahi'	0.06	0.00	0.00	0.00	2.23	0.00	0.00	0.00
'Elginbridge'	732.60	387.00	362.90	445.30	1459.0	950.40	943.10	1025.00
'Ankinghat'	387.60	17.86	49.21	31.97	942.00	252.80	377.50	287.70
'Lucknow'	0.00	0.00	0.00	0.00	1.37	0.00	0.00	0.00
'Ayodhya'	732.50	364.10	321.40	419.30	1480.0	922.90	904.00	1005.00
'Etawah'	48.43	0.00	0.00	0.00	149.40	0.00	0.00	0.00
'Basti'	0.18	0.00	0.00	0.00	4.68	0.00	0.00	0.00
'Dheng Bridge'	26.90	0.95	0.95	1.59	90.44	6.90	6.90	7.64
'Regauli'	32.23	0.00	0.00	0.00	108.20	0.00	0.00	0.00
'Birdghat'	35.35	0.00	0.00	0.00	115.20	0.00	0.00	0.00
'Lalbegia Ghat'	44.76	12.76	12.76	13.12	104.50	17.27	17.27	17.54
'Udi'	367.00	0.00	0.00	0.00	1019.0	0.00	0.00	0.00
'Bhind'	0.13	0.00	0.00	0.00	14.75	0.00	0.00	0.00
'Jainagar'	7.27	0.00	0.00	0.00	30.54	5.77	0.00	6.06
'Kanpur'	408.70	1.27	26.31	13.02	960.40	205.60	345.20	224.60
'Dholpur'	380.00	0.00	0.00	0.00	1043.0	0.00	0.00	0.00
'Saulighat'	7.80	0.00	0.00	0.00	37.58	0.00	0.00	0.00
'Auraiya'	523.40	0.00	0.00	0.00	1243.0	0.00	0.00	0.00

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Stream flow station	Q_{75}				Q_{50}			
	Virgin	Present	Future	Increased. Eff.	Virgin	Present	Future	Increased. Eff.
'Manderial'	384.70	0.00	0.00	0.00	1042.0	0.00	0.00	0.00
'Tonk'	36.22	0.00	0.00	0.00	130.40	0.01	0.01	0.02
'Jhanjharpur'	14.23	0.00	0.00	0.00	56.51	1.62	0.00	2.77
'Lalpur'	0.21	0.00	0.00	0.00	12.59	0.00	0.00	0.00
'Benibad'	3.41	0.00	0.00	0.00	16.72	0.00	0.00	0.00
'Raibareli'	1.86	0.00	0.00	0.00	16.63	0.00	0.00	0.00
'Sikandarpur'	57.46	69.74	69.74	70.51	139.90	84.90	84.90	85.94
'Ekmighat'	0.44	0.00	0.00	0.00	3.52	0.00	0.00	0.00
'Turtipur'	911.70	142.50	132.10	249.80	1764.0	1037.00	1050.00	1119.00
'Kalpi'	523.90	0.00	0.00	0.00	1263.0	0.00	0.00	0.00
'Baranwada'	50.89	0.00	0.00	0.00	176.50	0.00	0.00	0.00
'Seonda'	1.51	0.00	0.00	0.00	37.52	0.00	0.00	0.00
'Hayaghat'	47.81	0.00	0.00	0.00	166.30	0.00	0.00	0.20
'Bhitaura'	428.10	0.16	22.13	6.93	966.00	186.00	332.50	222.50
'Dumariaghat'	643.50	291.80	284.30	347.80	1231.0	834.90	841.50	886.40
'Hamirpur'	519.90	0.00	0.00	0.00	1289.0	0.00	0.00	0.00
'dhengra ghat'	68.64	0.00	0.00	0.00	256.70	2.02	0.52	2.99
'Shahjina'	0.74	0.00	0.00	0.00	78.37	0.00	0.00	0.00
'Pali'	284.10	0.00	0.00	0.00	720.00	0.00	0.00	0.00
'Lalganj'	643.20	251.60	248.20	317.30	1230.0	792.30	776.30	856.10
'Mohana_LY'	0.70	0.00	0.00	0.00	74.42	0.00	0.00	0.00
'Rudrapur'	1177.0	0.00	0.00	0.00	2492.0	0.00	0.00	0.00
'Tola Bala Rai '	2352.0	27.41	44.01	206.20	4229.0	1146.0	1244.0	1207.00
'Khatoli'	53.16	0.00	0.00	0.00	137.60	1.67	1.67	1.78
'Jaunpur'	4.11	0.00	0.00	0.00	45.12	0.00	0.00	0.00
'Gangajal'	2475.0	54.45	72.54	212.40	4612.0	1168.0	1277.0	1256.00
'Bijalpur'	1179.0	0.00	0.00	0.00	2543.0	0.00	0.00	0.00
'Patna '	3279.0	524.40	481.10	725.40	5704.0	1829.0	1938.0	1985.00
'Jalalpur'	1.62	0.00	0.00	0.00	30.30	0.00	0.00	0.00
'Baltara'	466.00	244.10	215.70	260.50	1129.0	617.60	596.70	638.00
'Narainpur'	1171.0	0.00	0.00	0.00	2481.0	0.00	0.00	0.00
'Labha'	127.50	0.00	0.00	0.00	404.00	1.21	0.92	3.69
'Birpur'	1133.0	0.00	0.00	0.00	2457.0	0.00	0.00	0.00

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Stream flow station	**Q_{75}**				**Q_{50}**			
	Virgin	**Present**	**Future**	**Increased. Eff.**	**Virgin**	**Present**	**Future**	**Increased. Eff.**
'Jamalpur'	1175.0	0.00	0.00	0.00	2446.0	0.00	1.10	0.00
'Barod'	100.50	0.00	0.00	0.00	259.70	0.00	0.00	0.00
'Gangbarar Jivpur'	1171.0	0.00	0.00	0.00	2457.0	0.00	0.76	0.00
'Mandawara'	105.90	0.89	0.89	1.35	282.80	4.65	4.65	5.90
'Hathidah Buzurg'	3292.0	476.00	436.80	707.90	5673.0	1787.0	1898.0	1951.00
'Sripalpur'	1.22	0.00	0.00	0.00	11.37	0.00	0.00	0.00
'Bigod'	22.02	0.00	0.00	0.00	60.60	0.00	0.00	0.00
'Mahespur'	3863.0	654.30	592.70	946.10	6906.0	2138.0	2152.0	2399.00
'Rajapur'	482.20	0.00	0.00	0.00	1564.00	0.00	0.00	0.00
'Rasalpur'	3328.0	454.70	406.80	656.60	5777.0	1820.0	1848.0	1909.00
'Allahabad (Chatnag)'	1106.0	0.00	0.00	0.00	2291.0	142.80	330.20	206.10
'Bariarpur'	3355.0	418.10	371.80	611.90	5873.0	1740.0	1805.0	1967.00
'Pratappur'	429.50	0.00	0.00	0.00	1558.0	0.00	0.00	0.00
'Kamlakund'	3347.0	396.60	387.60	594.90	5876.0	1716.0	1775.0	1932.00
'Gangania'	3358.0	414.10	367.90	616.20	5857.0	1740.0	1809.0	1966.00
'Ramchandipur'	1118.0	0.00	0.00	0.00	2370.0	2.30	11.30	3.19
'Banda'	0.07	0.00	0.00	0.00	61.63	0.00	0.00	0.00
'Katesar'	1122.0	0.00	0.00	0.00	2370.0	0.01	0.74	0.04
'Pachauli'	0.57	0.00	0.00	0.00	11.35	0.00	0.00	0.00
'HR Farakka'	3960.0	608.20	545.20	892.40	7360.0	2065.0	2104.0	2347.00
'Ithara'	1143.0	0.00	0.00	0.00	2370.0	40.90	211.10	139.70
'Mirzapur'	1129.0	0.00	0.00	0.00	2370.0	21.25	201.20	132.80
'Englishbazar'	6.91	0.00	0.00	0.00	40.62	0.00	0.00	0.00
'Sangod'	37.95	0.00	0.00	0.00	94.99	0.00	0.00	0.00
'Chittorgarh'	3.64	0.00	0.00	0.00	9.22	0.00	0.00	0.00
'Garrauli'	0.22	0.00	0.00	0.00	11.27	0.00	0.00	0.00
'Madla'	1.08	0.00	0.00	0.00	57.47	0.00	0.22	0.00
'Chopan'	52.18	114.80	61.73	219.90	296.60	259.90	249.50	270.60
'Aklera'	27.19	0.00	0.00	0.00	64.21	0.00	0.00	0.00
'Salavad'	29.85	3.87	3.87	3.19	75.42	16.88	16.88	14.85
'A. B. Road X-ing'	23.30	0.00	0.00	0.00	57.40	0.39	0.39	1.07
'Islampur'	0.05	0.00	0.00	0.00	0.56	0.00	0.00	0.00

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Stream flow station	Q_{75}				Q_{50}			
	Virgin	Present	Future	Increased. Eff.	Virgin	Present	Future	Increased. Eff.
'Gaisabad'	0.07	0.00	0.00	0.00	17.90	0.33	0.33	0.33
'Berhampore'	2.90	0.00	0.00	0.00	19.13	0.00	0.00	0.00
'Duddhi'	1.08	0.51	0.51	0.52	30.18	1.06	1.06	1.33
'Bazarsau'	0.01	0.00	0.00	0.00	0.38	0.40	0.40	0.52
'Palasipara'	0.42	0.00	0.00	0.00	5.32	0.00	0.00	0.00
'Basoda'	1.37	0.00	0.00	0.00	27.16	0.00	0.00	0.00
'Garhakota'	0.66	0.00	0.00	0.00	8.07	0.00	0.00	0.00
'Katwa'	14.60	0.00	0.00	0.00	98.63	0.00	0.00	0.34
'Goverdheghat'	19.97	0.00	0.00	0.00	93.24	3.84	3.84	7.69
'Chapra'	0.46	0.00	0.00	0.00	6.77	0.00	0.00	0.00
'Sarangpur'	8.40	0.09	0.09	0.17	24.93	1.60	1.60	1.93
'Tal'	15.15	0.32	0.32	0.61	37.77	4.73	4.73	5.67
'Mahidpur'	18.31	0.01	0.01	0.07	45.28	3.35	3.35	3.72
'Hanskhali'	0.09	0.00	0.00	0.00	1.10	0.00	0.00	0.00
'Kalna (Ebb)'	18.70	0.00	0.00	0.00	123.40	0.00	0.00	0.00
'Kalna (Flow)'	18.70	0.00	0.00	0.00	123.40	0.00	0.00	0.00
'Ujjain'	9.60	0.00	0.00	0.00	20.85	0.00	0.00	0.00
'Dhareri'	4.98	0.00	0.00	0.00	13.20	0.00	0.00	0.00

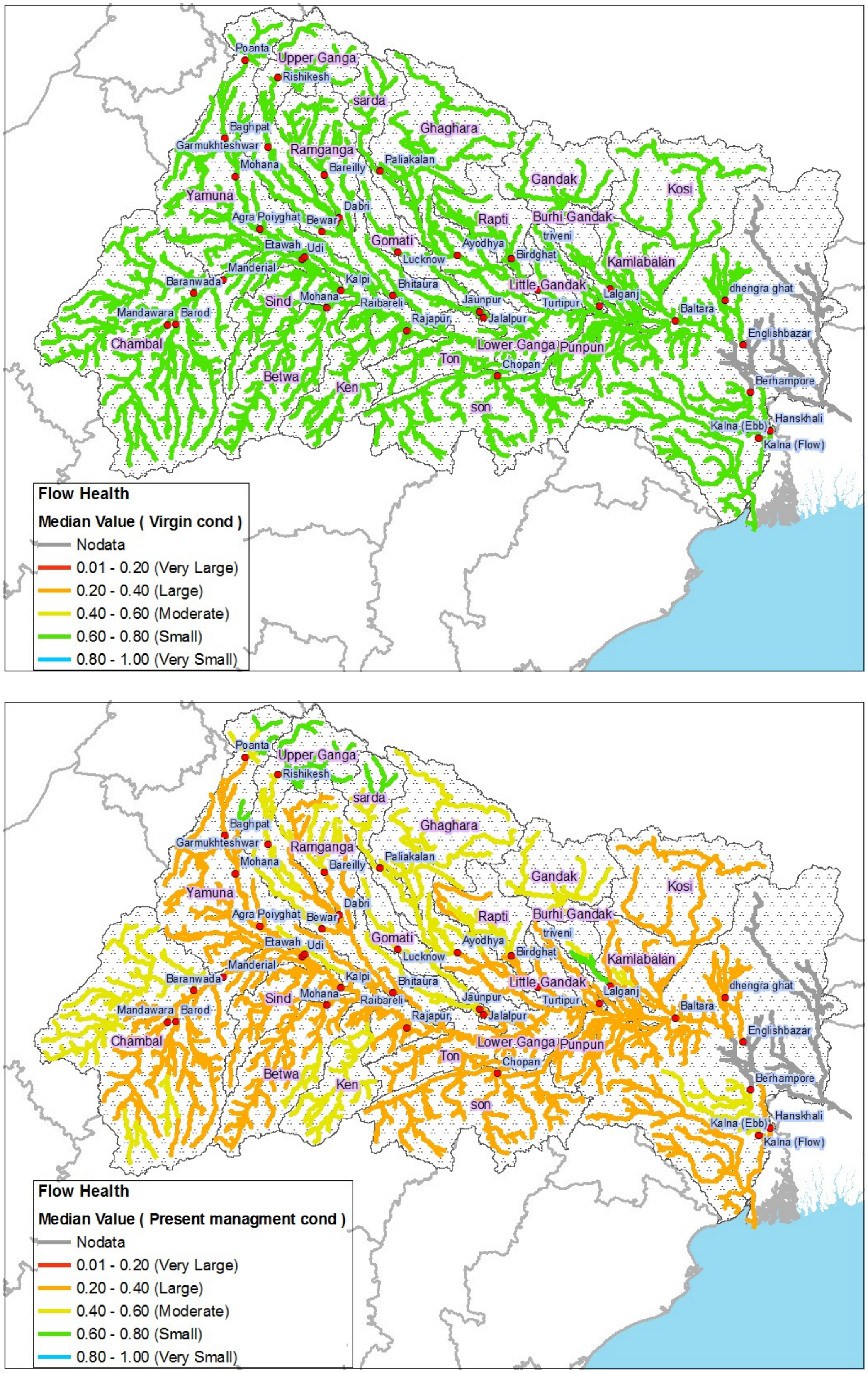

Figure 5: **Median flow Health scores based on 29 years of simulation a) Virgin state and b) current state of management**

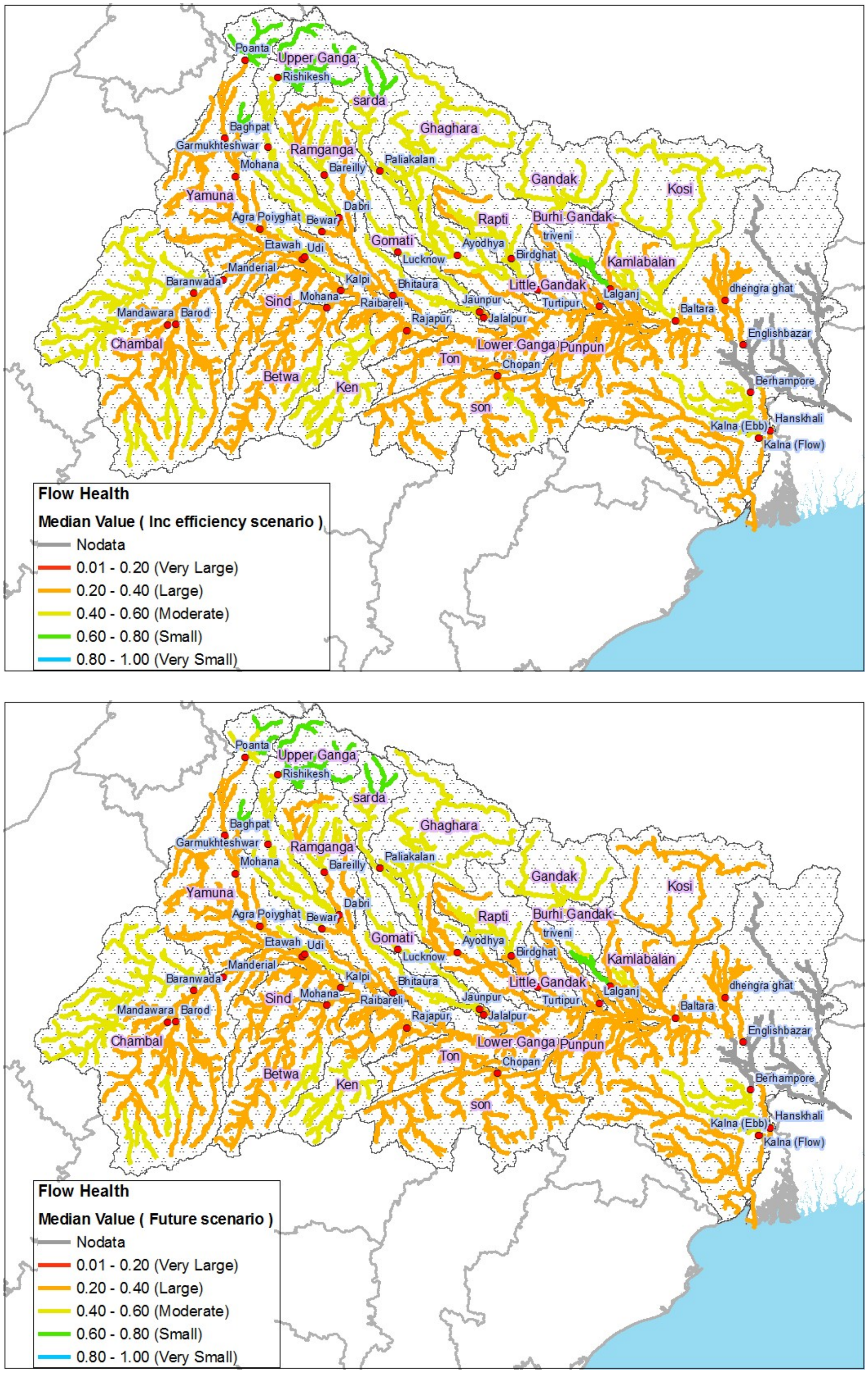

Figure 6 : **Median flow Health scores based on 29 years of simulation a) Increase irrigation efficiency scenario and b) Implementation of future projects**

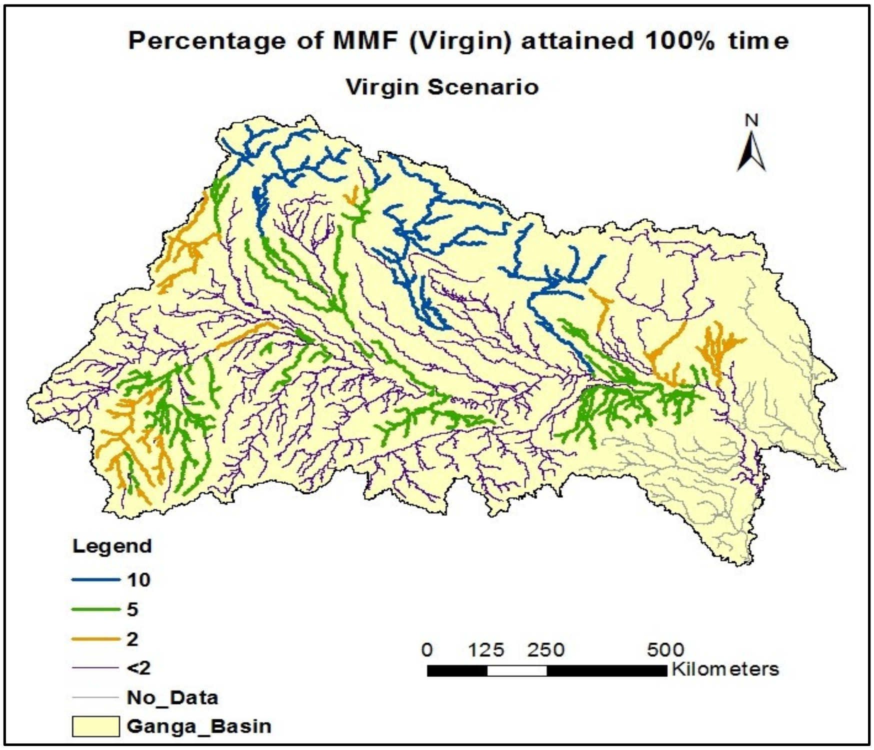

Figure 7: Percentages of MMF attained 100% time on monthly basis-Virgin Scenario

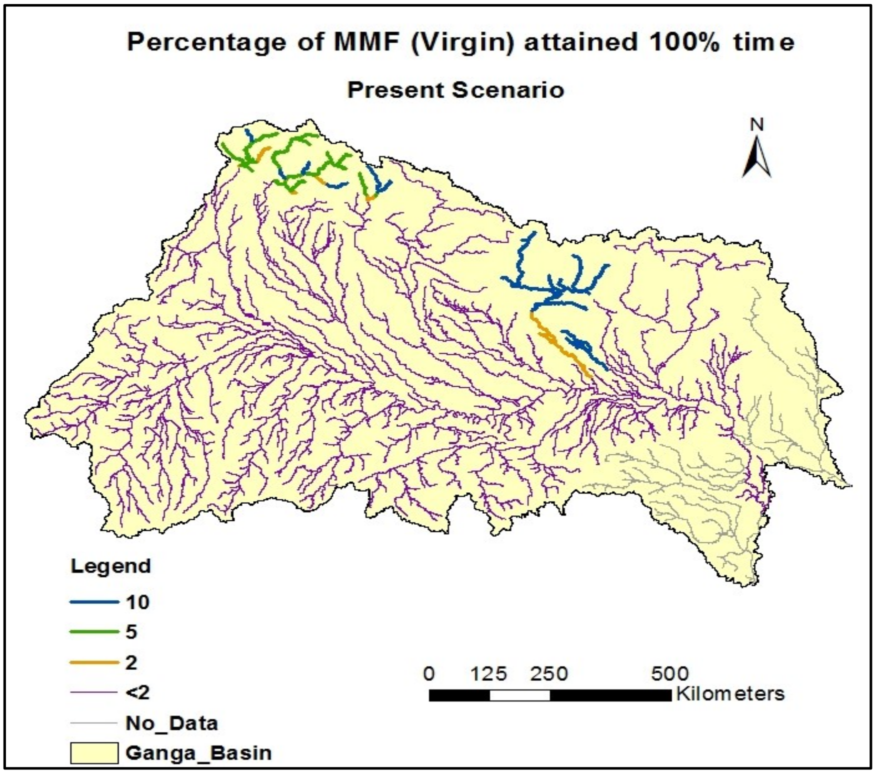

Figure 8: Percentages of MMF attained 100% time on monthly basis-Present Scenario

