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Hydrological Model (SWAT) for Ramganga RBM Plan

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Abbreviations

%	Percentage
AR6	Sixth Assessment Report
BL	Baseline
CGWB	Central Ground Water Board
CMIP6	Coupled Model Inter comparison Project-6
CO_2	Carbon-di-oxide
CORDEX	Coordinated Regional Downscaling Experiment
cumecs	Cubic Meter per second
CVFD	Control Volume Finite Difference
CWC	Center Water Commission
D	Discharge
DEM	Digital Elevation Model
EQM	Empirical Quantile Mapping
ET	Evapotranspiration
FAO	The Food and Agriculture Organization
FDC	Flow Duration Curve
G	Gauge
GCMs	General Circulation Models
GDSQ	Gauge Discharge Sediment Quality
GHG	Greenhouse gases
GIS	Geographic Information System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
GWF	Groundwater Flow
GWT	Groundwater Transport
Ha	Hectares
HRU	Hydrologic Response Unit
IMD	India Meteorological Department
IPCC	Intergovernmental Panel on Climate Change
IPCC AR5	Intergovernmental Panel on Climate Change Fifth Assessment Report
IPCC AR6	Intergovernmental Panel on Climate Change Sixth Assessment Report
Km	Kilometer
LT	Long-term
LULC	Land Use and Land Cover
m	Meters
masl	Meters above mean sea level
mm	Millimeter
MODFLOW 6	Modular Hydrologic Model for Groundwater
MT	Mid-term
NBSSLUP	National Bureau of Soil Survey and Land Use Planning
NMCG	National Mission for Clean Ganga
NPK	Nitrogen (N), Phosphorus (P), Potassium (K)

NRLD	National Register of Dams
NRSC	National Remote Sensing Centre
NS	Nash Sutcliffe coefficient
NSE	Nash-Sutcliffe efficiency
NT	Near-term
NWIC	National Water Information Centre
Obs	Observed
PBIAS	Percent bias
PoM	Programme of Measures
ppm	parts per million
Q	Water Quality
R^2	Coefficient of determination
RBM	River Basin Management
RCM	Regional Climate Models
RF	Rainfall measuring station
RMSE	Root Mean Squared Error
RSR	Root Mean Standard Deviation Ratio
S	Sediment
Sim	Simulated
sq km	Square Kilometers
SRTM	Shuttle Radar Topography Mission
SSPs	Shared Socioeconomic Pathways
SWAT	Soil Water Assessment Tool
USDA/ARS	United States Department of Agriculture/Agricultural Research Service
vs	Versus
WRIS	Water Resources Information System

1 INTRODUCTION

Background

This technical report presents the details of hydrological modelling carried out towards the development of Ramganga River Basin Management Plan by NMCG and GIZ Support to Ganga Rejuvenation Project (SGR) under the Indo-German bilateral technical cooperation.

In 2015, on the request of the Government of India (GoI), GIZ was commissioned by the German Federal Ministry of Economic Cooperation and Development (BMZ) to implement Phase 1 of the *Support to Ganga Rejuvenation* project. As part of the India-EU Strategic Partnership, the European Union (EU) and India established the India-EU Water Partnership (IEWP) in 2015. It was set-up to consolidate the political and strategic framework for a more coherent and effective cooperation between the EU and India on water management issues. Since November 2020, GIZ is implementing the Indo-German Technical Cooperation Project *Support to Ganga Rejuvenation, Phase II* (SGR II) on behalf of the BMZ in conjunction with the *Development and implementation support to the India-EU Water Partnership, Phase 2 (IEWP Action, Phase 2)*. The main implementation partners from the Indian side are the National Mission for Clean Ganga (NMCG) and the Central Water Commission (CWC). Measures at the regional level target the states of Uttarakhand and Uttar Pradesh as well as the Tapi Basin (Madhya Pradesh, Maharashtra, and Gujarat).