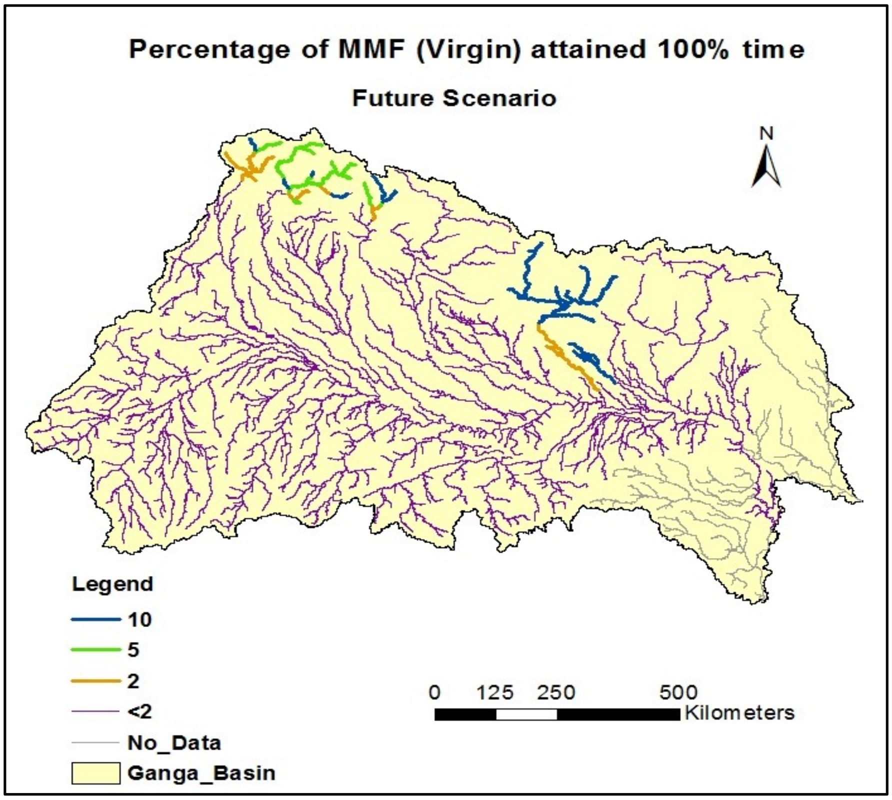

Figure 9: Percentages of MMF attained 100% time on monthly basis-Future Scenario

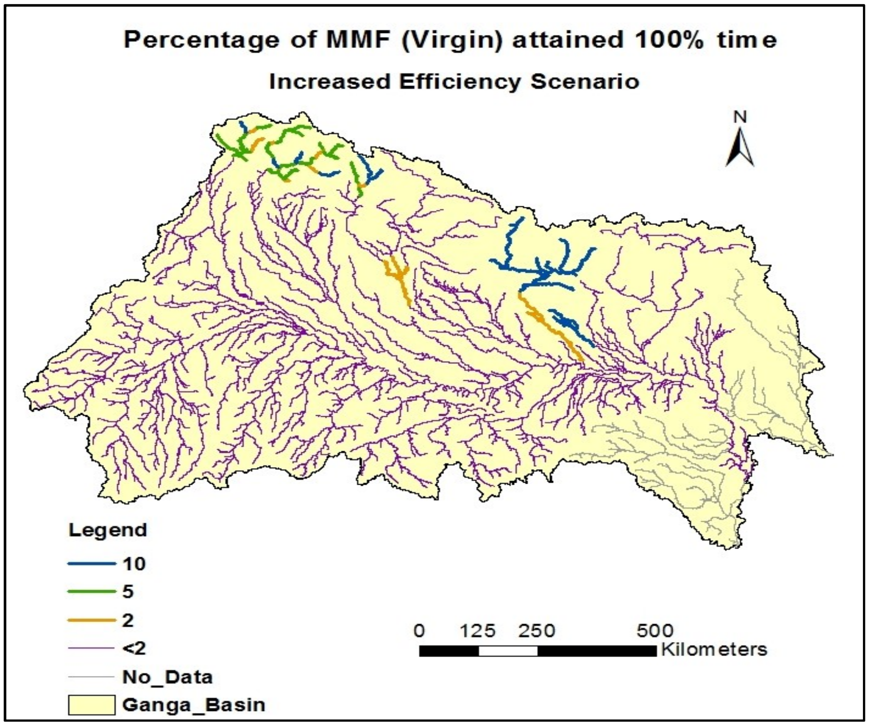

Figure 10: Percentages of MMF attained 100% time on monthly basis-Increased Irrigation efficiency Scenario

7. Recommendations

1. Based on the hydrologic flow health analysis, the health of the river in terms of low flows at the main stem of the river is mostly moderate to good. Hence, the problems in terms of water quality during the low flows are not due to hydrologic conditions, but are due to overloading of pollutants beyond the assimilation capacity of the river. Therefore the water quality problems in Ganga cannot be addressed by improving the low flow conditions only beyond the current levels. The water quality problems should be addressed by reducing the pollution loading.
2. Low flows (for example Q_{90}) are seen to be less violated in Upper Ganga Basin up to Rishikesh and in Upper Yamuna Basin up to Poanta. Middle to lower Ganga region ranging from Garhmukteshwar to upstream of Farakka Barrage shows considerable variations in Q_{90} compared with Virgin conditions. Lower Chambal and Lower Yamuna region also show similar trend but with comparatively smaller differences. These reduced low flows show the altered river hydrology and so the river health. More detailed investigation of these reduces low flows will provide a way forward to find its causes and solutions. Flow Duration Curves testimony the above mentioned observations.
3. The hydrologic flow health during high flows is affected significantly and is poor in few stretches across the basin, especially from Gomukteshwar to Fategarh in Upper Ganga and from Mohana to Etawah in Middle Yamuna. This can have an effect on the in stream ecology (flora and fauna) and geomorphology. Therefore, it is recommended that the present diversions upstream of these stretches may be reduced to the extent possible in order to improve the river health.
4. The hydrologic flow health during high flows is moderate at present in several stretches across the basin. For e.g. the flow health is only moderate in the stretch between Bhitaura to Allahabad on Ganga. Also the flow health in entire Chambal, Sind Gomati and Gandak basins is moderate. Therefore, we recommend no more additional diversions of water in the upstream stretches in order to maintain the flow health at the moderate level. For example, further diversions of water in Ganga basin upto Allahabad could impair the river health.

5. The hydrologic flow health in the rest of the stretches is good especially upstream of Rishikesh, Kosi and Sone basins. However, any further diversions in these basins could have a cascading effect on the main steam of Ganga at Allahabad and downstream. Hence, we recommend thorough scientific investigations to be carried out before permitting any further development in these basins.
6. Mean Monthly flows analysis suggested that considerable variation in flow regime has occurred from virgin to present situation. This study also suggests that, hydrological indices suggested and used worldwide as minimum flow requirements needs to be tested thoroughly and cannot be simply accepted as thumb rules for Ganga River basin. Just like '% of MAF' test '% of MMF' test also fails even under Virgin conditions. In this situation, instead of suggesting unique percentage of MMF for whole basin, distributed suitable percentages can be suggested for different sub-basins.
7. While finalizing the habitat based E-flow requirement for different stretches, we propose that one may check the hydrological flow health along different stretches and see if it is at least 0.6 or higher.
    a. Even with the recommended level of habitat based E-flow, if the hydrological flow health score falls below 0.6, then we need to make interventions on the diversions upstream to augment this flow further to achieve a hydrological flow health target of at least 0.6. This higher flow to maintain the hydrological flow health could be the recommended E-flow. Prescription of this higher flow will not be detrimental to the ecosystem or the geomorphology.
    b. On the other hand, if the recommended level of habitat based E-flow itself achieves a hydrological flow health score of 0.6 or higher, then the same flows could be used as the recommended E-flow.

Note: The hydrologic modeling and flow health analysis carried out here are indicative of only the overall flow conditions in stretches. However, there could be some localized conditions such as immediately downstream of the run of the river projects where the flow conditions may not be adequate, however further downstream, it may become normal due to return flows of water used in the power production. Longitudinal and lateral connective of the river along such local stretches should be thoroughly investigated even though the overall flow health in these stretches may appear good.

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Environmental Flows

State-of-the-Art with special reference to Rivers in the Ganga River Basin

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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: Environment Management Plan (GRB EMP) 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.

Estimates on Environmental Flows or simply E-Flows are a critical input in preparation of the GRBMP. Not much work has been done on E-Flows in Indian rivers, particularly the rivers in the Ganga Basin. Also, E-Flows assessment is both a social and a scientific process requiring expert knowledge of various fields including, but not limited to hydrology, hydraulics, geomorphology, ecology and biodiversity, socio-cultural, livelihood, and water quality and pollution. Keeping this in view, IIT Consortia has constituted an E-Flows Group with experts within and outside the IIT system.

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 GRBMP and Indexing of Reports is presented on the inside cover page.

Many of the E-Flows group members participated in a two year long study on estimation of E-Flows in selected stretch of the river Ganga sponsored by WWF – India as part of Living Ganga Project. This study provided opportunity for experts within and outside India to exchange knowledge and experience on the subject and help in selection and adoption of an appropriate methodology. This report heavily draws from the knowledge gained from such pioneering multi-institutional and interdisciplinary study. Many people contributed to the preparation of this report directly or indirectly. A list of persons who have contributed directly and names of those who have taken lead in preparing this report is given on the reverse side.

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Contents

1. Introduction

The modern governance of river basins has shifted towards "Integrated River Basin Management (IRBM)"—an approach that looks at both water and land management to ensure that river systems can be used and developed in a sustainable manner. A critical part of this approach is the assessment and maintenance of Environmental Flows – 'sufficient water to sustain the integrity and functioning of aquatic ecosystems and the associated socio-economic and cultural functions' (UN, 2005).

It is becoming increasingly evident that on regional and global scales, freshwater biodiversity is more severely endangered than that of terrestrial or marine systems (O'Keeffe and Le Quesne, 2009). Freshwater systems are home to 40% of all fish species in less than 0.01% of the world's total surface water, and when water-associated amphibians, reptiles and mammals are added to the fish totals, they together account for as much as one third of global vertebrate biodiversity (O'Keeffe and Le Quesne, 2009). Even at a conservative estimate, there have been global population declines of freshwater vertebrates averaging 55% between 1970 and 2000 (O'Keeffe and Le Quesne, 2009).

The best recent examples of good legislation about consideration of Environmental Flows are from Australia and South Africa. In South Africa, Environmental Flows (called "ecological reserve") have the priority over other water users (Smakhtin, 2004).

Flows – the main driver of biodiversity in rivers

Most rivers around the world are highly variable and unpredictable; animals and plants species that live in them have adapted to sudden extremes such as floods and droughts. As a result, most river ecologists agree that the communities of animals and plants found in riverine ecosystems are largely controlled by physical rather than biological processes (O'Keeffe and Le Quesne, 2009). Thus to maintain freshwater biodiversity, it is necessary to manage the physical and physicochemical processes in rivers. These processes mainly influence water quality, sediment dynamics, and, of course, flow. Flow is the main driver of biodiversity in rivers – it creates the aquatic habitats, brings the food down from upstream, covers the floodplain with water during high flows, and flushes the sediment and poor quality water through the system (O'Keeffe and Le Quesne, 2009).

A recent World Bank document (World Bank, 2008) states that river scientists refer to the flow regime in freshwater systems as a "*Master Variable*" due to the strong influence it has on the other key environmental factors (water chemistry, physical habitat, biological composition, and interactions). During recent decades, scientists have amassed considerable evidence that a river's flow regime – its variable pattern of high and low flows throughout the year, as well as variation across many years – exerts great influence on river ecosystems. Each component of a flow regime – ranging from low flows to floods – plays an important role in shaping a river ecosystem.

2. Environmental Flows – The Concept and its Rationale

Recognition of the escalating hydrological alterations of rivers on a global scale and resultant environmental degradation, has led to the establishment of the science of Environmental Flows (E-Flows) Assessment, whereby the quantity and quality of water required for ecosystem conservation and resources protection are determined. Several attempts have been made to define E-Flows in rivers.

The 3rd World Water Forum held at Kyoto in 2003 defined E-Flows as the provision of water within rivers and ground water systems to maintain downstream ecosystems and their benefits, where the river and underground system is subject to competitive uses and flow regulations. The E-Flows are thus considered as an amount of water that is kept flowing down a river in order to maintain the river in a desired environmental condition. All of the elements of a natural flow regime, including floods and droughts, are important in controlling the characteristics and natural communities in a river.

The IUCN (2003) defines "E-Flows as the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated". The IUCN makes a clear conceptual distinction between the water needed to maintain the ecosystem in near pristine condition, and that which is eventually allocated to it, following a process of a holistic assessment for E-Flows.

Section 5.2.5 of National Environment Policy (2006) of India on 'Freshwater Resources' calls for promotion of 'integrated approaches to management of river basins by the concerned river authorities, considering upstream and downstream inflows and withdrawals by season, interface between land and water, pollution loads and natural regeneration capacities, to ensure maintenance of adequate flows, in particular for maintenance of in-stream ecological values, and adherence to water quality standards throughout their course in all seasons'. This typically sets attributes for defining E-Flows.

Brisbane Declaration (2007) defines E-Flows as the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems.

After critical study of various definitions of E-Flows, the consortia of 7 IITs for preparation of Ganga River Basin Management Plan (GRBMP) concludes that environmental flows refer to a regime of flows that mimics the natural pattern of a river's flow, so that the river can perform its natural functions such as transporting water and solids from its catchment, formation of land, self-purification and sustenance of its myriad systems along with sustaining cultural, spiritual and livelihood activities of the people or associated population. Considering this following definition for E Flows is considered most appropriate and is being adopted.

> *"Environmental Flows are a regime of flow in a river or stream that describes the temporal and spatial variation in quantity and quality of water required for freshwater as well as estuarine systems to perform their natural ecological functions (including sediment transport) and support the spiritual, cultural and livelihood activities that depend on these ecosystems"*

3. Overview of E-Flows Estimation Methods

From global experience, the assessment and establishment of E-Flows has significantly contributed to the management of natural resources in a judicious manner. O'Keeffe and Le Quesne (2009) have explained this phenomenon in detail. Some salient points are reproduced as follows for ready reference.

1. The characteristics and ecosystems of rivers are controlled in a very significant way by the flows. A good E-Flows regime mimics all flow variations that are needed to keep the river and all its aspects functioning in a desired condition.
2. E-Flows assessment is both a social and a scientific process. There is no one correct E-Flows regime for rivers – the answer will depend on what people want from a river.
3. E-Flows assessment is based on the assumption that there is some 'spare' water in rivers that can be used without unacceptably impacting on the ecosystem and societal services that the river provides.
4. E-Flows are not just about establishing a 'minimum' flow level for rivers; it actually considers all the elements of a natural flow regime, including floods, diurnal variations, and droughts, as they are important with respect to silt transport and in controlling the characteristics and natural communities of a river.
5. E-Flows don't always require an increase from present flows. In some cases, e.g. where low season flows have been artificially increased by inter-basin transfers or releases from dams for hydropower, the E-Flows recommendations may be for lower flows.
6. E-Flows assessments are also very useful to know the environmental requirements before any development plans are made, so that these flows can be factored into the planning process at an early stage.

In order to reach a consensus about E-Flows, people need to have trade-off between river's natural functions and river's uses such as (i) growing more crops using its water, (ii) generate electricity, (iii) supply towns with water for domestic and municipal purposes, (iv) national/cultural heritage, e.g. river Ganga in India or river Thames in England. This guides in deciding the desired state of the river. In most cases people want to make use of the water and other resources of the river, so they do not want to keep it entirely natural. Also, in most cases (all cases hopefully) they do not want to turn it into a dry river bed or a drain for wastes. Thus the decision is to choose the state of the river somewhere between natural and completely ruined. This is the role of E-Flows assessment. Further, it is also aimed at keeping at least some of the natural flow patterns along the whole length of a river, so that the people, animals and plants downstream can continue to survive and use the river's resources. This is essential for sustenance of the river itself as E-Flows are envisaged to sustain various river functions.

Acreman and Dunbar (2004) state that there is no simple figure which can be considered as E-Flows requirement for a river. It is actually related to number of factors: (i) size of the river, (ii) river's natural state, type or perceived sensitivity, and (iii) a combination of desired state of river and in practice, the uses to which it is put. They have classified the E-Flows settings into two distinct categories, where one of them is called the 'Objective Based Flow-Setting' and the other one is 'Scenario Based Flow-Setting'. Both these categories have merits and limitations. The answer to select the appropriate methodology lies in the requirements and aspirations of the people from their rivers. O Keeffe and Le Quesne (2009) also essentially advocate the same concept.

Objective Based Flow-Setting: In certain cases, people intend to have specific pre-defined ecological, economical and social objectives for the river. In such situations objective based flow setting can be adopted. For applying such an approach, the experts have to build a consensus on desired state of river. An example of such an application is from central valley of Senegal River basin, where the objective is to spare 50,000 hectares of floodplain for flood recession agriculture. As approximately, half the flooded area is cultivated, this equates to inundation of 1,00,000 hectares, which require around 7,500 MCM of water to be released from Manantali dam (Acreman, 2003). WWF-India's study on Assessment of E-Flows in the Upper Stretch of river Ganga also considered objective based flow-setting wherein the geomorphologic, ecological, socio-economic and cultural objectives of the river were first established by the expert groups and then river flow regime is established using hydraulic and hydrologic modeling to meet these objectives (WWF-India, 2011).

Scenario Based Flow-Setting: This is basically an alternative to the above one, where the water managers are able to understand and make decision on water allocations and scenarios for trade offs in managing and balancing the water demands/requirements. For instance – Under the Lesotho Highland Water Project, various scenarios of E-Flows releases from dams were considered. For each scenario, the impacts on the downstream river ecosystems and dependent livelihoods were determined (King *et al*., 2003). These scenarios permitted the Lesotho government to assess the trade-offs presented by different E-Flows options.

Review of various methodologies developed across the world for assessment of E-Flows

As stated earlier, E-Flows are required for (i) maintaining river regimes, (ii) self purification, (iii) maintaining aquatic biodiversity, (iv) groundwater recharge, (v) supporting livelihoods, and (vi) allowing the river to play its role in cultural and spiritual lives of people. In all contexts, determining E-Flows should be an adaptive process, in which flows may be successively modified in the light of increased knowledge/information, changing priorities, and changes in infrastructure over time.

E-Flows assessment is thus a combination of scientific and social aspects. The scientists can do the best assessment of flow needs, but it won't be implemented unless people know why the flows should be left in the river, and think that it is important to do so. The E-Flows assessment was developed as an eco-hydrological process in the 1970's and 80's. There was a gradual realization in the 1980's that there needed to be a social component to the process – that the stakeholders needed to have a say in the uses and consequent condition of the resource (O'Keeffe, Le Quesne, 2009). But, it wasn't until the 1990's that there has been a full realization that E-Flows assessment is social process with an eco-hydrological process as an essential ingredient.

As the concept of E-Flows has evolved, there has been significant development of approaches to the assessment of E-Flows. There is no one correct E-Flows regime for rivers – the answer will depend on what people want from a river and not just about establishing a 'minimum' flow level for rivers. E-Flows assessments are not just useful on rivers for which the water resources have been developed – it's very useful to know the environmental requirements before any development infrastructure plans are made, so that these flows can be factored into the planning process at an early stage.

Assessment of E-Flows can be referred as to how much water can be withdrawn from the river without disturbing essential flow requirements of the river to an extent that, the specified and valued features of the river and its ecosystem are maintained and not depleted to significant level.

A global review of E-Flows Assessment methodologies by Tharme (2003) reveals that there are more than 200 methodologies, some are very quick modeling or extrapolation methods, requiring no or minimal extra work; others require years of fieldwork and specialists from a number of disciplines. Various E-Flows assessment methodologies can be broadly classified into four categories.

Hydrology-based

Hydrology based methods are confined to the use of existing, or modeled flow data, on the assumption that maintaining some percentage of the natural flow will provide for the environmental issues of interest.

Hydrology based methodologies constituted the highest proportion of the overall number of methodologies recorded with a total of over 60 different hydrological indices or techniques applied till date. Many of such methodologies have become obsolete over time, due to the fact that they are monotonous and there were no provision to integrate other associated aspects, for instance – the ecology, biodiversity, etc.

Hydraulic rating

These methods measure changes in the hydraulic habitat available (wetted-perimeter, depth, velocity, etc.) based on a single cross-section of the river that measures the shape of the channel. This cross-section is used as a surrogate for biological habitat, and allows for a rough assessment of changes to that habitat with changing flows.

Of the 23 hydraulic rating methodologies reported representing roughly 11% of the global total, most of them were developed to recommend in-stream flows for economically important salmonid fisheries in the United States during 1960s and 70s. These methodologies have been superseded by sophisticated habitat simulation and holistic methodologies in the recent years.

Habitat simulation

These are a development of the hydraulic rating methodologies. With these methods, multiple rated cross-sections are used in a hydraulic model to simulate the conditions in a river reach, again based on wetted perimeter, and average depth and velocity of flow. Habitat simulation methodologies ranked second (28%) only to hydrological methodologies at a global scale. There are about 60 such methodologies recorded throughout the world. These methodologies are more popular in the United States.

Holistic methodologies

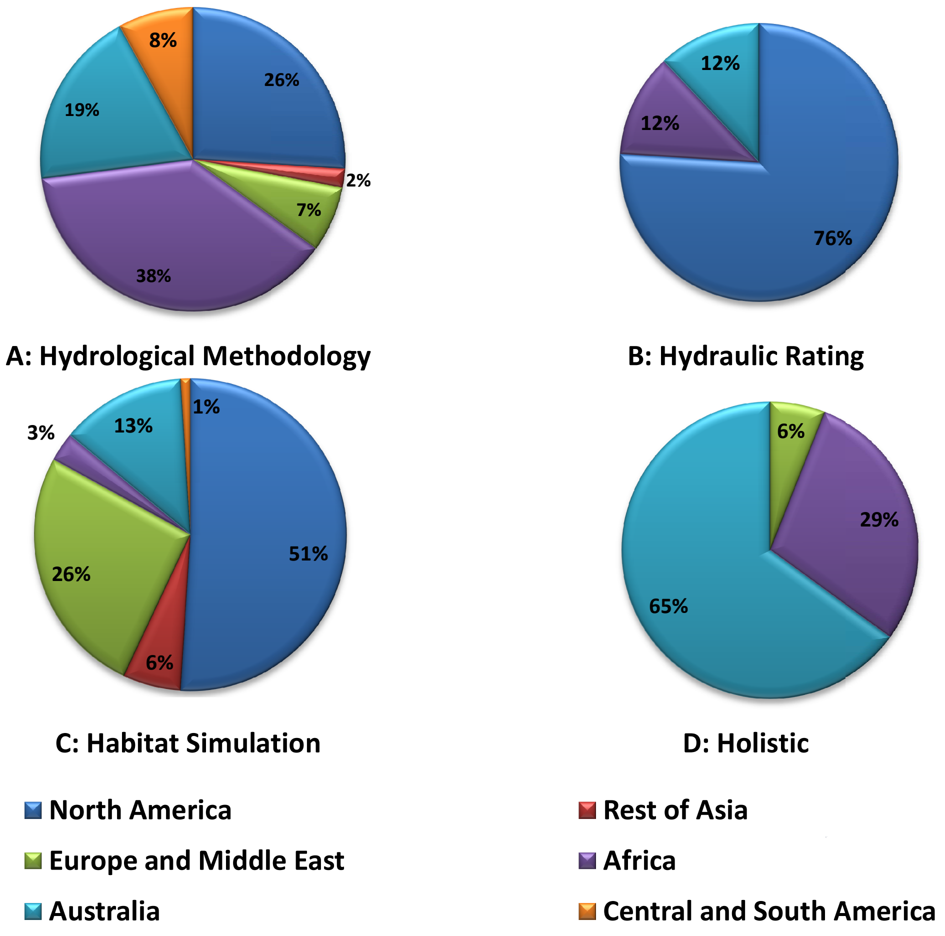
These are based on the use of multiple specialists in different fields to provide a consensus view of the appropriate flows to meet a pre-defined set of environmental objectives, or to describe the consequences of different levels of modification to the flow regime. Most of these methods make use of (i) a hydrologist and a hydraulics engineer to provide the baseline data on flows and hydraulic conditions, (ii) freshwater biologists for fish, invertebrates, and riparian vegetation to characterize the requirements of the biotic communities, (iii) a geomorphologist to predict the changes in sediment transport and channel maintenance at different flows, (iv) a water quality specialist, and (v) a socio-economist.

Over the period of time, the primitive methodologies are being replaced by more comprehensive holistic methodologies in the UK, Australia and South Africa. While emphasizing the role of multi-disciplinary expert's team in assessment of E-Flows, Acreman and Dunbar (2004) pointed out that, in earlier days, the opinion of one expert was used to assess E-Flows. However, a better alternative that has gradually replaced earlier methodologies is the use of a multi-disciplinary team, which comes out with E-Flows recommendations, after much needed deliberations and brainstorming. It is largely the holistic methodologies which provide the greater opportunity to have a multidisciplinary team of experts.

The choice of method from the list of various holistic methodologies depends on (a) the urgency of the problem, (b) resources available for the analysis, (c) the importance of the river, (d) difficulty of implementation, and (e) the complexity of the system.

Acreman and Dunbar (2004) state that no single methodology can be considered as the best and all the methods would benefit from further development and refinement. Moreover, the science of E-Flows is still young and much is still to be learnt.

Historically the United States has been at the forefront to develop, experiment and exercise various methodologies for assessment of E-Flows. However, in the recent times, other countries like Australia, South Africa, China, England, New Zealand, Brazil, Japan, Portugal, Latin America, Czech Republic, etc. are also involved in E-Flows assessment and establishment. Geographical distribution of application of various methodologies is presented in Figure 1.



A: Hydrological Methodology

B: Hydraulic Rating

C: Habitat Simulation

D: Holistic

Figure 1: Geographical Distribution of Application of Various E-Flows Estimation Methodologies

A closer analysis of various methodologies for assessment of E-Flows suggests that the simpler and primitive methodologies including hydrology based, hydraulic rating and habitat simulation are getting outdated and various holistic methodologies are replacing them as a comprehensive tool for assessment of E-Flows. An investigation of the different methodologies involving a team of experts from various institutes/organizations and with variety of expertise conducted by WWF-India about three years back suggested that holistic methodologies are most suitable for the rivers like Ganga. Holistic methods are not only comprehensive, but also allow consideration of socio-economic and environmental aspects along with scientific and technical aspects.