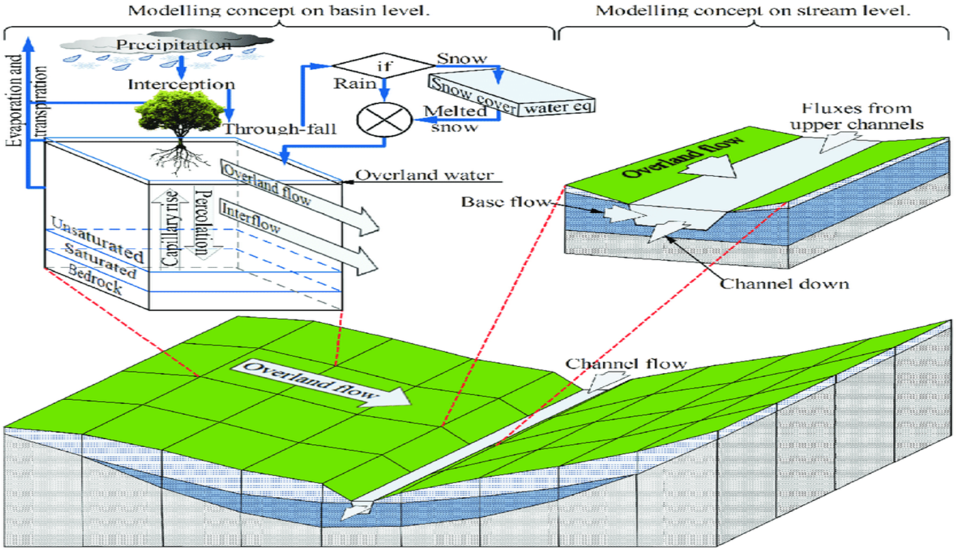
Building on the work of Phase 1 of the SGR Project, it was decided together with the NMCG to develop a River Basin Management Plan for the Ramganga Basin. The development of the Ramganga RBM Plan follows the RBM Cycle approach which was earlier used to develop Tapi RBM Plan. The first step is the characterization of the Ramganga River basin, which includes the identification of 5 Key Water Management Issues (KWMIs) and a pressure/impact analysis and a risk assessment for each identified KWMI. Based on this, a Programme of Measures (PoM) will be developed for the Ramganga Basin, suggesting a set of management options and measures for implementation to achieve the set RBM targets and to improve the overall water management situation in the Ramganga Basin.

Towards the development of Ramganga BRM Plan, GIZ contracted INRM Pvt Consultants Pvt Ltd. to implement hydrological Model (SWAT) for the Ramganga Basin.

Hydrological Models

The inherent complexity of basin systems introduces a substantial degree of uncertainty, making it difficult to fully comprehend how different hydrological processes interact with one another. While modern hydrological modelling techniques recognize the need for high-resolution geographical and temporal data, such data often remain elusive or incomplete, creating a significant limitation. Spatio-temporal gaps persist between the physical scales of hydrological processes and the resolution achievable with applied models. Therefore, it becomes important to select a modelling approach that can efficiently, accurately, and effectively represent all the diverse physical hydrological processes occurring within a given basin. This choice is critical to advancing our understanding of complex hydrological systems and improving our ability to make informed decisions regarding water resource management and environmental sustainability. Complete hydrological processes are explained in **Error! Reference source not found.**.

Figure 1: Hydrological Processes



Source: Paper [1]

The demand for model validation, calibration, and parameter optimization has witnessed a significant surge, primarily driven by the growing complexity of hydrological modelling across extensive geographical areas and extended time periods. Calibration serves as concrete evidence that a model can effectively and accurately represent the values of various hydrologic variables observed in the field, such as streamflow, soil moisture, and well-monitored groundwater levels. Without proper calibration, the predictions of different hydrologic variables generated by a model lack meaning and often prove unreasonable. In calibrated models, the goodness of fit between the simulated and measured variables is typically quite satisfactory, depending on the initial values assigned to hydrologic and hydraulic parameters within the model. To enhance this goodness of fit, parameter values may be adjusted or optimized after assessing the tolerable difference between the model's simulated and measured variables. This adjustment process often involves fine-tuning one parameter while keeping the values of other parameters constant, typically through a trial-and-error approach. Additionally, some hydrological models, such as SWAT (Soil and Water Assessment Tool), offer an automatic calibration procedure, as seen in SWATCUP for SWAT, streamlining the parameter optimization process.