4. Comparative Analysis of various Holistic Methodologies for Assessment of E-Flows

Arthington *et al*. (2004) have given detailed account of various holistic methodologies developed and being applied across the world. For sake of brevity, an attempt has been made to present a comparative analysis of various important holistic methodologies in Table 1. Much of the information given in Table 1 has been adopted from Arthington *et al*. (2004).

Table 1: Comparative Assessment of Various Holistic E Flow Estimation Methods

S No	Name of Methodology and its origin	Features and Strengths	Limitations
1	**Expert Panel Assessment Method (EPAM)** (Swales and Harris, 1995). First multidisciplinary panel based E-Flows Methodology developed and used by Department of Water Resources & Fisheries in New South Wales, Australia.	- Low resource intensive - Bottom-up, reconnaissance-level approach - Rapid, inexpensive and site-specific - Requires limited field data - Suitable for sites where dam releases are possible - Aim to address river ecosystem health - Relies on field based ecological interpretations	- Recommendations purely based on opinion of experts and no role of other stakeholders, mainly users - Focused on fish species - No explicit guidelines for application - Subjective scoring approach, so poor congruence in opinion of different panel experts

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S No	Name of Methodology and its origin	Features and Strengths	Limitations
2	**Scientific Panel Assessment Method (SPAM)** (Thoms *et al.* 1996; Cottingham *et al., 2002*) Developed during E-Flows assessment for Barwon-Darwin River system, Australia	- Bottom-up, mixed approach i.e. includes field and desktop - Evolved from EPAM as more sophisticated and transparent expert panel approach - Considers other biodiversity actors like – fish, trees, macrophytes, invertebrates and geomorphology - Incorporates systemic hydrological variability and elements of ecosystem functioning - Includes stakeholders panel workshop - Moderately rapid, flexible and resource intensive - Simpler, less rigorous in compared to DRIFT and BBM	- appears limited to single application in Australia in its original form - Highly generalized approach - Requires significant modifications before adopting in other river basins
3	**Habitat Analysis Method** (Walter *et al.* 1994; Burgess and Vanderbyl 1996; Arthington, 1998) Developed by former Queensland's Dept. of Primary Industries and Water Resources (now called Department of Natural Resources [DNR]) in Australia, as part of water allocation and management planning initiative.	- Relatively rapid and inexpensive - Basin-wide reconnaissance method for determining preliminary E-Flows requirements at multiple points in catchment - Superior to simple hydrological methodologies - Bottom-up approach, field data requirement is limited or absent - Identifies generic aquatic habitat types existing in the catchment - Determines flow related ecological requirement of each habitat	- Inadequate for comprehensive E-Flows assessment - Little consideration of specific flow needs of individual ecological components - Requires standardization of process - Represents simplified version of holistic approach and largely superseded by Benchmarking Methodology

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S No	Name of Methodology and its origin	Features and Strengths	Limitations
4	**Benchmarking Methodology** (Brizga *et al.* 2001, 2002) Developed in Queensland by local researchers and DNR in Australia, to provide a framework for assessing risk of environmental impacts due to water resources development at basin level	- Rigorous and comprehensive - Scenario based, top-down approach for application at basin level - Uses field and desktop data for multiple river sites - Assesses ecological conditions and trends - Includes formation of multi-disciplinary expert team and development of hydrological model for catchment - Defines link between flow regime components and ecological processes - Presents a comprehensive benchmarking process and transparent reporting system	- No explicit consideration of social aspects - Requires evaluation of several aspects including – (i) applicability and sensitivity of key flow statistics, (ii) degree to which benchmarks from other basins/ sites within basins are valid considering differences in river hydrology and biota - Doesn’t provide the room to integrate other local significant aspects like cultural and spiritual ones
5	**Environmental Flow Management Plan Method (FMP)** (Muller 1997; DWAF 1999) Developed in South Africa by the Institute for Water Research, for use for intensively regulated river systems	- Simplified bottom-up approach - Applicable in highly regulated and managed river systems with considerable operational limitations - Workshop based - Multidisciplinary assessment including ecologists and system operators - Determines current ecological status and desired future state	- Limited scope for applicability as structure and procedures for application are not formalized and well documented - No provision of evaluation, so limited applicability - Not replicable as the methodology is marred with uncertainties

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S No	Name of Methodology and its origin	Features and Strengths	Limitations
6	**Downstream Response to Imposed Flow Transformations (DRIFT)** (King *et al*. 2003; Arthington *and Pusey,* 2003) Developed in South Africa with inputs from Australian researchers as an interactive scenario based holistic methodology	- Rigorous, top-down, well-documented approach - Scenario based approach with interactive scenario development - Appropriate for comprehensive exercises for assessment of E-Flows - Mix of biophysical, economical and sociological approach - High potential for application in other aquatic ecosystems - Amendable to simplification for more rapid assessments	- Provides limited consideration for synergetic interact-tions among different ecosystem components - Requires significant documentation of generic procedures - Limited inclusion of flow indices describing system variability
7	**Flow Restoration Methodology (FLOWRESM):** (Arthington *et al*. 1999; Arthington *et al.* 2000) Developed in a study of the Brisbane river in Queensland, Australia.	- Suitable for river systems exhibiting a long history of flow regulations and requiring flow restoration - Preliminary bottom-up, field and desktop approach - Emphasize on identification of the essential features that need to be built back into the hydrological regime to shift the regulated system towards the pre-regulation state - More rigorous than expert panel methods - Include flexible top-down process for assessing ecological implications of alternate modified flow regimes	- Risk of inadvertent omissions of critical flow events - Requires significant documentation of generic procedures - Single application in Australia till date

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S No	Name of Methodology and its origin	Features and Strengths	Limitations
8	**Flow Events Method (FEM):** (Stewardson and Cottingham, 2002) Developed in 'Australian Cooperative Research Centre for Catchment Hydrology' to provide state agencies with a standard approach	- Top-down method for regulated rivers - Based on empirical data and expert judgment - Integrates existing analytical techniques and expert opinion to identify vital aspects of flow regime - Assesses ecological impacts of changes in flow regimes - Specifies E-Flows rules and targets - Optimizes flow management rules to maximize ecological benefits within the constraints of existing WRD schemes	- Limited application in other river basins, so far applied in Australia only - No consideration of an associated expert panel
9	**River Babingley (Wissey) Method:** (Petts *et al.* 1999) Developed for application in groundwater dominated rivers in Anglian region of England	- Bottom-up field and desktop approach - Uses hydro-ecological, habitat and hydrological simulation tools to assist in identification of E-Flows - Allows for flexible examination of alternate E-Flows scenarios - Includes provision for both drought and wet year conditions - Considers biota	- loosely structured approach with limited explanation of procedures for integration of multidisciplinary inputs - Specific to base E-Flows dominated rivers - Requires further research in intricate basins - Wider application is very limited

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S No	Name of Methodology and its origin	Features and Strengths	Limitations
10	**Building Block Methodology (BBM)** (King and Louw 1998; King *et al.* 2002) Developed in South Africa by local researchers through applications in numerous water resources development projects to address E-Flows requirements for entire riverine ecosystems under conditions of variable resources. Adapted for intermediate and comprehensive determinations of the ecological Reserves under the new South Africa Water law.	- Rigorous and extensively documented - Manual and case studies available - Perspective bottom-up approach with interactive scenario development - Takes account of number of sites within the critical stretch of the river - Well established socio-economic component - Flexible to accommodate other local aspects, like religious and spiritual requirements (hence applicable for Indian rivers) - Functions well in data-rich and data-poor situations - Multidisciplinary approach with continuous deliberations/ workshops among various experts - Designed to provide specific pre-defined river condition - High potential for application to other aquatic ecosystems - Links to external stakeholders and public participation processes - Less time and cost intensive in comparison to DRIFT methodology - Applicable to regulated and non-regulated river regimes - Globally, most frequently used methodology - Adopted as a standard methodology for South African Reserve determinations	- Moderate to highly resource intensive

In the recent times, as the science of E-Flows has gained significant impetus, the viability and acceptability of various methodologies is being contested. Therefore, there has been changing pattern in the preferences for adoption of methodologies for E-Flows assessment. As a result of this, the researchers, practitioners, academicians and people from the civil society has apparent inclination towards various methodologies falling under the category of 'holistic' ones, for the simple reason that, the methodologies under this category have a comprehensive approach and takes into consideration various associated aspects of a river regime and not only the hydrology and hydraulics. In a nutshell, the process of development of various E-Flows assessment methodologies is an evolutionary one, where a specific methodology takes lesson from previous methodologies and in the process the methodology under consideration gets refined.

Out of the different holistic methodologies, the E-Flows group constituted by the IIT Consortia considers Building Block Methodology (BBM) to be one of the most advanced and refined methodology. Its suitability and applicability with flexibility gives it an edge over other methodologies. The complexity and interests of multi-stakeholders can be handled by the BBM in estimation of E-Flows. Further details on BBM are presented in Appendix I for ready reference.

5. Importance of E-Flows Assessment for Rivers in the Ganga Basin

The spiritual significance of most rivers in the Ganga basin is well known and beyond any doubt. Imperial Gazetteer of India described the Ganga saying: "There is not a river in the world which has influenced humanity or contributed to the growth of material civilization, or of social ethics, to such an extent as the Ganges. The wealth of India has been concentrated on its valley, and beneath the shade of trees whose roots have been nourished by its waters, the profoundest doctrines of moral philosophy have been conceived, to be promulgated afar for the guidance of the world".

The diverse and conflicting demands of the Ganga river system pose challenges in estimating E Flows. Some of these are briefly described as follows.

- The cultural and religious community (saints) in India holds the view that, "there is no dearth of faith for Ganga among the Indians, but it's actually the conservation and preservation of river which is paramount and needs immediate attention".
- Demography has an important bearing on the state of river Ganga, as it is significantly affected by the population living within the basin. Average population density in the Ganga basin is 520 persons per square km as against 312 for the entire country (2001 census). Further, the cities in the basin have large and ever-growing populations. In fact, from 1991 to 2001, the urban population has increased by 32% within the basin (AHEC, 2009). This alarming trend is likely to continue, which escalates the pressure on already diminishing natural resources, including river Ganga. Moreover, the ever-exploding demographic trends in the basin lead to crumbling of sewage treatment facilities of utility providers.

- There have been major water abstractions from river Ganga for the purpose of irrigation. Canal Systems including the Upper Ganga Canal, Madhya Ganga Canal, Lower Ganga Canal, etc. has been fulfilling irrigation needs of the farmers residing within the upper Ganga river basin, mainly – parts of Uttarakhand and Western and Central Uttar Pradesh. However, this has also led to severe problem of water availability in the stretch from downstream of Haridwar to upstream of Allahabad. In addition there has been significant increase in industrial activities at the banks of river at various points and this has led to diminishing water quality as in most of the cases the river becomes a dumping body for the industrial waste. Further, the Persistent Organic pollutants (POP) and hazardous wastes also find their way to the river Ganga, thus polluting the river for a long time.
- The rising standards of living and exponential growth of industrialization and urbanization have further exposed the water resources of river Ganga.

All these issues have compounded the problem of both water quality and quantity, which make it absolutely vital to assess and maintain the E-Flows for the river Ganga and her tributaries.

6. Review of Information Available on E-Flows Estimation on Rivers in Ganga Basin

There have been very few attempts in regard to E-Flows assessment in the context of Indian rivers. Mohile (2009) has worked out Natural Flow of the Bramhani-Baitarni river in the form of monthly time series. This was worked out from the observed flow, through series of corrections.

The environmental water need of the country is estimated at 5 BCM for 2010 and is projected to increase to 10 BCM in 2025, and 20 BCM in 2050 by National Commission on Integrated Water Resources Development Plan (NCIWRDP, 1999). Further, the National Water Policy (2002) states that: 'minimum flow should be ensured in the perennial streams for maintaining ecology and social considerations'.

The High Powered Committee (HPC) constituted by the River Conservation Authority (RCA), MOEF, GOI recommended 40 and 10 m^3/s as minimum flow for maintaining ecological system and natural self purification capacity downstream of Narora in river Ganga and in Delhi stretch in Yamuna respectively (Dutta, 2009). The river flow is considered inadequate for Kumbh Bath at Allahabad during Dec-Jan in the lean flow months and the Courts are bound to order more and more releases towards social needs of people. This indicates inadequacies in estimation of E-Flows.

The Working Group constituted by the Water Quality Assessment Authority (WQAA) of Government of India used "modified Tennant Method" to assess the minimum flow requirements in Indian rivers. The tenant method requires very short time for assessment. The relative confidence in output, however, is said to be "low". The working group made following recommendations for minimum flows based on a classification of rivers into two categories, namely Himalayan and Other Rivers (WQAA, 2007).

- Himalayan Rivers: Minimum flow to be not less than 2.5% of 75% dependable Annual Flow expressed in m^3/s; One flushing flow during monsoon with a peak not less than 250% of 75% dependable Annual flow expressed in m^3/s.
- *Other Rivers:* Minimum flow in any ten daily period to be not less than observed ten daily flow with 99% exceedance. And where 10 daily flow data is not available this may be taken as 0.5% of 75% dependable Annual Flow; One flushing flow during monsoon with a peak not less than 600% of 75% dependable annual flow expressed in m^3/s.

Since the confidence level of the Working Group was 'low', these recommendations were neither tried nor tested, and are not accepted.

Workshop on Environmental Flows organised by the National Institute of Ecology (NIE), jointly with the International Water Management Institute (IWMI), World Wide Fund for Nature – India (WWF-India), Ministry of Environment and Forests (MoEF), Ministry of Water Resources (MoWR), and the Indian Council of Agricultural Research (ICAR) in March 2005 in Delhi made following resolution regarding E-Flows (NIE, 2005):

- The Environmental Flows requirements differ considerably in different rivers and their different reaches, and have therefore to be assessed and prescribed separately for different reaches of the river and its estuary.
- The assessment of Environmental Flows requirements should employ comprehensive holistic (whole ecosystem-focused) methods. The hydrological methods for E-Flows do not adequately account for the ecological requirements and therefore, recommendations based on simple hydrological methods alone, could be merely an immediate step in the right direction.

As can be inferred from the aforementioned information, the concept of E-Flows has been inadequately applied for rivers in the Ganga basin. At most E-Flows have been considered as some minimum flow as percentage of annual mean flow or in some cases as percentage of dry weather flow or in some cases as some percentage of 10 daily average flows. A few open access software, with default settings based on data available in public domain, are available for E-Flows estimation. The default settings can be user modified if some specific information about the site at which E-Flows are to be estimated is available. Such tools can possibly be used for estimating E-Flows in rivers in Ganga basin. For example, the Global Environmental Flow Calculator (GEFC) is a software package developed by the International Water Management Institute, Sri Lanka in 2007. It is a desktop assessment of E-Flows incorporating an in-built global database of simulated flow time series. The key objective of this software is to support training and initial quick assessments of E-Flows requirements in river basins. GEFC is supplied with the Global Database of simulated flow time series. These data are provided by the Water Systems Analysis Group of the University of New Hampshire, USA. The GEFC uses a simple approach which has been proposed by Smakhtin and Anputhas (2006) to determine the default Flow Duration Curve representing a summary of E-Flows for each Environmental Management Class (EMC).

The minimum requirement for this desktop Environmental Flow Assessment (EFA) application at any site in a river basin is sufficiently long (at least 20 years) monthly flow time series reflecting, as much as possible, the pattern of 'natural' flow variability. This flow time series is referred to as the ‘Reference Hydrological Time Series’. The default flow time series can be replaced by observed/simulated flow time series supplied by the user in a user-defined file as the ‘Reference Hydrological Time Series’. However, sites where E-Flows are required are often either un-gauged, or significantly impacted by upstream basin developments. Therefore representative 'unregulated' monthly flow time series, or corresponding aggregated measures of unregulated flow variability, like Flow Duration Curves (FDCs), have to be simulated or derived from available observed source records. The IWMI, in its disclaimer, clearly mentions that this software product is being provided ‘as is and with all faults’ and without warranty of any kind. Nevertheless, this could be used as one of the preliminary tools towards assessment of E-Flows and thus provides basic information about hydrology-based assessment of E-Flows.

Maintenance of minimum ecological flows in the river Ganga with aim of ensuring water quality and environmentally sustainable development has been assigned second priority after IWRDM Plan for National Ganga River Basin Authority created by an Act of Indian Parliament, February 20, 2009. It is stated that maintaining E-Flows will be at the cost of other requirements, and it is feared that the trade-off will be mostly with agriculture in the context of Ganga Basin (Ravindra Kumar, 2009). A much detailed study on E-Flows estimation at a few selected sites (refer Figure 2) in the stretch Gangotri to Kanpur of the river Ganga was undertaken under the Living Ganga Programme (2007-2011) being run by the World Wide Fund for Nature – India (WWF – India). After some field visits and workshops, an international multi institute team was constituted to develop a framework for estimation of E-Flows on Indian rivers with special emphasis on river Ganga. After extensive debate, some field work, and the fact that socio-cultural aspects are highly significant for river Ganga, it was decided that the Building Block Methodology could be further developed and adopted due to the flexibility that the method offers for incorporating additional factors in estimating E-Flows. Several specialist groups drawing from different institutes within and outside India were setup to study following aspects.

6.1. Hydrology

- Identify and review previous hydrological modeling studies and assessment of their usability
- Set up model and calibrate under existing conditions of land and water use

- Examine the feasibility of different ways of modeling the past 'natural' and present-day flows, using observed flow data

6.2. Fluvial Geomorphology and Hydraulic Modeling

- Analysis of sediments in the river, and the assessment of the effects that will result from different flow regimes
- Analyze the channel and floodplain morphology in terms of the geomorphic features, and their stability
- Generate the cross section and longitudinal profile for hydraulic modeling

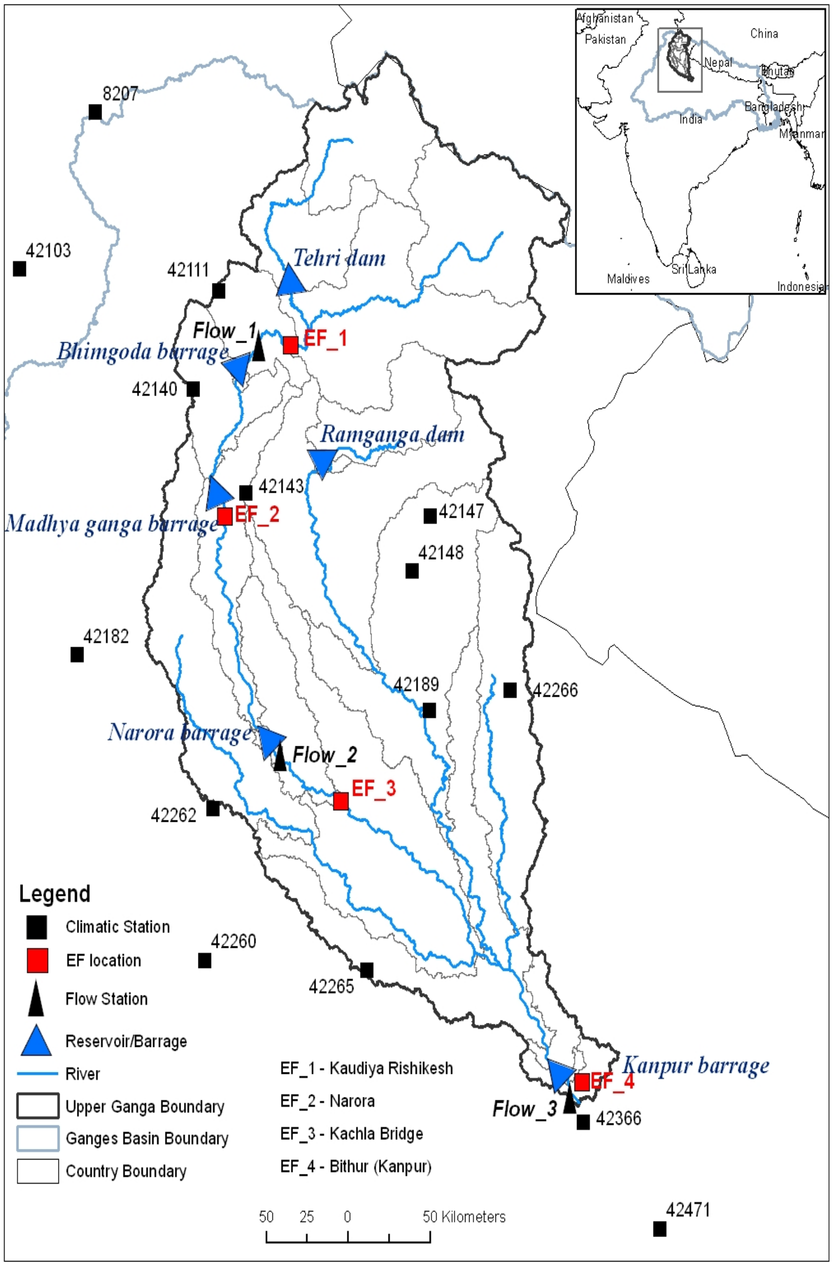

Figure 2: **Map Showing Sites for E-Flows Assessment under WWF's Living Ganga Programme**

6.3. Establishing the Habitat Preferences of Selected Aquatic Species

- Assess present condition in terms of the difference between the reference condition and survey results
- Describe measured depths, average velocities and substratum types most commonly associated with sensitive species and families, and/or with maximum biodiversity

6.4. Economic and Livelihood Objectives and Assessment of Cultural and Spiritual in Stream flow required

- Evaluate livelihood activities and its implications on E-Flows for the river
- River's representation in mythology, folklore, folk art, popular literature and art
- Historical evidence of civilizations along the river, and its influence on society
- Cultural, religious, spiritual importance of the Ganga, with special focus on rituals and festivals that are linked to the river

6.5. Collation of Water Quality and Pollution Data

- Generation of data on certain water quality parameters that is not likely to be available from any sources and considered essential by the water quality group.
- Assessment of various types of pollution loads in different stretches/sub-stretches

After extensive studies by various expert groups involving hydrological, hydraulic, geomorphologic, ecological, socio-cultural, livelihood and water quality aspects from different institutes/organizations at three sites, namely Kaudiyala, Kachla Bridge and Bithoor, E-Flows assessments were carried out in a five day workshop where all specialty groups participated. Kaudiyala, Kachla Ghat and Bithoor sites were considered to represent Gangotri to Rishikesh, Narora to Farrukhabad, and Kannauj to Kanpur stretches of the river Ganga respectively. Typical results of the E-Flows estimates at three sites for maintenance or normal year are presented in Figures 3 - 5. Details are available elsewhere (WWF-India, 2011). The WWF - India exercise for assessment of E-Flows was pioneering and was a first attempt of its kind in India, whereby the capacity of various experts/teams was strengthened to undertake similar tasks in future for other river basins. Further, the process adopted for this exercise was found to be well accepted and understood among various team members and external experts, and could be applied in future for rivers in the Ganga basin.

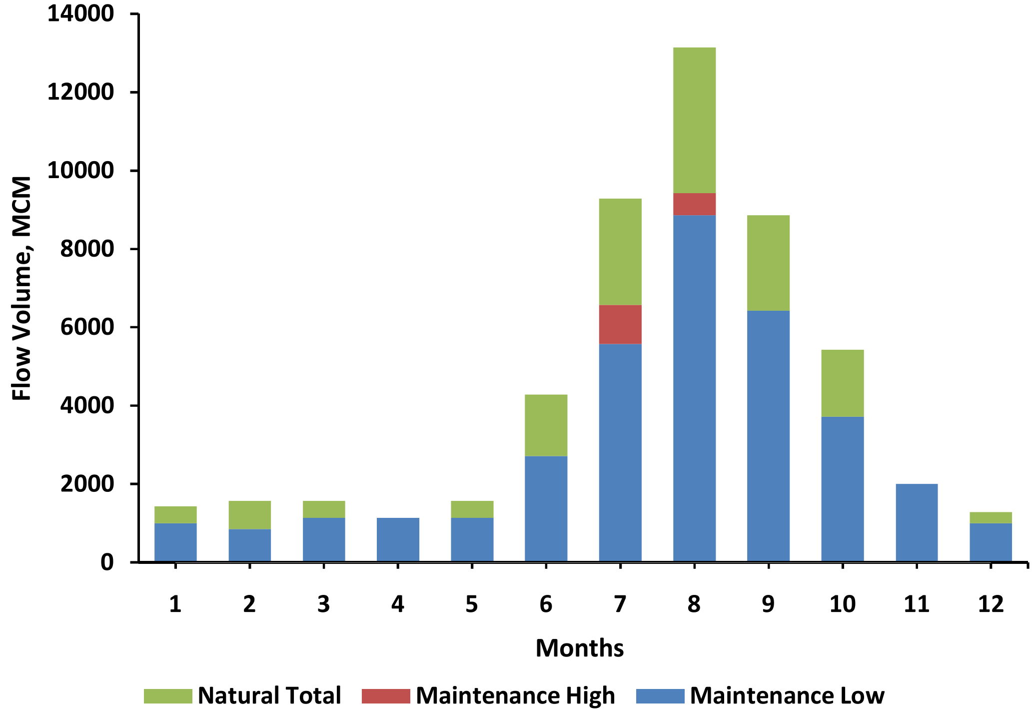

Figure 3: **Typical Results of the E-Flows Estimates for Zone I: Gangotri to Risheksh for Maintenance or Normal Year** (Adopted from WWF-India, 2011)

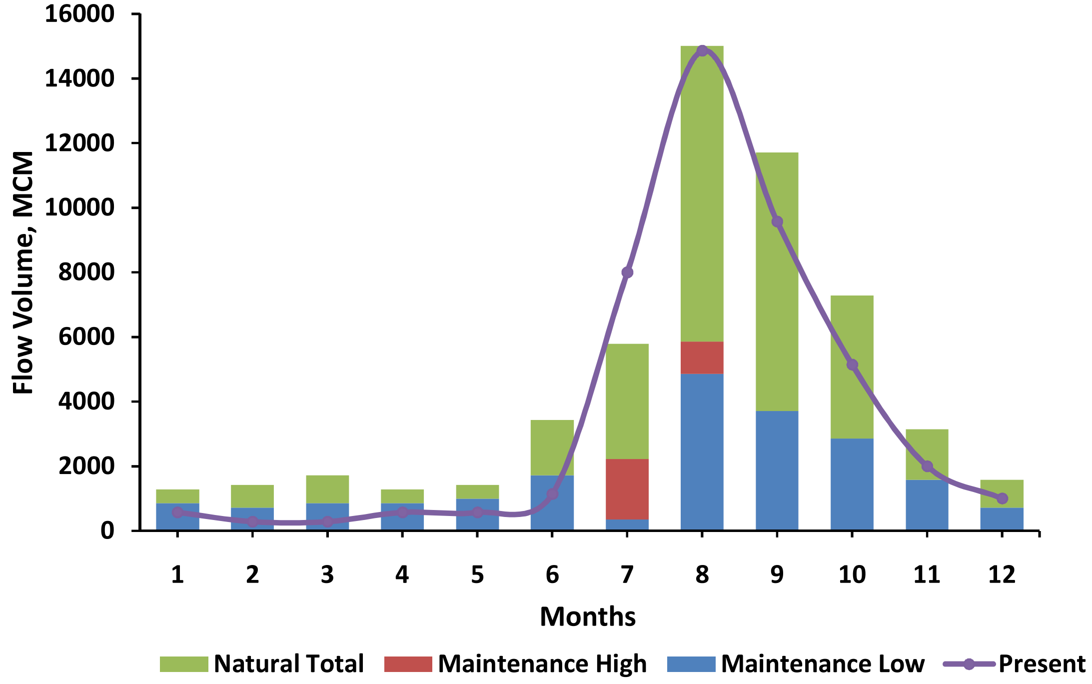

Figure 4: **Typical Results of the E-Flows Estimates for Zone II: Narora to Farrukhabad for Maintenance or Normal Year** (Adopted from WWF-India, 2011)

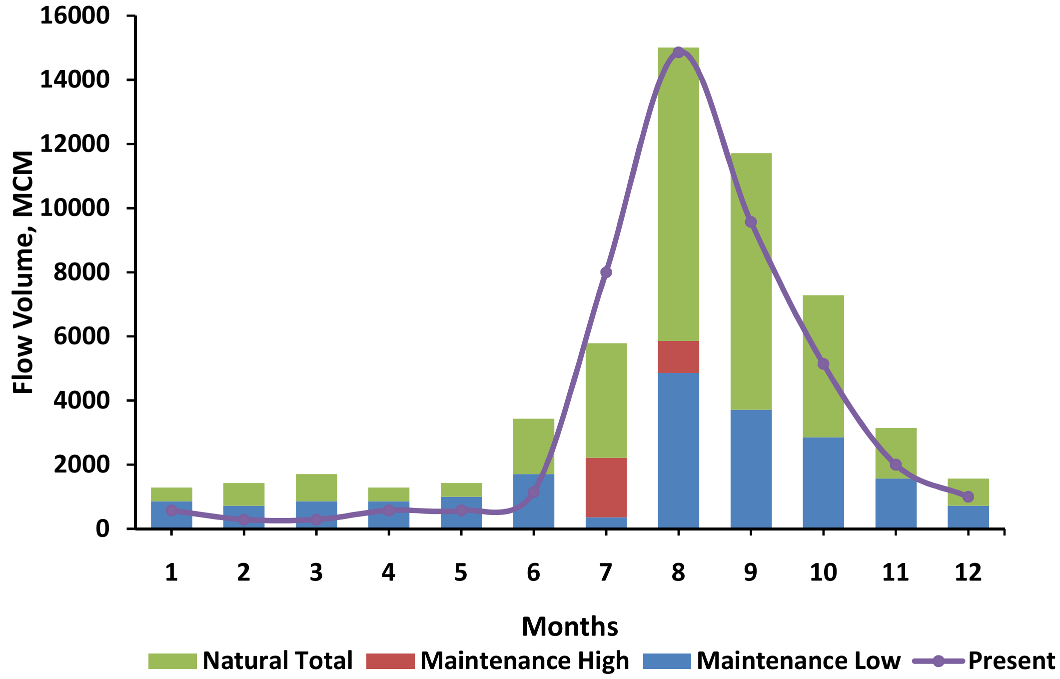

Figure 5: Typical Results of the E-Flows Estimates for Zone III: Kannauj to Kanpur for Maintenance or Normal Year (Adopted from WWF-India, 2011)

In the opinion of the experts who participated in the E-Flows estimation exercise, the BBM methodology was found to be robust with high confidence level. However, the experts were less confident and quite uncertain about the specific flow recommendations presented in Figures 3 - 5.

During this exercise, the specialist groups recommended that the long term Ecological Management Class (EMC) for all three zones should be 'A'. This is with reference to the unique spiritual importance of the river, it being an essential part of the history and culture of the subcontinent. Near-pristine flows will safeguard the spiritual satisfaction that devotees obtain from gazing at the river. In the short term, some augmentation of the flow is required to ensure satisfactory ritual worship. An EMC of 'B' was recommended as an acceptable goal in the short term.

The major uncertainties under this study were centered on the hydrological and hydraulic models due to lack of availability of reliable data. However, the Central Water Commission data on discharge, sediment load and gauge being made available to the IIT Consortia, the confidence level on hydrological modeling should be high. This would be beneficial for the E-Flows estimations.

Based on the aforementioned information and discussion it may be inferred that Building Block Methodology (BBM) appears to be promising and can be adopted by IIT Consortia for E-Flows estimation in rivers of Ganga Basin. However, the estimated E-Flows given in Figures 3-5 need to be revised.

7. Concluding Remarks

- Environmental flows refer to a regime of flows that mimics the natural pattern of a river's flow, so that it can perform its natural functions such as transporting water and solids from its catchment, formation of land, self-purification and sustenance of its myriad systems along with sustaining cultural, spiritual and livelihood activities of the people or associated population.
- E-Flows assessment is based on the assumption that there is some 'spare' water in rivers that can be used without unacceptably impacting on the ecosystem and societal services that the river provides.
- E-Flows assessment is both a social and a scientific process. There is no one correct Environmental Flow regime for rivers – the answer will depend on what people want from a river.
- The fact that socio-cultural and livelihood aspects are highly significant for river Ganga, the Building Block Methodology, having flexibility for incorporating additional factors in estimating E-Flows, could be further developed and adopted.
- The WWF - India exercise for assessment of E-Flows was pioneering and first of its kind in India, whereby the capacity of various experts/teams was strengthened to undertake similar tasks in future for other river basins. Further, the process adopted for this exercise was found to be well accepted and understood among various team members and external experts, and could be applied in future for rivers in the Ganga basin.
- The BBM methodology is found to be robust with high confidence level. However, specific flow recommendations are difficult to justify at this stage, and will have to worked out afresh. The major uncertainties centered on the hydrological and hydraulic models due to lack of availability of reliable data.

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Appendix I

The Building Block Methodology and Its Process

The Building Block Methodology (BBM) is a flexible participatory and robust multi-disciplinary methodology that can be applied for differing levels of information and data availability. It allows the user to focus on key issues of local importance, for instance –in case of River Ganga – the spiritual and cultural aspects which are of immense importance. The BBM is found to be the most appropriate process for large river basins with multiple user and interest groups. As with other assessment methodologies, it is based on the principle that some water can be used from rivers without unacceptably degrading them. The BBM is based on the following steps.

1. Using a stakeholder consultation process to set objectives for the environmental condition of the river.
2. Assessing a modified flow regime that will meet those objectives.
3. Using flow-dependent indicators (e.g. river dolphins, gharial, turtles, fish, invertebrates, floodplain plants) and non-consumptive human requirements, as well as water quality metrics and sediment transport, to identify water depths, velocities, river widths, and substrate types that will provide the required habitats and conditions. Such hydraulic requirements can then be converted to hydrological (flow) requirements.
4. Identifying the critical components (building blocks) of the flow regime that govern environmental conditions (e.g. dry and wet season base flows, and different-sized high flows and floods).

This methodology has been extensively applied in South Africa, Mexico, Brazil, Kenya, Tanzania and Australia. Salient features of this methodology include:

- Bottom up approach, with each recommended flow carefully motivated.
- Multi-disciplinary approach means that each recommended flow is carefully analyzed by a group of specialists from different fields (ecology, geomorphology, water quality, sociology).
- Flexible - can be tailored to suit local conditions as required, for instance – in case of rivers in Ganga Basin cultural and spiritual aspects can be integrated.
- Most frequently used holistic methodology around the world
- Process is driven by baseline data
- Rigorous and well documented, with an explicit user manual.

The overall process chart of Building Block Methodology for assessment of E-Flows is very comprehensive and complex, therefore for the sake of brevity and clarity the same is simplified and presented in Figure AI.1

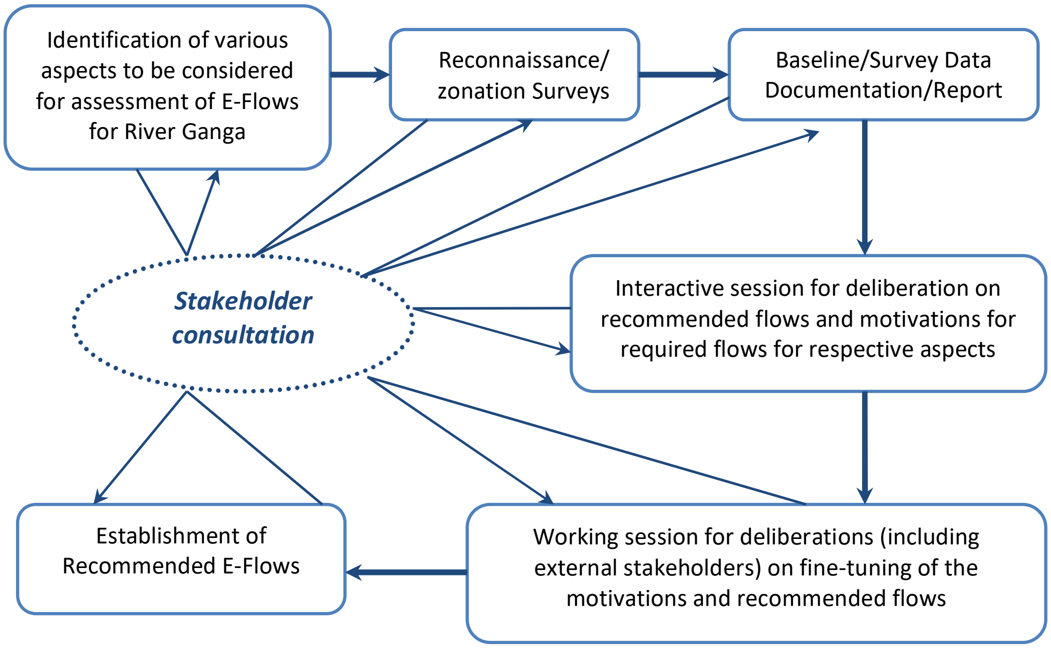

Figure AI.1: Block Diagram Illustrating Various Steps of Building Block Methodology

Note: Much of the information given in this Appendix has been reproduced from WWF – India (2011) report.

River Connectivity, Flow Regimes and Assessment of Environmental Flows at Some Select Sites in Upper Ganga Segment

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 are members of the concerned thematic groups and those who have taken lead in preparing this report are given on the reverse side.

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Contents

1. Introduction

To achieve the objective of "Rejuvenation and Development of Ganga", assessment of Environmental Flows (E-Flows) is considered as one of the most important aspects.

Flow is one of the main drivers of biodiversity in rivers, and a river's flow regime – the variation of high and low flows through the year as well as variation over the years – exerts great influence on its ecosystem. Environmental Flows (or E-Flows) are a regime of flow in a river that mimics the natural pattern of a river's flow. E-Flows consider the equitable distribution of water between needs of aquatic ecosystems and the services availed from such systems. E-Flows refer to the quality, quantity, and timing of water flows required to maintain the components, functions, processes, and resilience of aquatic ecosystems that provide goods and services to people [Nature Conservancy 2006]. Specification of the E-Flows enables the river to at least perform its minimal natural functions such as transporting water and solids received from its catchment and maintaining its structural integrity, functional unity and biodiversity along with sustaining the cultural, spiritual and livelihood activities of people. As per the Brisbane Declaration [2007], "Environmental Flows describe the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems." In other words, E-Flows describe the temporal and spatial variations in quantity and quality of water required for freshwater and estuarine systems to perform their natural ecological functions (including material transport) and supports the spiritual, cultural and livelihood activities that depend on them [IITC-TR22, 2011].

The objective of E-Flows is to recognize the physical limit beyond which a water resource suffers irreversible damage to its ecosystem functions, and systematically balance the multiple water needs of society in a transparent and informed manner. E-Flows are one of the central elements in water resources planning and management for sustainable development.

After reviewing several different holistic methods of estimating E-Flows and in consultation with stakeholders and expert groups, the Building Block Method (BBM) was found to be robust and scientifically most suitable [IITC-TR22, 2011]. The method had been developed in South Africa through numerous applications in water resources development to address E-Flows requirements for riverine ecosystems under conditions of variable resources. The Inter Ministerial Group (IMG) chaired by Mr B K Chaturvedi and Expert Body constituted by the Ministry of Environment, Forests and Climate Change (Mo E, F & CC) had also opined in favour of adopting BBM for E-Flows assessment [IMG, 2013; Expert Body Report, 2014]. But since it was found that the method effectively results in Bigger Block governing E-Flows, BBM was considered to denote Bigger Block Method in GRBMP [IITC, 2015]. Based on this method, E-Flows were computed for different sites of interest in the Ganga River System. It should be noted here that the BBM method quantifies only the lower bound on flow rates required at different times to sustain the river, and does not specify other conditions to be maintained in the river. One of these conditions is, of course, the connectivity in river flow. However, maintenance of the water-sediment balance is also an essential condition. It is desired that E-Flows should carry suspended load and bed load in approximately the same proportions as present in the virgin flow.

2. Concept of Aviral Dhara

Among many aspects, the vision for Ganga River includes the concept of Aviral Dhara. This can be defined as "the flow of water, sediments and other natural constituents of River Ganga are continuous and adequate over the entire length of the river throughout the year". As it can be seen from the above definition, a minimum quantity of flow is required in the river for it to support its natural processes. However, the increase in anthropogenic activities in the watershed of a river has the potential to alter the flows in the river leading to interference with the natural processes of a river.

In the river systems, several processes lead to differentially structured river sections, varying in geomorphology, hydrology, bio- & geo- chemistry, and ecosystem variables. In terms of stream habitats, a hierarchical classification based on temporal and spatial scales is a necessary tool to understand biodiversity. Fluvial and ecological processes are correlated at a range of scales and the sensitivity to disturbance and recovery times of communities in river systems differ at various scales. The continuum characters of rivers become very clear in the case of construction of the dams and embankments (dikes), because these disrupt the longitudinal and lateral continuum, resulting in shifts in abiotic and biotic parameters and processes (Velde, 2014).

Given the increase in anthropogenic activities in the Ganga River Basin in the last few decades, it is critical now to understand the drivers that are deviating the flows in the river from their natural conditions spatially and temporally. Further, maintaining river connectivity that allows for the energy, nutrients, sediment and organisms exchange between different parts of the river pathways is imperative before establishing the environmental flows for a stretch of a river.

2.1 River Connectivity

Connectivity is defined as the maintenance of lateral, longitudinal, and vertical pathways for biological, hydrological, and physical processes (Annear, 2004). This connectivity refers to the flow, exchange and pathways that move organisms, energy and matter throughout the watershed system. These interactions create complex, interdependent processes that vary over time. As with hydrology, stream connectivity can be described in four dimensions:

1) Longitudinal – linear connectivity: It refers to the pathways along the entire length of a stream. As the physical gradient changes from source to mouth, chemical systems and biological communities shift and change in response. Along its length, the rivers change from small, rocky-based, shaded streams in the upland mountainous region to wider rivers in the valleys to broad, muddy rivers in the lowland floodplain. While most movement is downstream, many fish move upstream at some stage in their life cycles.

2) Lateral – Floodplain connectivity: Lateral (or sideways) linkages occur between the river, the adjacent riverside land and the floodplain. In the uplands, the riverside zone provides organic matter (e.g. leaf litter) to the river. Organic matter is a major energy source for the in-stream aquatic life. In the lowland floodplain, lateral linkages are more important and come into operation when rivers flow over their banks and inundate the floodplain on a regular basis. Flooding is the key to maintaining the health of both the river and the floodplain. Transfer of sediments, nutrients and organic material between the river and the floodplain is vital to the maintenance of both ecosystems. A flood stimulates a boom in floodplain productivity with the regeneration of floodplain and riverside plants, and the breeding of invertebrates and vertebrates such as water birds, frogs and tortoises. It opens the floodplain as new habitat for fish and macro-invertebrates and is often the

cue for breeding for these species. As the flood recedes, it transfers organic matter back to the river, replenishing in-stream energy sources and ensuring recruitment in fish populations and insect communities.

3) Vertical – hyporheic (below the stream bed): A river links vertically with groundwater systems. The base flow in rivers is maintained by groundwater, and rivers can also recharge shallow groundwater aquifers. Groundwater provides organic carbon (an energy source) to the streams, and during high flows the stream bed can provide a refuge for invertebrates as they move down below the stream surface to take shelter.

4) Temporal (continuity over time) – many scales; seasonal, multiyear, generational: A stream exhibits temporal connectivity of continuous physical, chemical, and biological interactions over time, according to a rather predictable pattern. These patterns and continuity are important to the functioning of the ecosystem. Over time, sediment shifts, meanders form, bends erode, oxbows break off from the main channel, channels shift and braid. A stream rises and falls according to seasonal patterns, depending on rain and snowmelt.

2.2 Flow regime

Flow regime influences the water quality, energy cycles, biotic interactions, and habitat of rivers (Naiman, 2002). It is possible to describe flow regime in terms of five states or environmental flow components, each of which supports specific ecological functions. The health and integrity of river systems ultimately depend on these components, which may vary seasonally (Mathews, 2007):

- Extreme low flows occur during drought. Extreme low flows are associated with reduced connectivity and limited species migration. During a period of natural extreme low flows, native species are likely to out-compete exotic species that have not adapted to these very low flows. Maintaining extreme low flows at their natural level can increase the abundance and survival rate of native species, improve habitat during drought, and increase vegetation.
- Low flows, sometimes called base flows, occur for the majority of the year. Low flows maintain adequate habitat, temperature, dissolved

oxygen, and chemistry for aquatic organisms; drinking water for terrestrial animals; and soil moisture for plants. Stable low flows support feeding and spawning activities of fish, offering both recreational and ecological benefits.

- High flow pulses occur after periods of precipitation and are contained within the natural banks of the river. High flows generally lead to decreased water temperature and increased dissolved oxygen. These events also prevent vegetation from invading river channels and can wash out plants, delivering large amounts of sediment and organic matter downstream in the process. High flows also move and scour gravels for native and recreational fish spawning and suppress non-native fish populations, algae, and beaver dams.
- Small floods occur every two to ten years. These events enable migration to flood plains, wetlands, and other habitats that act as breeding grounds and provide resources to many species. Small floods also aid the reproduction process of native riparian plants and can decrease the density of non-native species. Increases in native waterfowl, livestock grazing, rice cultivation, and fishery production have also been linked to small floods.
- Large floods take place infrequently. They can change the path of the river, form new habitat, and move large amounts of sediment and plant matter. Large floods also disperse plant seeds and provide seedlings with prolonged access to soil moisture. Importantly, large floods inundate connected floodplains, providing safe, warm, nutrient-rich nursery areas for juvenile fish.

2.3 Geomorphological processes

Geomorphological processes contribute to the changes that will occur to a stream channel in response to alterations in watershed conditions; and, in turn, how these changes will impact human infrastructure and fish habitat. Stream morphology is dynamic and constantly changing in both space and time. A stable stream channel is in a state of equilibrium and responds physically to the stream flow and sediment it receives from upstream.

Geology and physical geography act as constraints to the level of geomorphic change and determine the nature and quantity of sediment supplied to the system. Stream geomorphology is to be studied because it influences flooding patterns, erosion rates, stream flow and sediment movement and deposition. For example, lowered stream depth associated with widening would impact fish communities through loss of cover, and suitable summer and winter habitat. In addition, stream aggradations leads to embedded riffle substrate and the loss of riffle habitat.

2.4 Social Aspects of River Ganga

The river Ganga has significant economic, environmental and cultural value in India. The river Ganga also serves as one of India‘s holiest rivers whose cultural and spiritual significance transcends the boundaries of the basin. Ganga River resources are unique in nature in promoting cultural, ecological and economic prosperity of India. It provides fertile land for agriculture, perennial source of fresh water, inseparable part of Indian culture, fisheries and has rich bio-diversity. River Ganga occupies a unique place in the hearts of millions of Indians whose faith is intimately connected with her. Rituals from birth to death take place all along the flowing river and at the confluence with its important tributaries in search for salvation.

Despite its importance, extreme pollution pressures pose a great threat to the biodiversity and environmental sustainability of the Ganga, with detrimental effects on both the quantity and quality of its flows. Also, due to increasing population in the basin and poor management of urbanization and industrial growth, both river water quantity and quality has significantly deteriorated, particularly in dry seasons. The water abstraction at the constructed barrage at many places for irrigation and dams across the river for hydropower have left the main stream of the river dry, impacting river health and leading to a state where the river may not be able to deliver its social and spiritual services that Ganga has been providing since time immemorial.

3. Overview of Different River Flow Regimes

Flow regime is a major component of physical river environment. Flow regulation through dam and weir construction and water abstraction has led to severe stress being placed on river ecosystems (e.g. Walker and Thoms, 1993;

Thoms and Sheldon, 1997). Hence there is an urgent need to recognize the requirements to allocate water to fulfil the needs of the riverine environments in order to protect these systems. The various components under flow regimes have been explained in this section.

3.1 Virgin Flows

Virgin flows can be referred to as the natural flows, which exist or would exist if the influence of humans such as artificial diversions, impoundments, or channels would not have taken place, on or along the stream or in the drainage basin. Human intervention along the river course has resulted in physical, chemical, hydrological, and biological modifications of its fluvial and estuarine ecosystems. The principal drivers of the physical modifications include rapid population growth and consequent exploitation of the natural resources.

Factors that have contributed significantly toward these modifications include construction for hydroelectric power generation and tributary dams, water withdrawal for irrigation, waste discharges (point and non-point), deforestation, diking and filling of shallow water and intertidal areas, and navigational development. In order to study the effects of anthropogenic influence and climate effects, the observed daily flow alone does not provide all the information. It is also essential to have an assessment of virgin flow of the river to deliver a historical perspective of water resources development, separate anthropogenic and climate effects, and compare present water use scenarios with those of the past decades. Virgin flows are also necessary for hindcasting the sediment transport under natural conditions. Finally, by taking the difference between the virgin flow and the observed flow it is possible to obtain the total change in flow, due both to flow regulation and irrigation depletion (Naik, 2005).