It's important to note that one of the pivotal steps in the simulation process is the careful selection of an appropriate model and the collection of relevant data. For the proposed study, a state-of-the-art distributed conceptual model known as SWAT (Soil and Water Assessment Tool) has been leveraged as hydrological model. This choice aligns with the complexity of the study and underscores the importance of utilizing advanced modelling techniques to gain a comprehensive understanding of hydrological processes in the given context.

[1] Kis, Anna & Pongracz, Rita & Bartholy, Judit & Szabó, J.A.. (2017). Application of RCM results to hydrological analysis. Idojaras. 121. 437-452.

2 STUDY AREA – RAMGANGA RIVER BASIN

The Ramganga River. one of the major tributaries of river Gang,a flows for over 596 km predominately in a southerly direction until it joins the Ganga in Kannuj District, Uttar Pradesh. The river Ramganga, originates near Gairsain (Uttarakhand) of Doodha-Toli ranges in the lower Himalayas of Pauri Garhwal at an altitude of about 3,110m (masl). Elevation of the total Ramganga catchment varies from 3101 m (masl) to 113 m (masl). Average elevation of the catchment is around 435 m (masl).

Ramganga, river enters the plains at Kalagarh in Bijnor district of Uttar Pradesh, where a dam has been constructed on the river for the purpose of irrigation and hydroelectric production. About 25 Km downstream of Kalagarh it is joined by the Khoh, after which it enters the Moradabad district, where on the alluvial lowlands it flows in a south-eastern direction. The Ramganga River is joined by several tributaries in Moradabad district, almost all on its left bank, most of which are Tarai streams flowing towards south or south-west. The first among them is the Phika, which rises in the Kumaon hills and joins the Ramganga near Surjannagar. Then the Khalia, Dhela River Rajera River, Koshi river joins Ramganga between Moradabad and Bareilly district.

After Bareilly, the Ramganga flows in the southeastern direction and many tributaries like Bhakra and Kichha (also called Baigul) from its left and the Gagan River from its right joins. Then the Deoranian and Nakatiya rivers joins from its left then the Ramganga River finally joins the Ganga River in Kannauj District after covering a total distance of about 596 Km.

The Ramganga is a 'nearly-pristine' river in the lower Himalayas (headwater catchment) until it reaches the foothills, where it starts facing fragmentation at Kalagarh Dam, abstractions, and transfers downstream of Kalagarh Dam and sewage and industrial pollution from industrial cities like Kashipur, Moradabad, and Bareilly. Encroachment, degradation of wetlands and other unsustainable activities leads to reduced recharge and potentially reduced flows. Ramganga restores its river health and flow to some extent, before confluence, because of reasonable amount of flow joining the river.

The detail characteristics of the Ramganga River Basin are presented in Chapter 2 of the Ramganga River Basin Management Plan.