3.2 River Flow Health

A biological system can be thought of as “healthy” when its inherent potential is realized, its condition is stable, its capacity for self-repair when perturbed is preserved, and minimal external support for management is needed. To properly understand how healthy a river is, three aspects of the river system need to be considered:

a) The diversity of the habitats, flora and fauna: Rivers and streams support a huge diversity of life. This is to a large extent because they provide a great range of habitats and link aquatic and terrestrial ecosystems. At the broader scale, river habitats include the river channels, the riverside (or riparian) vegetation, the floodplains, wetlands and lakes. Sustaining this diverse range of habitats and the species they support is a key component to maintaining the ecological health of a river.

b) The effectiveness of the linkages: Maintaining linkages is essentially about making sure that a river is part of the total landscape and is not just regarded as a channel running through the land. A river links with its catchment in three different dimensions: Along the river, lateral and vertical. Recognition of these important linkages in river functioning is a key part of study of the ecological health of the rivers.

c) The maintenance of ecological processes: To maintain river health, in particular to maintain biodiversity, it is essential to maintain the ecological processes operating within the system. They can be grouped into three types: Energy and nutrient dynamics, processes which maintain animal and plant populations, such as reproduction or regeneration, dispersal, migration, immigration and emigration & species interactions, which can affect community structure.

3.3 90% Dependable Flows

Dependable flows can be described as the nature of flow in a river based on which activities such as water supply, irrigation, power generation etc. can be planned. It gives an estimate of the water availability in the river system at any time of the year. Dependable flows are obtained by studying daily discharge in a stream for a very long time period such as 50 years. 90% dependable flow means that, the observed flow obtained by analyzing historical data, would be available in the river at least 90% of the time.

3.4. Environmental Flows

An environmental flow is the water regime that needs to be provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated. Environmental Flows provide critical contributions to river health, economic development and poverty alleviation. They ensure the continued availability of the many benefits that healthy river and groundwater systems bring to society.

To start with Environmental Flows, one needs to consider all aspects of the river and drainage system in their context. This means looking at the basin from its headwaters to the estuarine and coastal environments and including its wetlands, floodplains and associated groundwater systems. It also means considering environmental, economic, social and cultural values in relation to the entire system. A wide range of outcomes, from environmental protection to serving the needs of industries and people, are to be considered for the setting of an Environmental Flows.

To set an Environmental Flows, one needs to identify clear objectives as well as water abstraction and use scenarios. Objectives should have measurable indicators that can form the basis for water allocations. Objectives and scenarios can best be defined with multi-discipline expert teams and stakeholder representatives.

4. Recommended Methodology

The basic procedure for assessing E-Flows adopting BBM (referred here in as Bigger Block Method rather than Building Block Method) is summarized as follows.

1. Generation of Stage-Discharge curve at the E-Flows site using river cross section and hydraulic modelling.
2. Identification of keystone species* for the stretch that represents the E-Flows site.
3. Assessment of temporal variations in depth of flow required to ensure survival and natural growth of keystone species*.
4. Assessment of temporal variations in depth of flow from geomorphological considerations factoring longitudinal connectivity in all seasons and lateral connectivity of active flood plain for the historically observed number of days during monsoon season.
5. Assessment of minimum ecological depth of flow (higher of steps 3 and 4 above) and generation of hydrograph for Minimum Ecological Requirements (MER) using Stage-Discharge Curve.

6. Determination of Average Flows and 90% Dependable Flows from historical flow data or hydrological modelling.
7. Applying the trend of variation of 90% Dependable Flows with the estimated Minimum Ecological Requirement to obtain E-Flows hydrograph for dry and wet seasons subject to the condition that minimum flow in wet season is to be more than or equal to the highest recommended E-Flows during the dry season.
8. Comparison of E-Flows and MER hydrograph with hydrographs for average and 90% dependable virgin flows.
9. Assessing the River Health for different Flow Regimes.

*Keystone species: A species that has disproportionately large effect on the environment relative to its abundance (Paine 1995). Such species are described as playing a critical role in maintaining the structure of an ecological community, affecting many other organisms in an ecosystem and helping to determine the types and numbers of various other species in the community.

4.1 Minimum Ecological Requirement

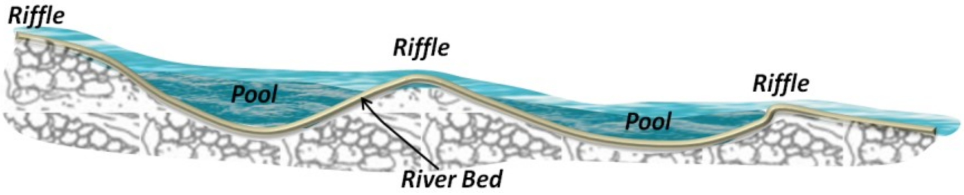
The objective of the E-Flows is the restoration of the river health. However, the river health itself depends on a wide range of variables. Identifying and addressing them individually is a complex and non-linear problem.

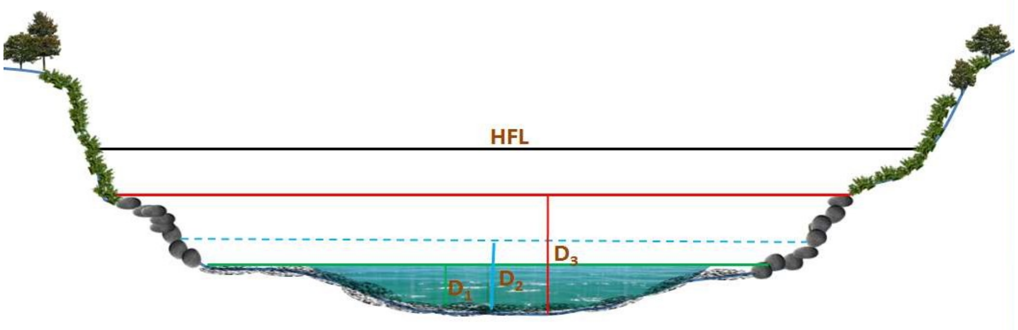
For upper Ganga Rivers, keystone fish species, such as Mahseer and Snow trout, are in danger due to fragmentation and loss of connectivity of the river due to the construction of numerous dams, barrages, and reservoirs. Also these fish species govern the minimum depth of flow required for sustenance of the aquatic species, and hence are given priority for assessing E-Flows. In general, for any specific site the relevant aquatic species in the stretch that represents the E-Flows site and governs the minimum depth of flow is referred as “key-stone species”.

Referring to Figure 1, flows corresponding to minimum depth D_1 are required during all seasons for general mobility of keystone species. For the spawning period of keystone species, flows corresponding to depth D_2 are needed throughout the spawning season.

Assessment of temporal variations in depth of flow from geomorphological considerations factoring longitudinal connectivity in all seasons and lateral connectivity of active flood plain for the historically observed number of days during monsoon season reveals that the increased discharges corresponding to depth D_3 are needed for almost 18 days during the monsoon season.

Riffle and Pool Locations in Longitudinal River Profile





River Cross-Section at E-Flow Site

D_1 – Depth of water required for mobility of keystone species during lean period.
D_2 – Depth of water required for mobility of keystone species during spawning period.
D_3 – Depth of water required to inundate some sand bars, riparian vegetation, etc. for …….18 days/year.

Figure 1: E-Flows Assessment – Conceptual Diagram

To determine these requirements, the keystone species in the given river stretches are identified, and the required depths D_1 and D_2 are determined for these species. Since flow depths at pools are higher than at riffles, hence the critical E-Flows sites are selected at riffle sections, thus ensuring that the flow depths in the entire reach will not be less than D_1 or D_2. The flows corresponding to D_1 and D_2 are then read from the stage-discharge curves for the given sites. To determine D_3, the virgin flows that were exceeded for 18 days (on an average) during the monsoon (i.e. between June and October, but generally between July and September) are computed. This, in concept corresponds to virgin flows having 20% dependability during monsoons. The depth D_3 is then read from the stage-discharge curve and verified against the available river flow depth at the site.

Estimating $D_{1,}$ D_2 and $D_{3,}$ and the corresponding discharges from the hydraulic model leads to estimation of minimum ecological requirements (MER) of the river for the corresponding periods (e.g. non-monsoon and monsoon).

4.2 E-Flows Hydrograph

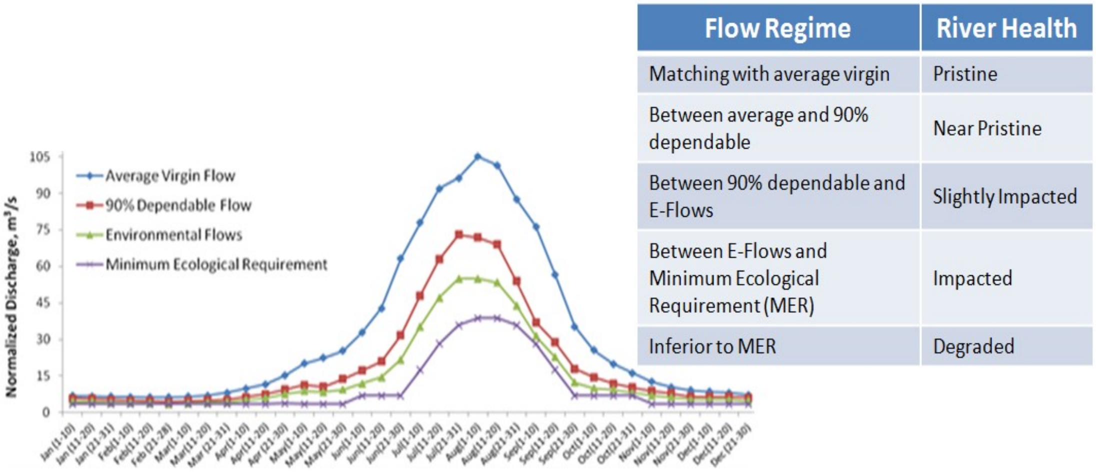
Environmental Flows are computed based on minimum ecological requirements and is done separately for monsoon (wet) and non-monsoon (dry) periods. Daily Average Flows and 90% Dependable Flows are first computed from historical flow data. The Environmental Flows are obtained by mimicking the trend in daily 90% dependable flow using the minimum ecological requirement for non-monsoon season as the minimum E-Flows for non-monsoon period. For monsoon season, the flows corresponding to D_3 is first deducted from the 90% dependable flow, and a higher value between the flow corresponding to D_2 and maximum E-Flows during non-monsoon seasons, is specified as minimum monsoonal flow. The Environmental Flows for monsoon period are obtained by mimicking the trend in daily 90% dependable flow using the minimum monsoonal flow. Later, the deducted flow magnitudes are added to the mimicked hydrograph.

4.3 River Health Regime (RHR)

The procedure mentioned above delineates the entire river flow distribution into several flow regimes. The limits of these regimes are determined by the (i) Average flow, (ii) 90% dependable flow, (iii) E-Flows, and (iv) Minimum Ecological Requirements.

The lower limit, Minimum Ecological Requirement, may be considered essential for minimal river functioning (with bare survival of biota), while the higher limit, average flow, will allow healthy river functioning (allowing maintenance of healthy biodiversity and production of ecosystem goods and services by the river). Thus, 5 health regimes for river flow condition called River Health Regimes (RHR), viz. Pristine, Near Pristine, Slightly Impacted, Impacted, and Degraded are defined.

Any river flow regime matching the average flow regime is considered to be in **Pristine** state/condition. River flow regime that is between 90% dependable flow and average indicates **Near-Pristine** state/condition. Flow regime between E-Flows and 90% dependable flows indicates the river to be in **Slightly Impacted** state/condition. Flow regimes inferior to E-Flows but better than Minimum Ecological Requirements is considered to be in **Impacted** state/condition. However, flow regime inferior than the flow corresponding to Minimum Ecological Requirement would render the river in **Degraded** state/condition. This conceptual framework for RHR is illustrated through Figure 2.



Flow Regime	River Health
Matching with average virgin	Pristine
Between average and 90% dependable	Near Pristine
Between 90% dependable and E-Flows	Slightly Impacted
Between E-Flows and Minimum Ecological Requirement (MER)	Impacted
Inferior to MER	Degraded

Figure 2: Conceptual Frame Work for River Health Regime Based on Flow Regimes

It should be noted, however, that this distinction of River Health status pertains to hydrological quantities only, and not to river water quality, geomorphology or biology.

5. Illustration of E-Flows Assessment for Some Select Sites in Upper Ganga Segment

To illustrate the E-Flows Concept and Assessment Methodology, some of the selected sites on Alaknanda and Bhagirathi rivers of the Upper Ganga Segment are considered. The geo-morphological and biological features of the respective sites were analysed and the sites were physically surveyed to map the river cross-sections. The Virgin River flows for sites on Bhagirathi river were considered for the period of data availability from CWC for the period 1972 to 1982 (prior to construction of Tehri Dam when the rivers could be considered 'virgin' or undisturbed), and for the site on Alaknanda for the period 1977 to 1987. The virgin flows at the E-Flows sites were then estimated from the virgin flows at the nearest measuring stations.

E-Flows at the sites selected consider the ecological and geo-morphological requirements, which in turn, ensure the minimum ecosystem goods and services of the river (including the cultural, spiritual and livelihood requirements that depend on these).

The sample results for E-Flows and Minimum Ecological Requirements for different sites are illustrated as follows, excluding quantitative flow data (which are classified government data).

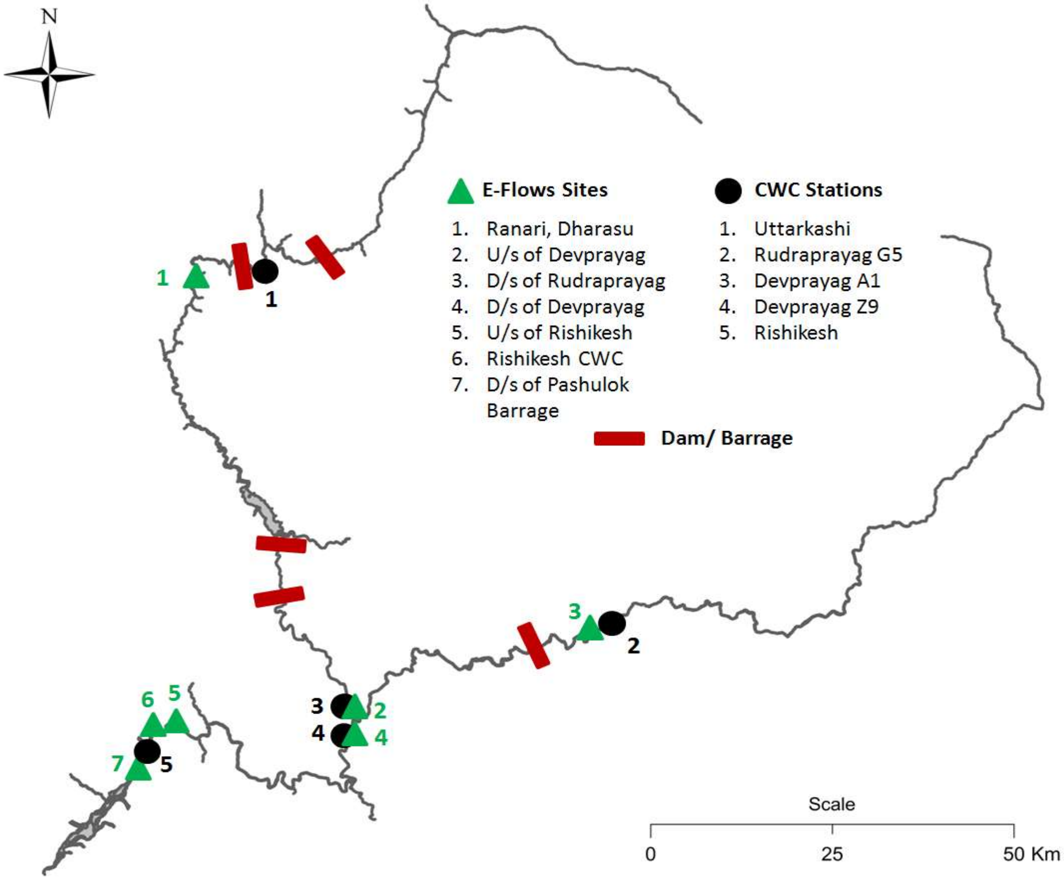


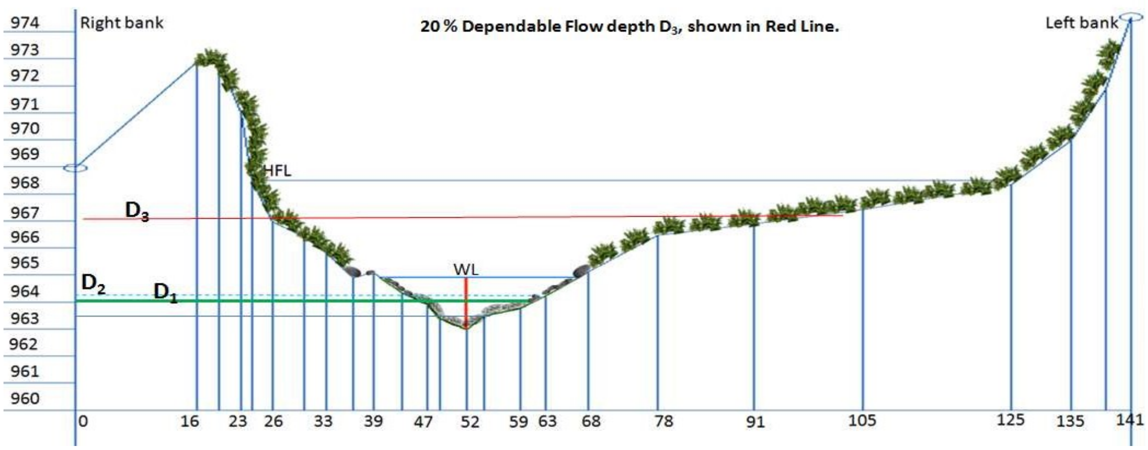
Figure 3: Location Map of Flow Monitoring Stations and E-Flows Sites

5.1 Site 1: Ranari, Dharasu on river Bhagirathi (30°43'02"N, 78°21'17"E)

Figure 4: Schematic and Photographic Representation of the E-Flows Site at Ranari, Dharasu on Bhagirathi

Table 1: Geomorphic Attributes

River style: Himalayan steep valley
Channel confinement: Confined
Channel features: Very less mid channel bars, side bars and confluence bars
Sinuosity: 1.03-2.42
No floodplain
Slope: (2.10^0) Moderate to steep slope
Symmetricity: Symmetrical channel
Bed material: Boulders, cobbles, pebbles and coarse sand in channel belt
Geomorphologically: Degradational regime



HFL (m)	Maximum Depth(m)	Bankfull Width(m)	Width/Depth ratio	Velocity (m/s)	Discharge (m^3/s)
968.4	1.9	26.5	13.9	NA	NA

Figure 5: River Cross-section at Ranari, Dharasu

Table 2: Salient Features of Biotic Components of the River Aquatic System at Ranari, Dharasu

River Stretch	UG2 (Gangnani to Devprayag)
Algal diversity	Total Taxa: 151; Diatoms: 123; Green algae: 21; Blue green: 06
Algal ratio (D* G* BG*)	100:17:5 (123, 21, 6)
Specific Zoobenthos	Plecoptera, Tricoptera, Ephemeroptera, Diptera, Coleoptera
Carps/All Fish taxa	0.65 (23/35)
Carps/Cat fishes	3.83 (23/6)
RET Fish species	14
Characteristic fish species	Snow Trout (*Schizothorax richardsonii*)
Higher vertebrates	No aquatic higher vertebrates

Table 3: Description of Key-stone Species, Corresponding D_1 and D_2, and Computed D_3 at Ranari, Dharasu

Keystone Species	**Required Depths for E-flows**		
	D_1	**D_2**	**D_3**
SnowTrout *(Schizothorax richardsonii)*	0.5 m	0.8 m	3.41 m
Golden Mahseer *(Tor putitora)*			

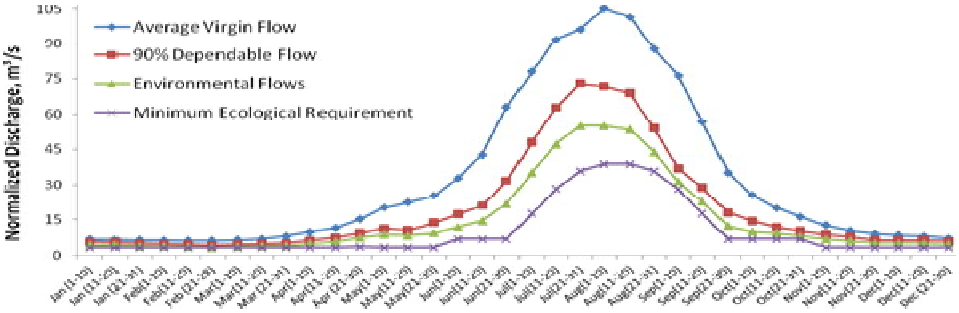


Figure 6a: Representation of Various Flow Regimes in Bhagirathi River at Ranari, Dharasu over 12 Months

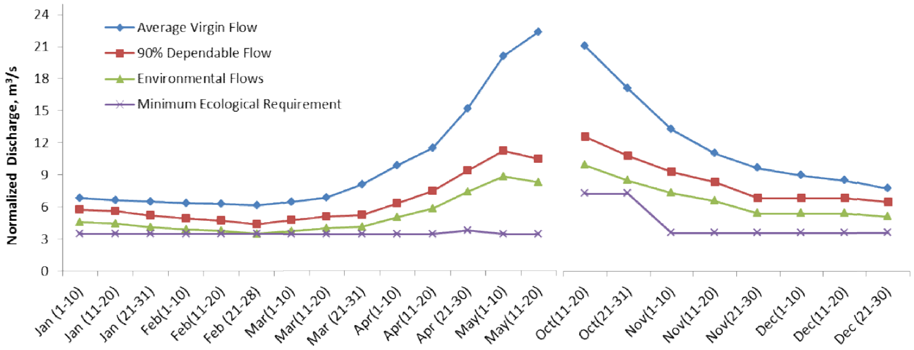


Figure 6b: Representation of Various Flow Regimes in Bhagirathi River at Ranari, Dharasu during Non-Monsoon Period

Table 4: Assessed E-Flows as Percentage of Virgin River Flows in Bhagirathi River at Ranari, Dharasu

Basis	Minimum Ecological Requirement as % of Average Virgin Flow	E-Flows as % of Average Virgin Flow	E-Flows as % of 90% Dependable Flow
Wet Period	32.59	46.13	61.04
Dry Period	32.96	53.12	67.23
Total	32.67	47.54	62.29

As seen from the above results, the minimum ecological flows required to maintain river integrity are about one-third of the average virgin flows of the river in both dry and wet seasons, while the E-Flows required are about half the average virgin flows. However, this fraction varies over the year and is relatively higher during dry season, river flows being minimum in winter.

5.2 Site 2: U/S Devprayag on Bhagirathi River (30°09'06"N, 78°35'56"E)

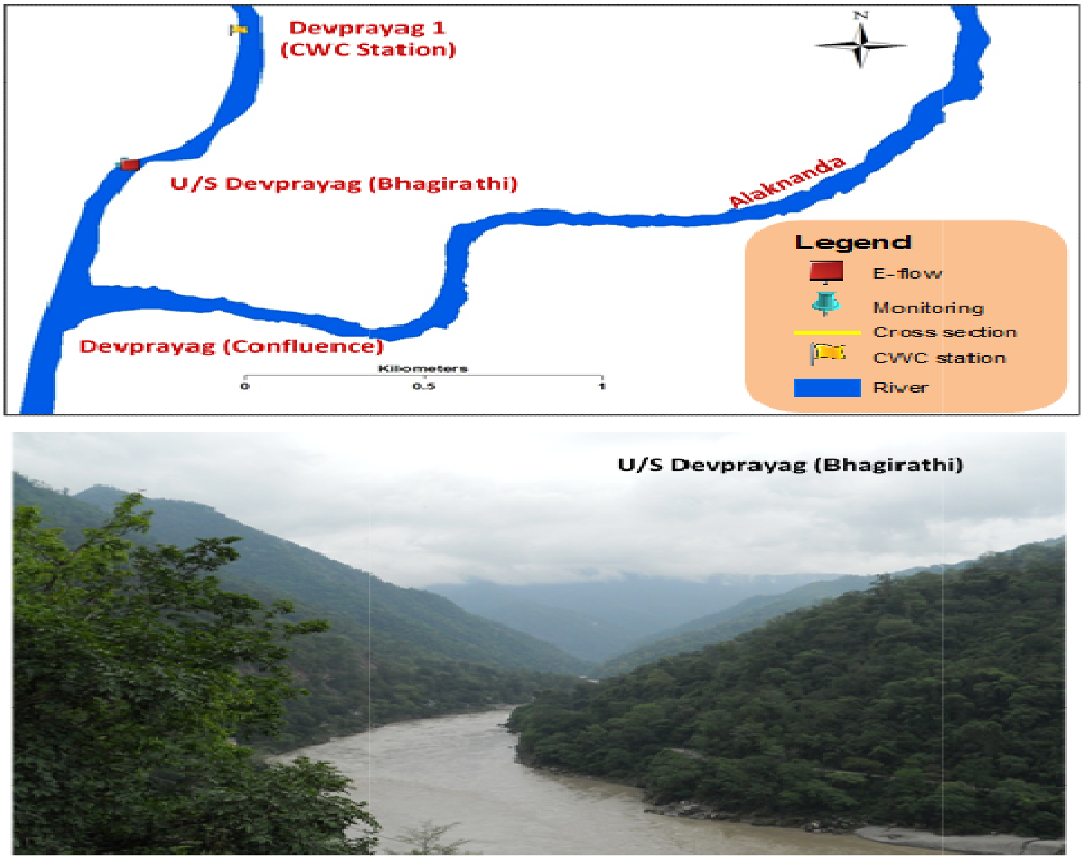
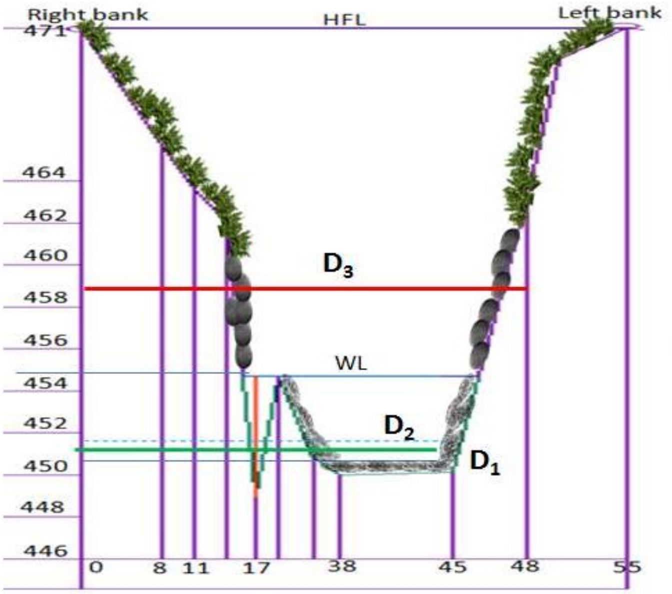


Figure 7: Schematic and Photographic Representation of the E-Flows Site at U/S Devprayag on Bhagirathi River

Table 5: Geomorphic Attributes

River style: Himalayan bedrock
Channel confinement: Confined
Channel features: Very less mid channel bars, side bars and confluence bars
Sinuosity: 1.05-1.55
No floodplain
Riffle and Pool: Present
Bed material: Boulders, cobbles, pebbles and sand are prominent bed material
Geomorphologically: Degradational regime



HFL (m)	Maximum Depth(m)	Bankfull Width(m)	Width/Depth ratio	Velocity (m/s)	Discharge (m^3/s)
471	5.7	24.2	4.2	NA	NA

Figure 8: River Cross-section at U/S Devprayag on Bhagirathi River

Table 6: Salient Features of Biotic Components of the River Aquatic System at U/S Devprayag on Bhagirathi River

River Stretch	UG2 (Gangnani to Devprayag)
Algal diversity	Total Taxa: 151; Diatoms: 123; Green algae: 21; Blue green: 06
Algal ratio (D* G* BG*)	100:17:5; (123, 21, 6)
Specific Zoobenthos	Plecoptera, Tricoptera, Ephemeroptera, Diptera, Coleoptera
Carps/All Fish taxa	0.65 (23/35)
Carps/Cat fishes	3.83 (23/6)
RET Fish species	14
Characteristic fish species	Snow Trout *(Schizothorax richardsonii)*
Higher vertebrates	No aquatic higher vertebrates

Table 7: Description of Key-stone Species, Corresponding D_1 and D_2, and computed D_3 at U/S Devprayag on Bhagirathi River

Keystone Species	Required Depths for E-flows		
	D_1	D_2	D_3
Snow Trout *(Schizothorax richardsonii)* **Golden Mahseer** *(Tor putitora)*	0.5 m	0.8 m	8.48 m

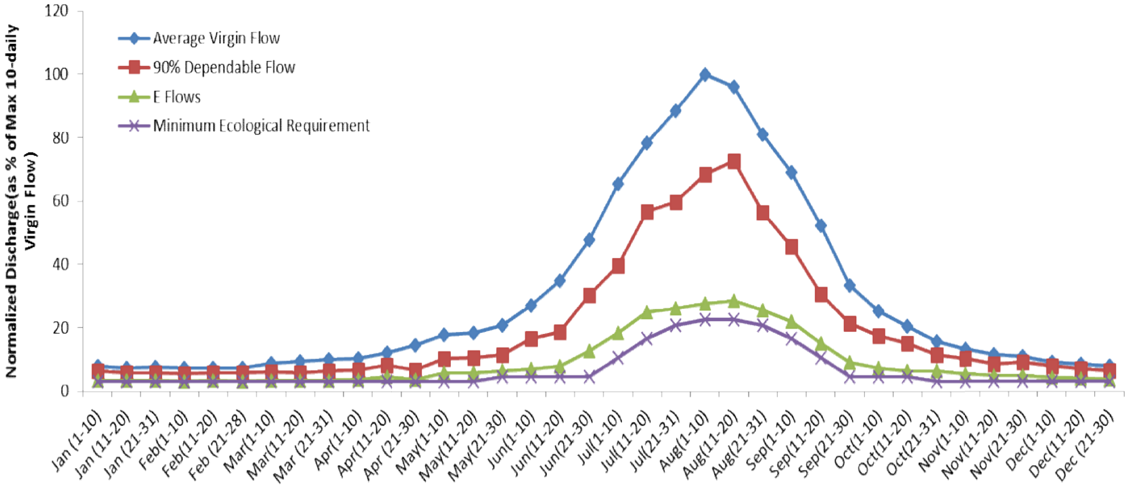


Figure 9a: Representation of Various Flow Regimes at U/S Devprayag on Bhagirathi River over 12 Months

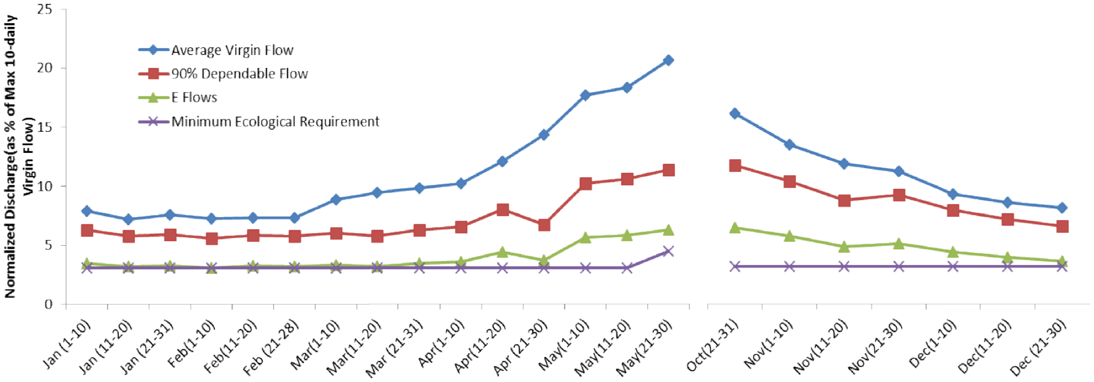


Figure 9b: Representation of Various Flow Regimes at U/S Devprayag on Bhagirathi River during Non-Mansoon Period

Table 8: Assessed E-Flows as Percentage of Virgin River Flows at U/S Devprayag on Bhagirathi River

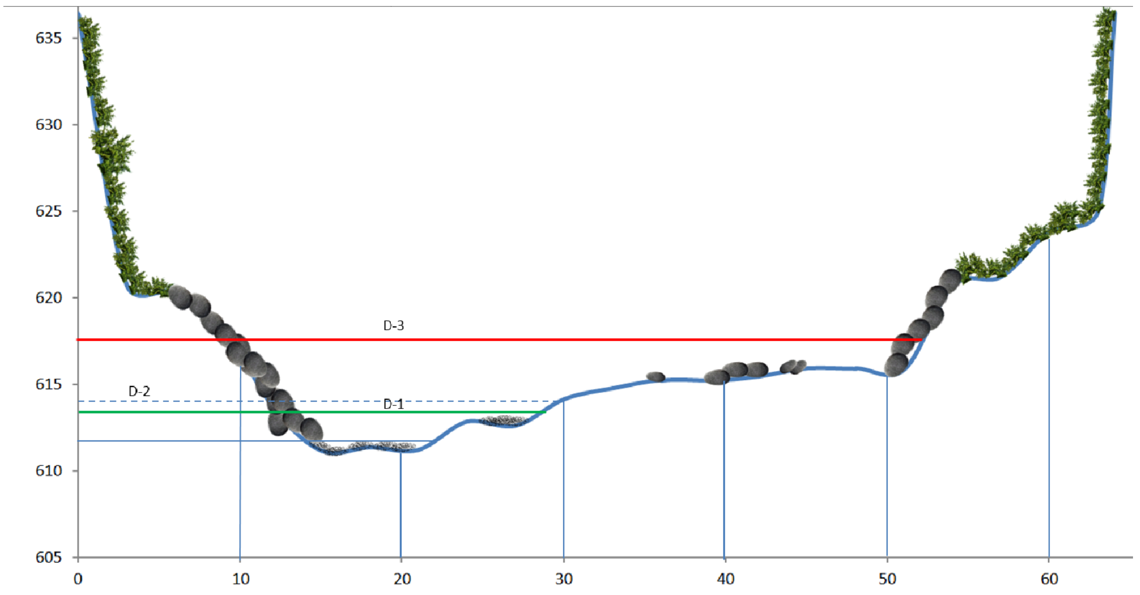
Basis	Minimum Ecological Requirement as % of Average Virgin Flow	E-Flows as % of Average Virgin Flow	E-Flows as % of 90% Dependable Flow
Wet Period	29.00	37.98	68.77
Dry Period	20.48	29.04	67.02
Total	22.27	31.09	67.42

5.3 Site 3: D/S Rudraprayag on Alaknanda River (30°16'23"N, 78°57'41"E)

Figure 10: Schematic and Photographic Representation of the E-Flows Site atD/S Rudraprayag on Alaknanda River

Table 9: Geomorphic Attributes

River style: Himalayan bedrock
Channel confinement: Confined
Channel features: Very less mid channel bars, side bars and confluence bars
Sinuosity: 1.05-1.55
No floodplain
Riffle and Pool: Present
Bed material: Boulders, cobbles, pebbles and sand are prominent bed material
Geomorphologically: Degradational regime



HFL (m)	Maximum Depth(m)	Bankfull Width(m)	Width/Depth ratio	Velocity (m/s)	Discharge (m^3/s)
471	5.7	24.2	4.2	NA	NA

Figure 11: River Cross-section at D/S Rudraprayag on Alaknanda River

Table10: Salient Features of Biotic Components of the River Aquatic System at D/S Rudraprayag on Alaknanda River

River Stretch	Vishnuprayag to Devprayag
Algal diversity	Total Taxa: 186; Diatoms: 164; Green algae: 15; Blue green: 7
Algal ratio (D* G* BG*)	100:9:4(164, 15, 7)
Specific Zoobenthos	Plecoptera, Tricoptera, Ephemeroptera, Diptera, Coleoptera
Carps/ All Fish taxa	0.60 (26/43)
Carps/ Cat fishes	5.4 (43/8)
RET Fish species	10
Characteristic fish species	Snow Trout (*Schizothorax richardsonii*)
Higher vertebrates	No aquatic higher vertebrates

Table 11: Description of Key-stone Species, Corresponding D_1 and D_2, and Computed D_3 at D/S Rudraprayag on Alaknanda River

Keystone Species	**Required Depths for E-flows**		
	D_1	**D_2**	**D_3**
SnowTrout *(Schizothorax richardsonii)*	0.5 m	0.8 m	4.23 m
Golden Mahseer *(Tor putitora)*			

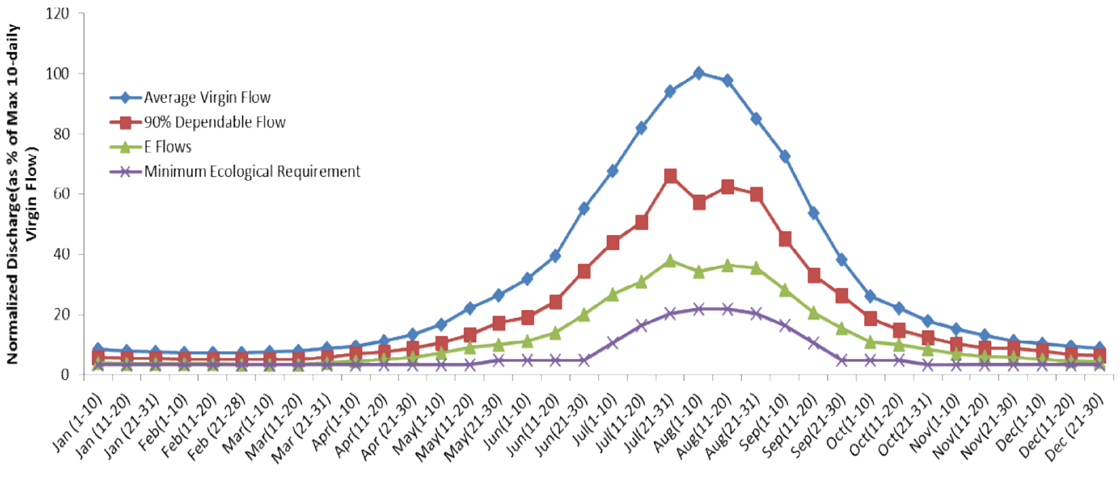


Figure 12a: Representation of Various Flow Regimes at D/S Rudraprayag on Alaknanda River over 12 Months

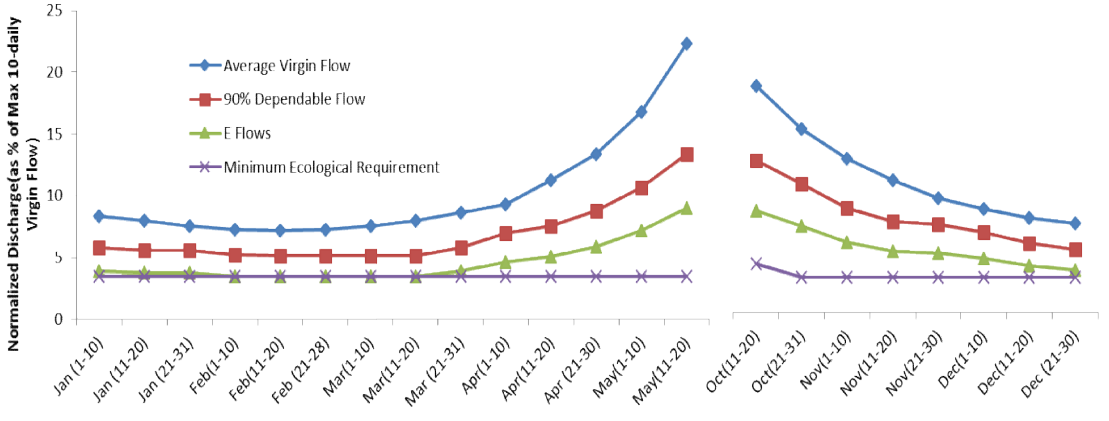


Figure 12b: Representation of Various Flow Regimes at D/S Rudraprayag on Alaknanda River during Non-Mansoon Period

Table 12: Assessed E-Flows as Percentage of Virgin River Flows at D/S Rudraprayag on Alaknanda River

Basis	Minimum Ecological Requirement as % of Average Virgin Flow	E-Flows as % of Average Virgin Flow	E-Flows as % of 90% Dependable Flow
Wet Period	31.71	46.19	68.62
Dry Period	19.30	38.16	64.29
Total	21.83	39.95	65.26

5.4 Site 4: D/S Devprayag on Ganga River (30°08'27"N, 78°35'47"E):

Figure 13: Schematic and Photographic Representation of the E-Flows Site at D/S Devprayag on Ganga River

Table 13: Geomorphic attributes

River style: Himalayan steep valley

Channel confinement: Confined

Channel features: Very less mid channel bars, side bars and confluence bars

Sinuosity: 1.03-2.42

No floodplain

Slope: (1.83^0) Moderate to steep slope

Channel incision: Incised

Symmetricity: Symmetrical channel

Bed material: Boulders, cobbles, pebbles ,sand

Geomorphologically: Degradational regime

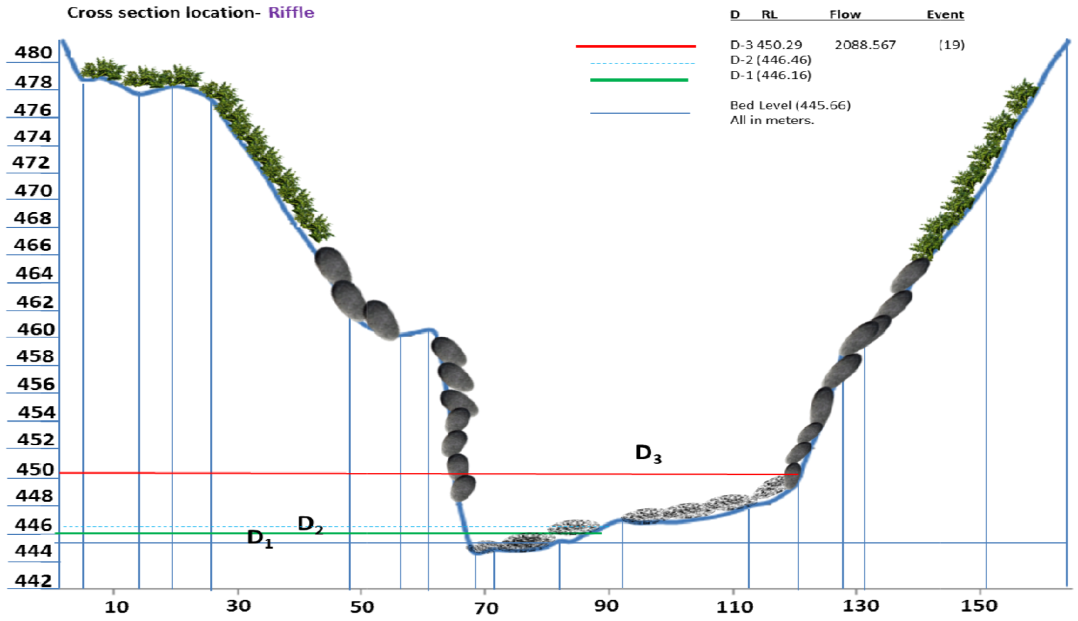


Figure 14: River Cross-section at D/S Devprayag on Ganga River

Table 14: Salient Features of Biotic Components of the River Aquatic System at U/S Devprayag on Ganga River

River Stretch	UG3 (Devprayag to Haridwar)
Algal diversity	Total Taxa: 123; Diatoms: 95; Green algae: 13; Blue green: 12
Algal ratio (D* G* BG*)	100:14:13 (95, 13, 12)
Specific Zoobenthos	Tricoptera, Ephemeroptera, Diptera, Odonata
Carps/ All Fish taxa	0.59(25/42)
Carps/ Cat fishes	3.57(25/7)
RET Fish species	8
Characteristic fish species	Snow Trout (*Schizothorax richardsonii*) Golden Mahseer(*Tor putitora*)
Higher vertebrates	No aquatic higher vertebrates

Table 15: Description of Key-stone Species, Corresponding D_1 and D_2, and Computed D_3 at D/S Devprayag on Ganga River

Keystone Species	**Required Depths for E-flows**		
	D_1	**D_2**	**D_3**
SnowTrout *(Schizothorax richardsonii)*	0.5 m	0.8 m	4.63 m
Golden Mahseer *(Tor putitora)*			

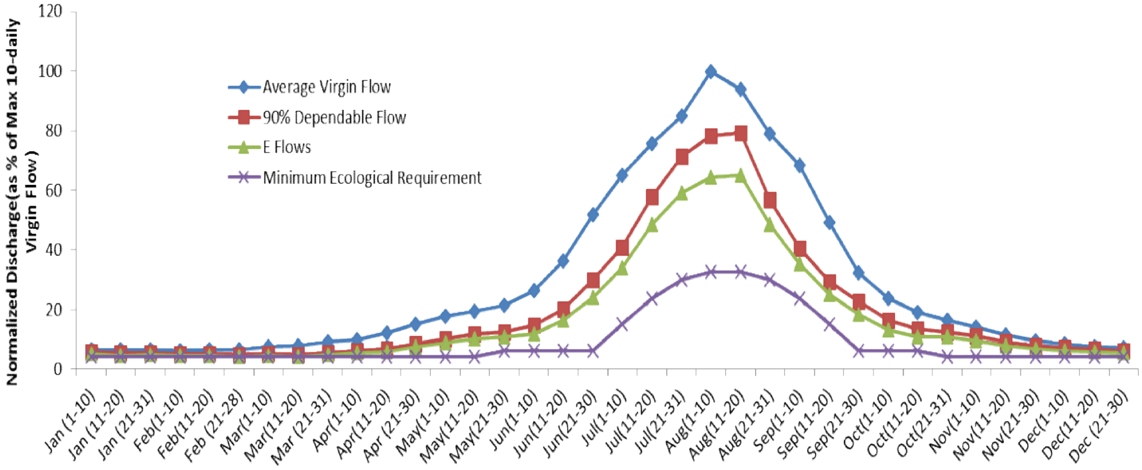


Figure 15a: Representation of Various Flow Regimes at D/S Devprayag on Ganga River over 12 Months

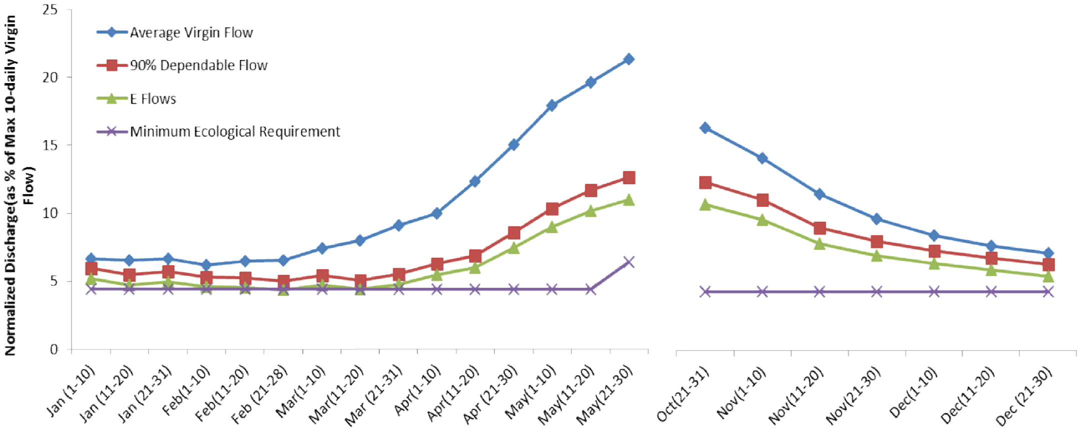


Figure 15b: Representation of Various Flow Regimes at D/S Devprayag on Ganga River during Non-Monsoon Period

Table 16: Assessed E-Flows as Percentage of Virgin River Flows at D/S Devprayag on Ganga River

Basis	Minimum Ecological Requirement as % of Average Virgin Flow	E-Flows as % of Average Virgin Flow	E-Flows as % of 90% Dependable Flow
Wet Period	43.21	61.47	70.83
Dry Period	29.98	59.00	71.05
Total	32.69	59.55	71.00

5.5 Site 5: U/S Rishikesh on River Ganga (30°43'02"N, 78°21'17"E)

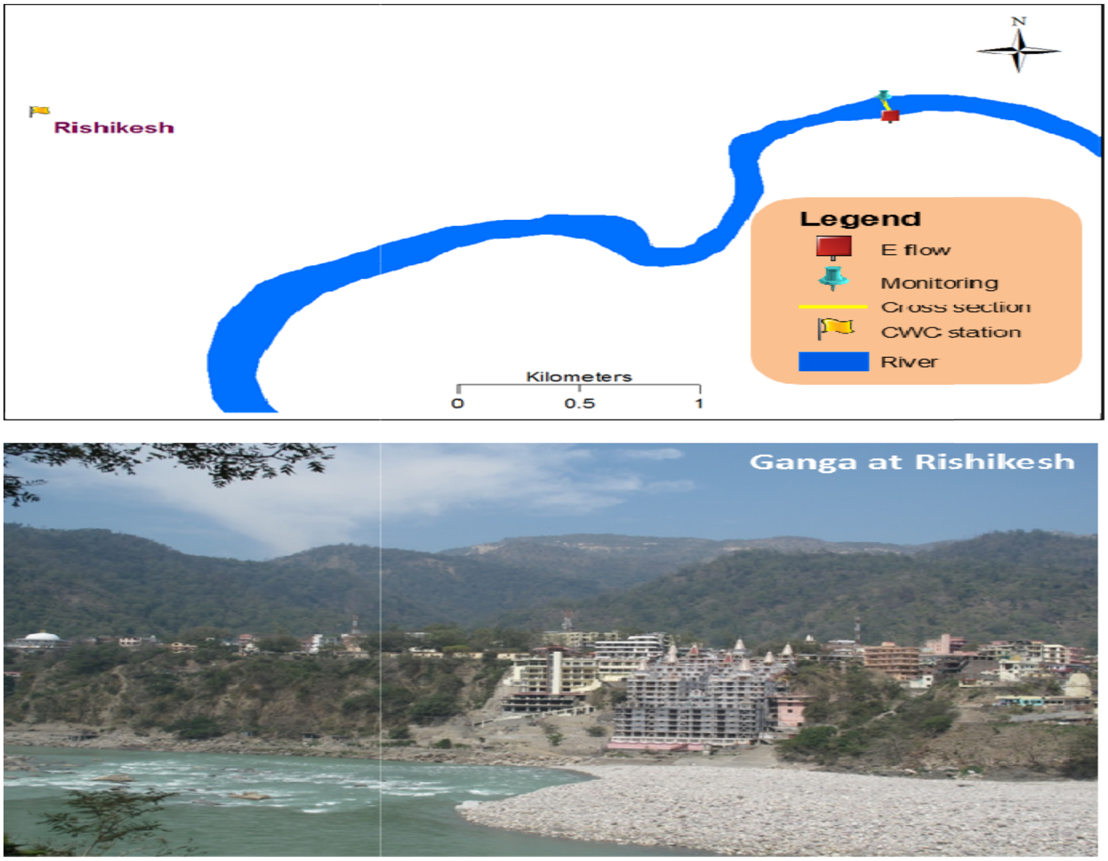
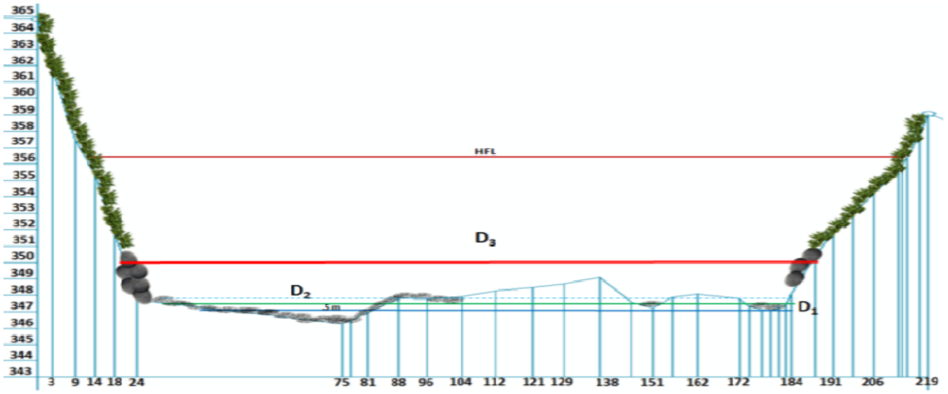


Figure 16: Schematic and Photographic Representation of the E-Flows Site at U/S Rishikesh on River Ganga

Table 17: Geomorphic Attributes

River style: Transition of Himalayan Bedrock and alluvial setting
Channel confinement: Partly confined
Channel features: Alluvial islands, mid channel bars and side bars
Sinuosity: 1.18.40
Active floodplain: Valley width-1:5
Slope: 0.518^0
Bed material: Conglomerate, cobbles, pebbles and sand are present
Geomorphologically: Agradational regime



HFL (m)	Maximum Depth(m)	Bankfull Width(m)	Width/Depth ratio	Velocity (m/s)	Discharge (m^3/s)
356.5	1.8	161.5	89.7	NA	NA

Figure 17: River Cross-section at U/S Rishikesh on River Ganga

Table 18: Salient Features of Biotic Components of the River Aquatic System at U/S Rishikesh on River Ganga

River Stretch	UG3 (Devprayag to Haridwar)
Algal diversity	Total Taxa: 123; Diatoms: 95; Green algae: 13; Blue green: 12
Algal ratio (D* G* BG*)	100:14:13 (95, 13, 12)
Specific Zoobenthos	Tricoptera, Ephemeroptera, Diptera, Odonata
Carps/ All Fish taxa	0.59 (25/42)
Carps/ Cat fishes	3.57(25/7)
RET Fish species	8
Characteristic fish species	Golden Mahseer (*Tor putitora*)
Higher vertebrates	No aquatic higher vertebrates

Table 19: Description of key-stone species, corresponding D_1 and D_2, and Computed D_3 at U/S Rishikesh on River Ganga

Keystone Species	Required Depths for E-flows		
	D_1	D_2	D_3
Golden Mahseer *(Tor putitora)*	0.5 m	0.8 m	2.91 m

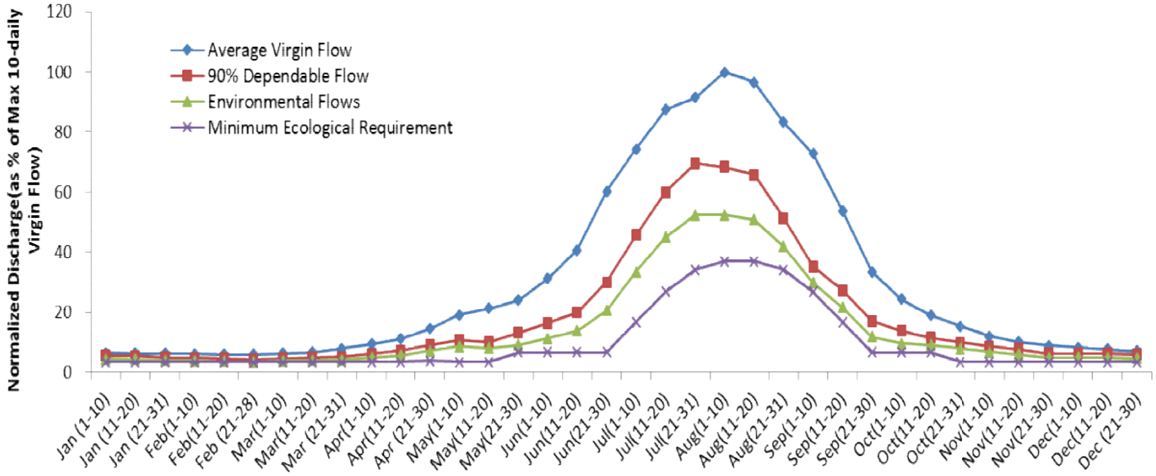


Figure 18a: Representation of Various Flow Regimes at U/S Rishikesh on River Ganga over 12 Months

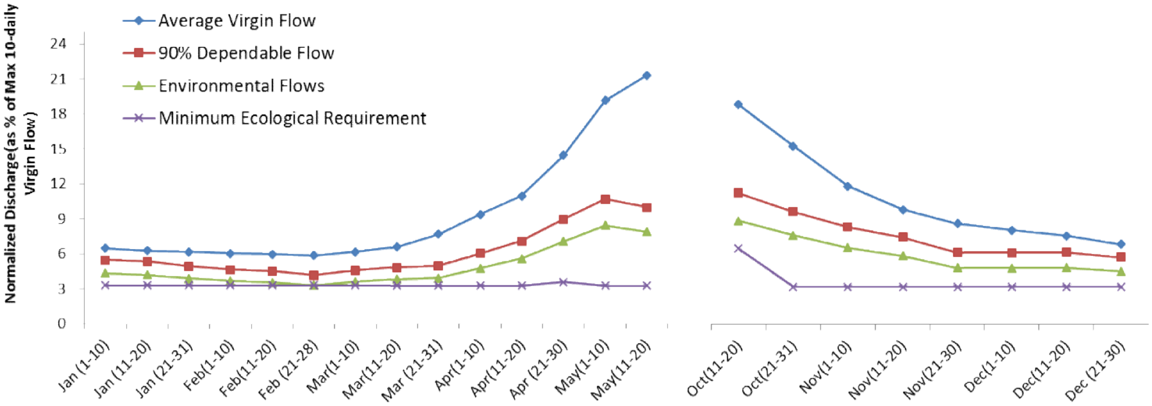


Figure 18b: Representation of Various Flow Regimes at U/S Rishikesh on River Ganga during Non-Monsoon Period

Table 20: Assessed E-Flows as Percentage of Virgin River Flows at U/S Rishikesh

Basis	Minimum Ecological Requirement as % of Average Virgin Flow	E-Flows as % of Average Virgin Flow	E-Flows as % of 90% Dependable Flow
Wet Period	53.00	67.29	72.42
Dry Period	30.23	50.23	64.16
Total	33.71	53.64	65.81

5.6 Site 6: Rishikesh CWC Monitoring Site on River Ganga (30°08'02”N, 78°20'11"E):

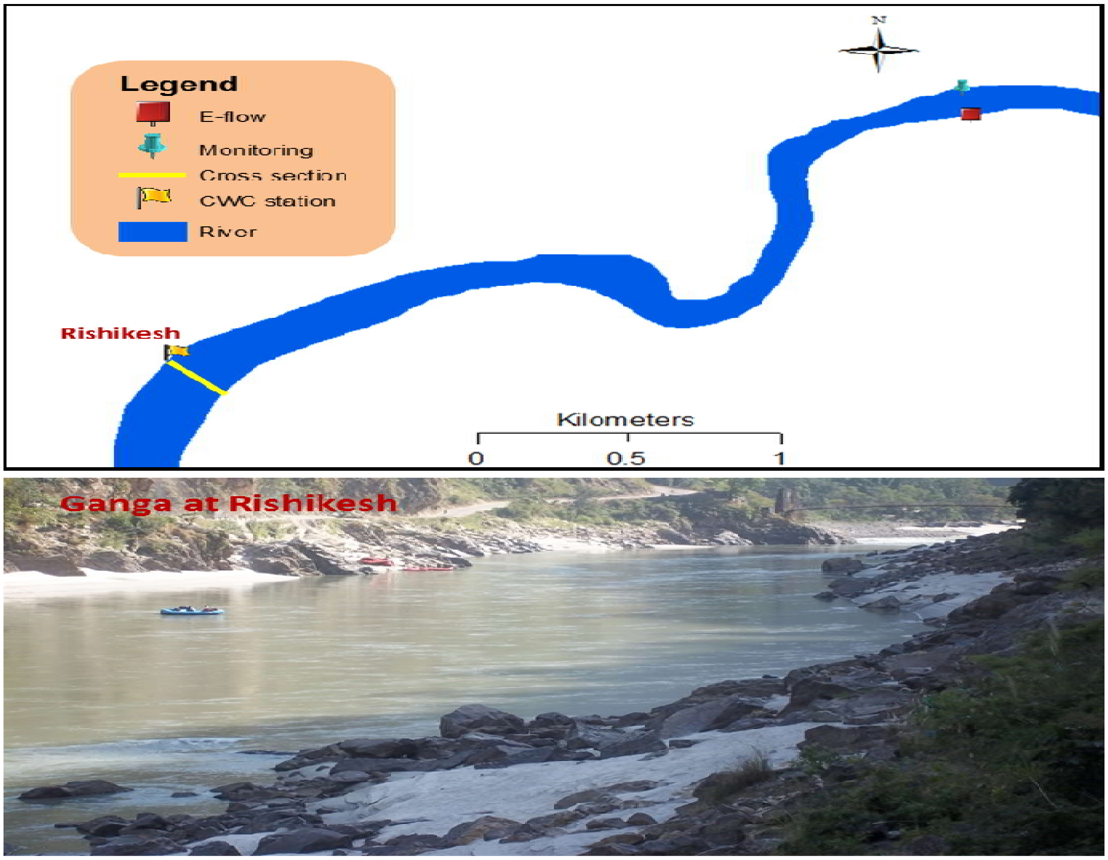
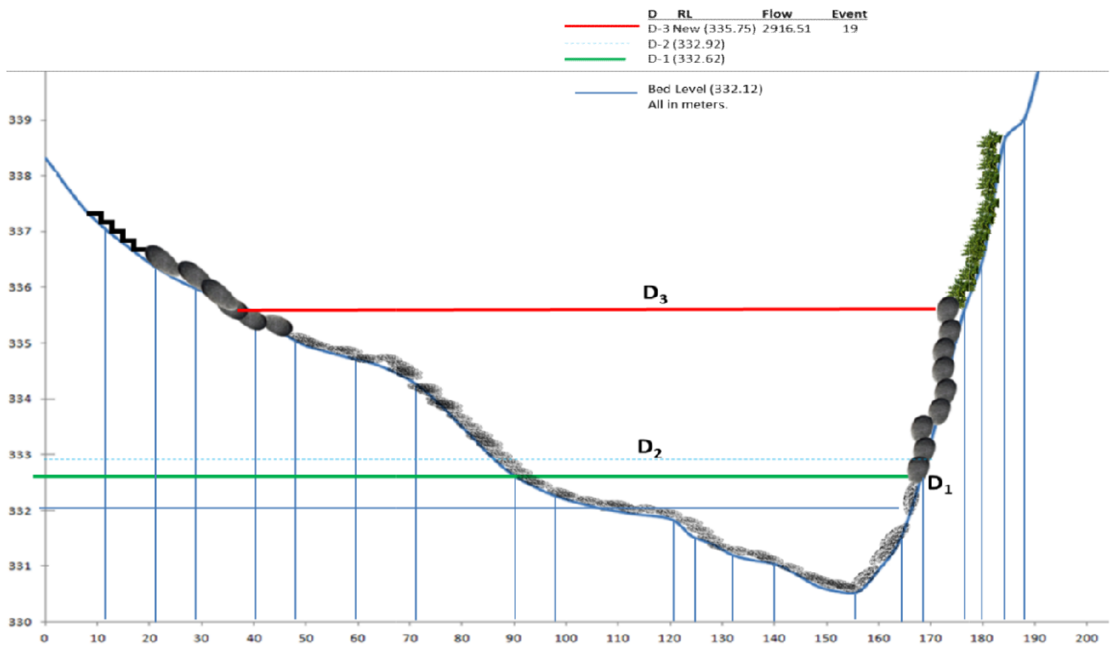


Figure 19: Schematic and Photographic Representation of the E-Flows Site at Rishikesh CWC Monitoring Site on River Ganga

Table 21: Geomorphic attributes

River style: Transition of Himalayan Bedrock and alluvial setting
Channel confinement: Partly confined
Channel features: Alluvial islands, mid
Sinuosity: 1.18.40
Active floodplain: Valley width-1:5
Slope: 0.518^0
Bed material: Conglomerate, cobbles, pebbles and sand are present
Geomorphologically: Agradational regime



HFL (m)	Maximum Depth(m)	Bankfull Width(m)	Width/Depth ratio	Velocity (m/s)	Discharge (m^3/s)
356.5	1.8	161.5	89.7	NA	NA

Figure 20: **River Cross-section at Rishikesh CWC Monitoring Site on River Ganga**

Table 22: **Salient Features of Biotic Components of the River Aquatic System at Rishikesh CWC Monitoring Site on River Ganga**

River Stretch	UG3 (Devprayag to Haridwar)
Algal diversity	Total Taxa: 123; Diatoms: 95; Green algae: 13; Blue green: 12
Algal ratio (D* G* BG*)	100:14:13 (95, 13, 12)
Specific Zoobenthos	Tricoptera, Ephemeroptera, Diptera, Odonata
Carps/All Fish taxa	0.59 (25/42)
Carps/Cat fishes	3.57 (25/7)
RET Fish species	8
Characteristic fish species	Golden Mahseer (*Tor putitora*)
Higher vertebrates	No aquatic higher vertebrates

Table 23: **Description of key-stone species, corresponding D_1 and D_2, and computedD_3 at Rishikesh CWC Monitoring Site on River Ganga**

Keystone Species	**Required Depths for E-flows**		
	D_1	**D_2**	**D_3**
Golden Mahseer *(Tor putitora)*	0.5 m	0.8 m	3.63 m

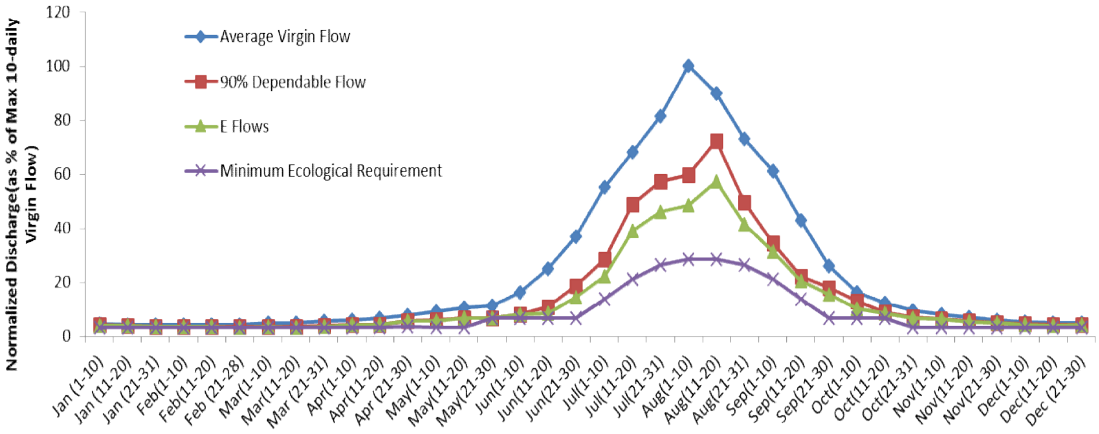


Figure 21a: Representation of Various Flow Regimes at Rishikesh CWC Monitoring Site on River Ganga over 12 Months

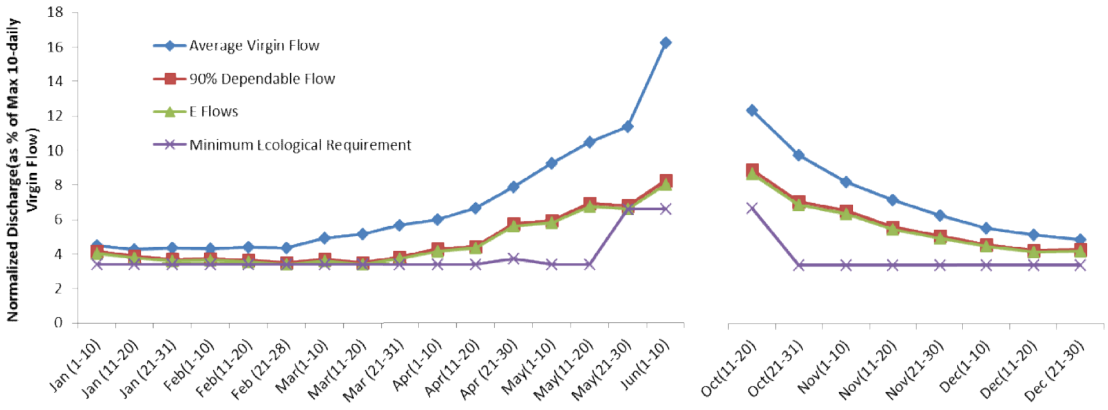


Figure 21b: Representation of Various Flow Regimes at Rishikesh CWC Monitoring Site on River Ganga during Non-Monsoon Period

Table 24: Assessed E-Flows as Percentage of Virgin River Flows at Rishikesh CWC Monitoring Site on River Ganga

Basis	Minimum Ecological Requirement as % of Average Virgin Flow	E-Flows as % of Average Virgin Flow	E-Flows as % of 90% Dependable Flow
Wet Period	55.83	70.55	72.42
Dry Period	31.72	52.55	64.16
Total	35.40	56.15	65.81

5.7 Site 7: D/S Pashulok Barrage, Rishikesh on River Ganga (30°08'02”N, 8°20'11"E)

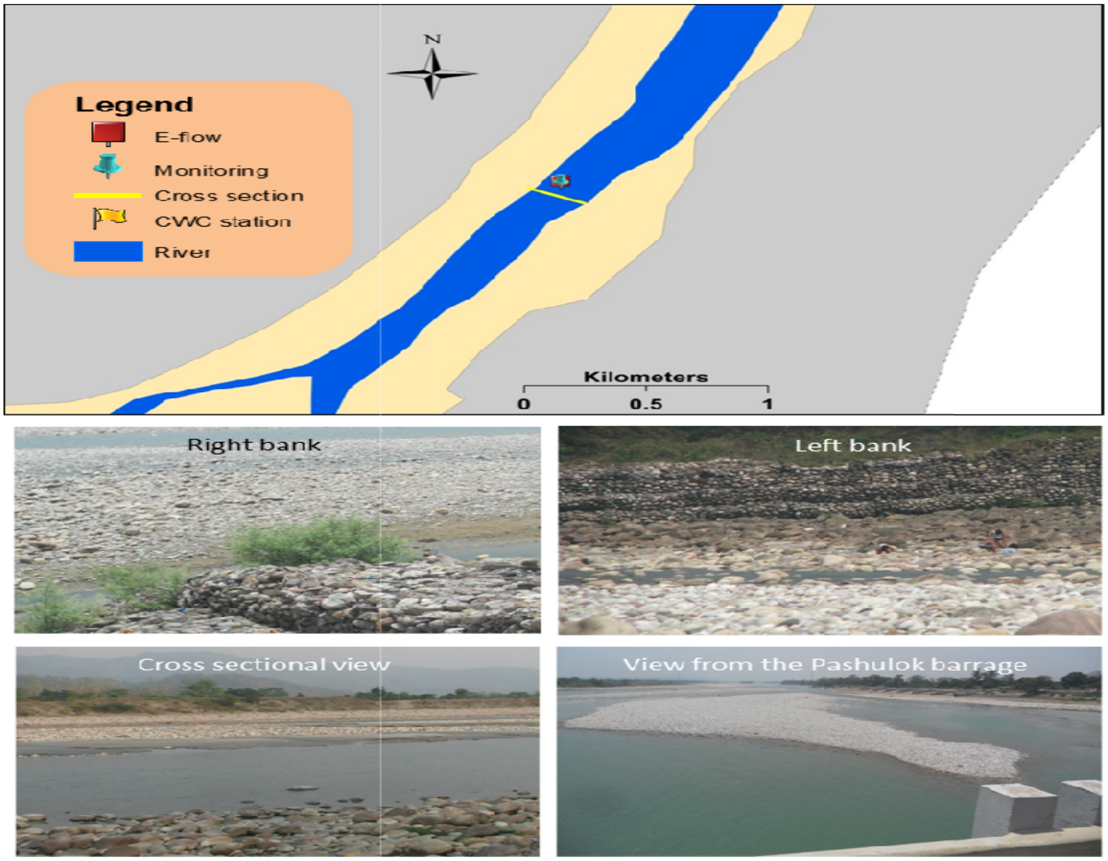
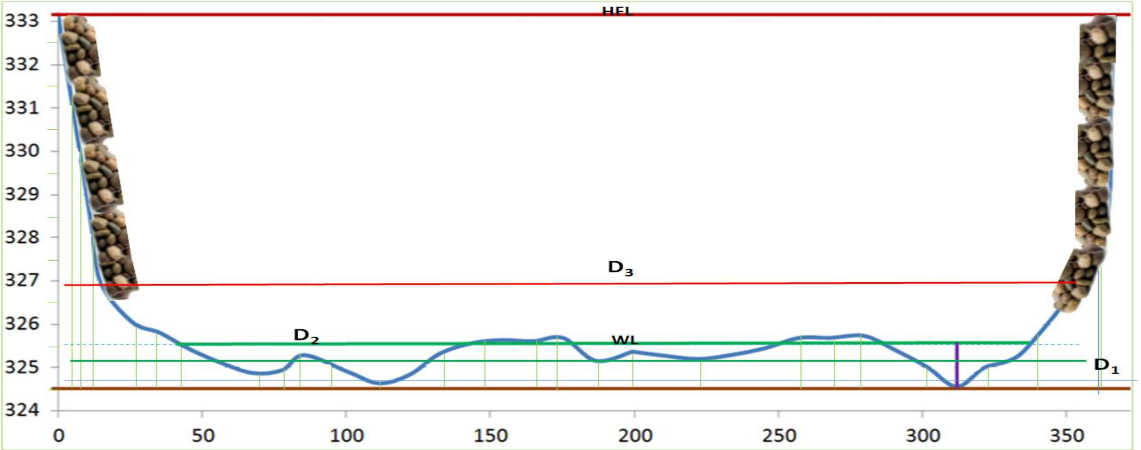


Figure 22: **Schematic and Photographic Representation of the E-Flows Site at D/S Pashulok Barrage, Rishikesh on River Ganga**

Table 25: Geomorphic attributes

River style: Himalayan Bedrock
Channel confinement: Confined
Channel features: Very less mid channel bars, side bars and confluence bars
Sinuosity: 1.18-1.40
Braid channel ratio: 1.21-2.78
Active floodplain: Valley margin width- 1:1.5
Slope: 0.518^0
Symmetricity: Asymmetrical channel
Bed material: Boulders, cobbles, pebbles and coarse sand in channel belt
Geomorphologically: Agradational regime



HFL (m)	Maximum Depth(m)	Bankfull Width (m)	Width/Depth ratio	Velocity (m/s)	Discharge (m^3/s)
333.141	1.04	294.25	282.9	NA	NA

Figure 23: River Cross-section at D/S Pashulok Barrage, Rishikesh on River Ganga

Table 26: Salient Features of Biotic Components of the River Aquatic System at D/S Pashulok Barrage, Rishikesh on River Ganga

River Stretch	UG3 (Devprayag to Haridwar)
Algal diversity	Total Taxa: 123; Diatoms: 95; Green algae: 13; Blue green: 12
Algal ratio (D* G* BG*)	100:14:13(95, 13, 12)
Specific Zoobenthos	Tricoptera, Ephemeroptera, Diptera, Odonata
Carps/All Fish taxa	0.59(25/42)
Carps/Cat fishes	3.57(25/7)
RET Fish species	8
Characteristic fish species	Golden Mahseer (*Tor putitora*)
Higher vertebrates	No aquatic higher vertebrates

Table 27: Description of key-stone species, corresponding D_1 and D_2, and Computed D_3 at D/S Pashulok Barrage, Rishikesh on River Ganga

Keystone Species	Required Depths for E-flows		
	D_1	D_2	D_3
Golden Mahseer *(Tor putitora)*	0.5 m	0.8 m	2.04 m

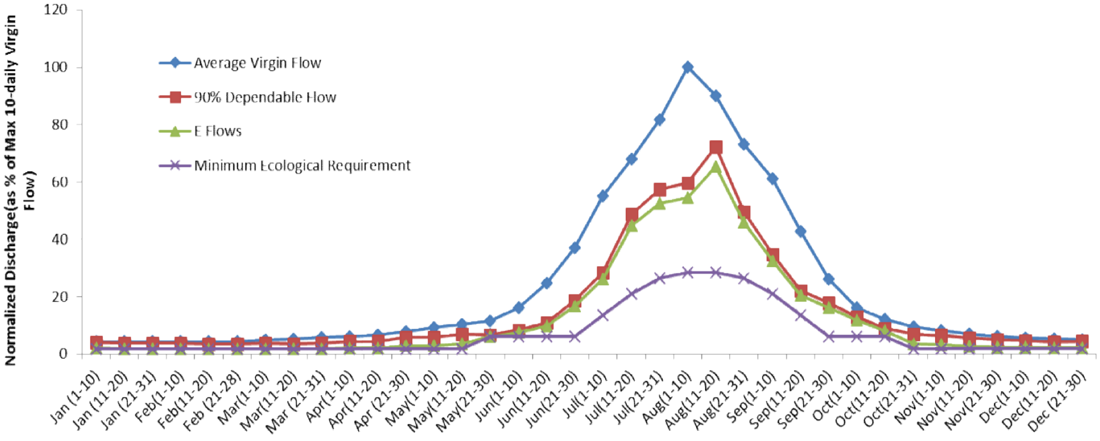


Figure 24a: Representation of Various Flow Regimes at D/S Pashulok Barrage, Rishikesh on River Ganga over 12 Months

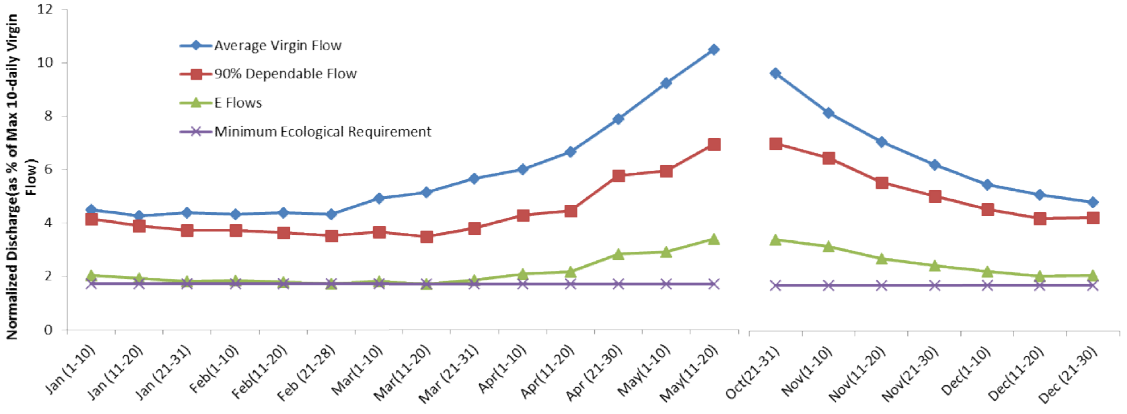


Figure 24b: Representation of Various Flow Regimes at D/S Pashulok Barrage, Rishikesh on River Ganga during Non-Maonsoon Period

Table 28: Assessed E-Flows as Percentage of Virgin River Flows at D/S Pashulok Barrage, Rishikesh on River Ganga

Basis	Minimum Ecological Requirement as % of Average Virgin Flow	E-Flows as % of Average Virgin Flow	E-Flows as % of 90% Dependable Flow
Wet Period	27.99	37.43	76.26
Dry Period	30.99	58.42	63.92
Total	30.53	55.22	65.80

6 Observations on EFA at Seven Select Sites

A summary of the Environmental Flow Assessment (EFA) exercise carried out for seven select sites in the Upper Ganga Segment is presented in Table 29. The assessed E-Flows are in the range of 35 to 59 %, 37 to 71 % and 42 to 83 % in the monsoon, non-monsoon and lean flow period respectively of the average virgin flows. Similarly, the assessed E-Flows are in the range of 61 to 71 %, 67 to 76 % and 71 to 85 % in the monsoon, non-monsoon and lean flow period respectively of the 90 % dependable virgin flows.

Table 29: Summary of EFA Results at Seven Select Sites in Upper Ganga Segment

Location	Monsoon		Non Monsoon		Lean Flow Period		Annual	
	A	B	A	B	A	B	A	B
Ranari, Dharasu on Bhagirathi River	46	61	53	67	62	79	47	62
U/S Dev Prayag on Bhagiathi River	35	67	38	69	43	77	35	67
D/S Rudra Prayag on Alaknanda River	40	64	46	69	48	71	42	65
D/S Dev Prayag on Ganga River	59	71	61	71	72	83	60	71
U/S Rishikesh on Ganga River	50	64	67	72	79	85	54	66
CWC Station Rishikesh on Ganga River	53	64	71	72	83	85	56	66
D/S Pashulok Barrage on Ganga River	58	64	37	76	42	85	55	66

Monsoon: June 1 – October 20; Non-Monsoon: October 21 – May 31; Lean Period: December 16 – March 15; A: as % of Average Virgin Flow; B: as % of 90% Dependable Flow

7 Concluding Remarks

1. E-Flows Assessment (EFA) is an important step in determining the River Health Regime (RHR).
2. E-Flows are location specific, and are essentially governed by ecological and geo-morphological requirements.
3. For EFA, information regarding (i) river hydrology, (ii) stage-discharge relationship, (iii) geo-morphological settings, (iv) bio-diversity of the stretch that represents and includes the river location under consideration is of critical significance.
4. E-Flows that maintain natural geo-morphology and biodiversity status can also be considered to fulfill and support the socio-cultural and local river-based livelihood aspirations.

5. EFA, thus is essentially a scientific process while the choice to maintain the river in a particular RHR is a social process that strives to strike a balance between societal aspirations and preservation of aquatic ecosystems.
6. Comparison of E-Flows with Virgin Flows (historical average and 90 % dependable flows) and minimum ecological requirements (MER) can guide in determining RHR in terms of Pristine, Near-Pristine, Slightly Impacted, Impacted and Degraded.
7. Achieving a specific RHR may warrant (i) certain policy decisions to set boundary conditions for planned actions (e.g. irrigation and hydropower projects that are at planning stage), and/or (ii) reversal of trends in ongoing activities (e.g. hydropower projects and water diversions schemes that are operational). The time line, resource requirements and challenges faced are expected to be different and may have to be based on strategic planning (e.g. Ganga River Basin Management Plan).
8. In this report Concept of Environmental Flows (E-Flows), Methodology for Assessing E-Flows, Concept of River Health Regime (RHR) and Criteria for assessing RHR for any specific flow regime based on state-of-the-art for Indian Rivers has been presented, which may be approved.
9. Water quality considerations are considered external to EFA as water quality is significantly influenced by anthropogenic pollution sources. Controlling pollution sources by adopting reuse and recycle policy rather than following the principle of “dilution is the solution to pollution” is a better strategy in water stressed regions.
10. The E-Flows methodology has been illustrated for seven locations on river Ganga and some of her head-streams up to Rishikesh for which the relevant data/information was available with IITC. Similar exercise may be carried out for all desired locations on the main stem of river Ganga as well as all her tributaries once the relevant data and information as stated at point 3 above are collated.
11. It is to be noted that EFA and RHR assessment are dynamic in nature and will get refined and improved as and when requisite information gets collated.

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- Sri Swami Avimukteshwaranand Saraswati
- Dr Madhav AChitale
- Dr Bharat Jhunjhunwala

PROJECT IMPLEMENTATION AND COORDINATION COMMITTEE [PICC]

Representatives from IIT Consortium:

- Dr ShyamAsolekar, IIT Bombay
- Dr A K Mittal, IIT Delhi
- Dr Mohammad Jawed, IIT Guwahati
- Dr Vinod Tare, IIT Kanpur
- Dr D J Sen, IIT Kharagpur
- Dr Ligy Philip, IIT Madras
- Dr I M Mishra, IIT Roorkee

Thematic Group Leads:

- Dr Purnendu Bose, Environmental Quality and Pollution (EQP)
- Dr A K Gosain, Water Resources Management (WRM)
- Dr R P Mathur, Ecology and Biodiversity (ENB)
- Dr Rajiv Sinha, Fluvial Geomorphology (FGM)
- Dr Vinod Tare, Environmental Flows (EFL)
- Dr S P Singh, Socio Economic and Cultural (SEC)
- Dr N C Narayanan and Dr Indrajit Dube, Policy Law and Governance (PLG)
- Dr Harish Karnick, Geospatial Database Management (GDM)
- Dr T V Prabhakar, Communication (COM)

COMPOSITION OF

1. Environmental Quality and Pollution (EQP)

Lead: Purnendu Bose, IIT Kanpur

Members: Shyam R Asolekar, Suparna Mukherjee (IIT Bombay); A K Mittal, A K Nema, Arun Kumar, T R Sreekrishanan (IIT Delhi); Ajay Kalmhad (IIT Guwahati); Saumyen Guha, Vinod Tare (IIT Kanpur); A K Gupta, M MGhangrekar, Sudha Goel (IIT Kharagpur); Ligy Philip, Mukesh Doble, R Ravi Krishna, S M Shivnagendra (IIT Madras); A A Kazmi, B R Gurjar, Himanshu Joshi, Indu Mehrotra, I M Mishra, Vivek Kumar (IIT Roorkee); Anirban Gupta (BESU Shibpur); P K Singh (IIT BHU); Rakesh Kumar (NEERI Nagpur); S K Patidar (NIT Kurukshetra); Sanmit Ahuja (ETI Dynamics, New Delhi)

2. Water Resources Management (WRM)

Lead: A K Gosain, IIT Delhi

Members: Rakesh Khosa, R Maheswaran, B R Chahar, C T Dhanya, D R Kaushal (IIT Delhi); Subashisa Dutta, Suresh Kartha (IIT Guwahati); Shivam Tripathi, Gautam Rai, Vinod Tare (IIT Kanpur); Anirban Dhar, D J Sen (IIT Kharagpur); B S Murty, Balaji Narasimhan (IIT Mdras); C S P Ojha, P Perumal (IIT Roorkee); S K Jain (NIH, Roorkee); Pranab Mohapatra (IIT Gandhi Nagar); Sandhya Rao (INRM, New Delhi)

3. Fluvial Geomorphology (FGM)

Lead: Rajiv Sinha, IIT Kanpur

Members: Vinod Tare (IIT Kanpur); Vikrant Jain (IIT Gandhi Nagar); J K Pati (Allahabad University); Kirteshwar Prasad, Ramesh Shukla (Patna University); Parthasarthi Ghosh, Soumendra Nath Sarkar, TapanChakarborty (ISI Kolkata); Kalyan Rudra (WBPCB); S K Tandon, Shashank Shekhar (University of Delhi); Saumitra Mukherjee (JNU Delhi)

4. Ecology and Biodiversity (ENB)

Lead: R P Mathur, IIT Kanpur

Members: A K Thakur, Vinod Tare (IIT Kanpur); Utpal Bora (IIT Guwahati); M D Behera (IIT Kharagpur); Naveen Navania, Partha Roy, Pruthi Vikas, R P Singh, Ramasre Prasad, Ranjana Pathania (IIT Roorkee); Sandeep Behera (WWF-India)

THEMATIC GROUPS

5. Socio Economic and Cultural (SEC)
Lead: S P Singh, IIT Roorkee

Members: Pushpa L Trivedi (IIT Bombay); Seema Sharma, V B Upadhyay (IIT Delhi); P M Prasad, Vinod Tare (IIT Kanpur); Bhagirath Behera, N C Nayak, Pulak Mishra, T N Mazumder (IIT Kharagpur); C Kumar, D K Nauriyal, Rajat Agrawal, Vinay Sharma (IIT Roorkee)

6. Policy Law and Governance (PLG)
Lead: N C Narayanan, IIT Bombay and Indrajit Dube, IIT Kharagpur

Members: ShyamAsolekar, Subodh Wagle (IIT Bombay); Mukesh Khare (IIT Delhi); Vinod Tare (IIT Kanpur); Deepa Dube, Uday Shankar (IIT Kharagpur); G N Kathpalia, Paritosh Tyagi (IDC, New Delhi)

7. Geo-Spatial Database Management (GDM)
Lead: Harish Karnick, IIT Kanpur

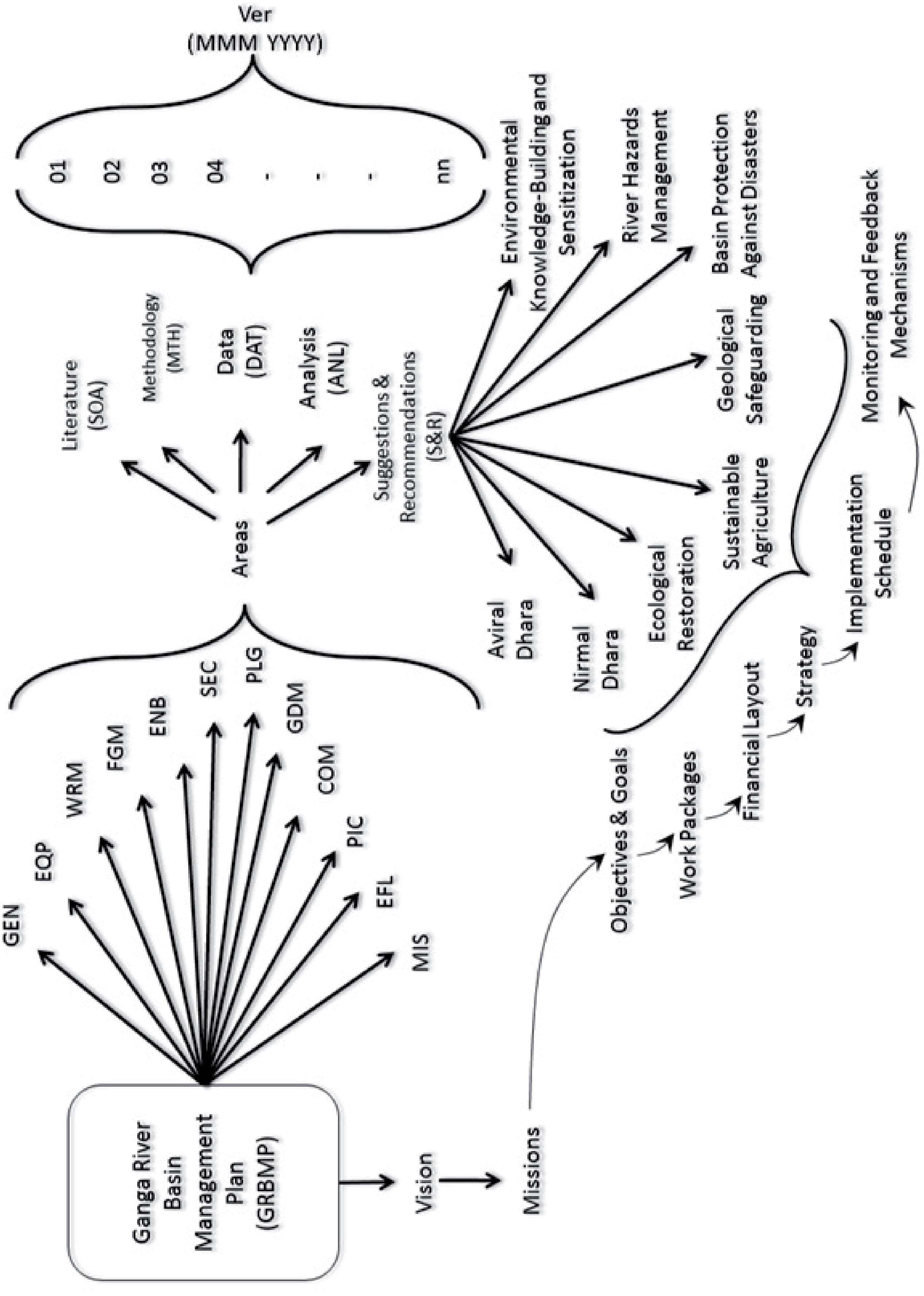
Members: N L Sharda, Smriti Sengupta (IIT Bombay); A K Gosain (IIT Delhi); Arnab Bhattacharya, Kritika Venkatramani, Rajiv Sinha, T V Prabhakar, Vinod Tare (IIT Kanpur)

8. Communication (COM)
Lead: T V Prabhakar, IIT Kanpur

Members: Purnendu Bose, Rajiv Sinha, Vinod Tare (IIT Kanpur)

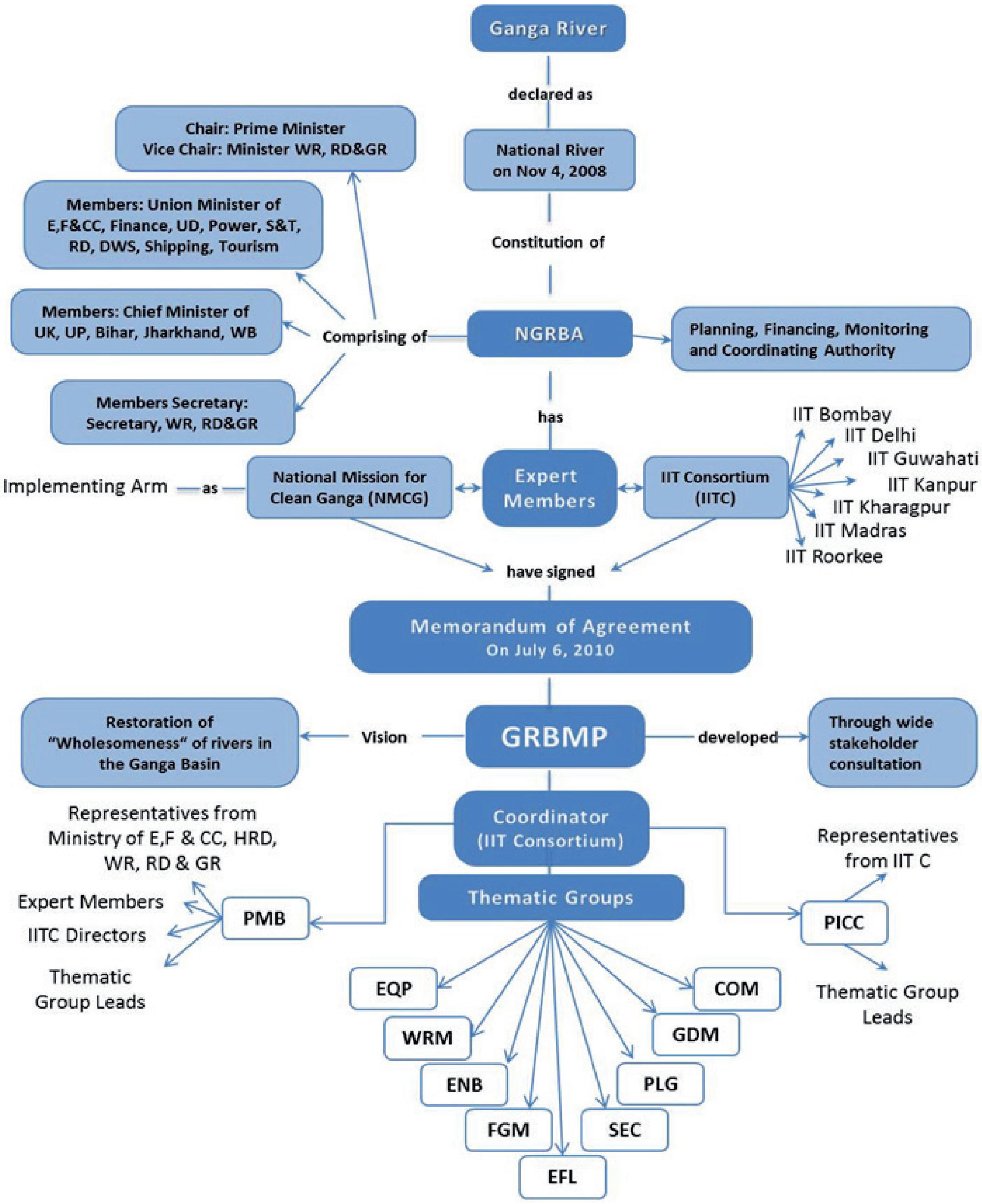
9. Environmental Flows (EFL)
Lead: Vinod Tare, IIT Kanpur

Members: ShyamAsolekar (IIT Bombay); A K Gosain (IIT Delhi); P M Prasad, R P Mathur, Rajiv Sinha, Shivam Tripathi (IIT Kanpur); M D Behara (IIT Kharagpur); B S Murthy, N Balaji (IIT Madras); Pranab Mohaparta, Vikrant Jain (IIT Gandhinagar); S K Jain (NIH Roorkee); Nitin Kaushal (WWF-India, New Delhi); Sandeep Behera (NMCG, MoWR, RD & GR, New Delhi); A P Sharma K D Joshi (CIFRI, Barrackpore); Ravindra Kumar (SWaRA-UP); Ravi Chopra (PSI, Dehradoon); Paritosh Tyagi, (IDC, New Delhi)



GRBMP WORK STRUCTURE

ORGANIZATIONAL STRUCTURE FOR PREPARING GRBMP



NGRBA: National Ganga River Basin Authority

NMCG: National Mission for Clean Ganga

MoEF: Ministry of Environment and Forests

MHRD: Ministry of Human Resource and Development

MoWR, RD&GR: Ministry of Water Resources, River Development and Ganga Rejuvenation

GRBMP: Ganga River Basin Management Plan

IITC: IIT Consortium

PMB: Project Management Board

PICC: Project Implementation and Coordination Committee

EQP: Environmental Quality and Pollution

WRM: Water Resources Management

ENB: Ecology and Biodiversity

FGM: Fluvial Geomorphology

EFL: Environmental Flows

SEC: Socio Economic and Cultural

PLG: Policy Law and Governance

GDM: Geospatial Database Management

COM: Communication

Centre for Ganga River Basin Management and Studies