3 HYDROLOGICAL MODELLING USING SWAT

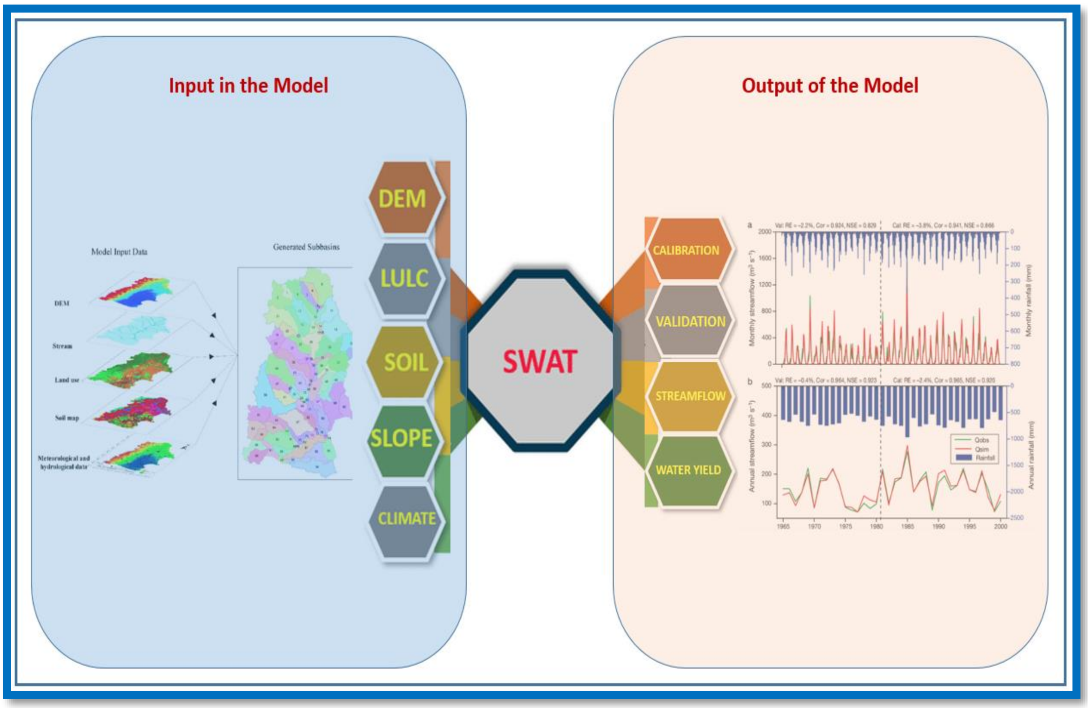
The expansion and intensification of agricultural activities have led to shifts in natural ecosystems and water availability. To assess the health of watersheds in this context, hydrological modelling techniques, such as SWAT (Soil and Water Assessment Tool), prove invaluable. SWAT, developed and supported by the USDA/ARS, is a physically based, daily time-stepping, watershed-scale model capable of simulating various aspects of water and pollutant transport in agricultural watersheds. The SWAT model can mimic and simulate runoff, sediment, nutrients, pesticide, and bacteria transport from agricultural watersheds[2]. Complete process of SWAT model is explained in Figure 2 and complete hydrological processes simulated by SWAT model is depicted in Figure 3. Here's an overview of how the SWAT model operates:

[2] Arnold J. G., Srinivasan R., Muttiah R. S., and Williams J. R. 1998. Large area hydrologic modeling and assessment, Part I: model development. Journal of American Water Resources Association, 34(1): 73-89.

- **Watershed Delineation**: SWAT delineates a watershed and further subdivides it into smaller units known as subbasins. Each subbasin is divided into hydrologic response units (HRUs) based on specific characteristics such as land cover, soil type, and topography.
- **Hydrological Processes**: The model simulates various hydrological processes, including runoff, sediment transport, nutrient transport, pesticide movement, and bacteria transport. These processes are represented within the HRUs and aggregated for each subbasin.
- **Water Routing**: Water is routed from HRUs to associated stream reaches within the SWAT model. The model accounts for the deposition of pollutants within the stream channels and their subsequent transport to the watershed outlet.
- **Spatial and Temporal Variability**: HRUs allow the incorporation of processes that account for potential spatial and temporal variations in model input parameters, enhancing the model's accuracy.
- **Soil Water Balance**: The hydrologic module of SWAT quantifies soil water balance at each time step during the simulation period, considering daily precipitation inputs.
- **Multiple Water Balance Processes**: SWAT distinguishes the effects of weather, surface runoff, evapotranspiration, crop growth, nutrient loading, water routing, and the long-term impacts of various agricultural management practices.
- **Daily Time Step**: The model operates on a daily time step and can predict the influence of land use and management on water, sediment, and agricultural chemical yields in ungauged watersheds.
- **Process-Based and Efficient**: SWAT is process-based, computationally efficient, and capable of continuous simulation over extended time periods.
- **Minimal Calibration**: A major advantage of the SWAT model is its relatively low requirement for calibration, making it suitable for application in ungauged watersheds.

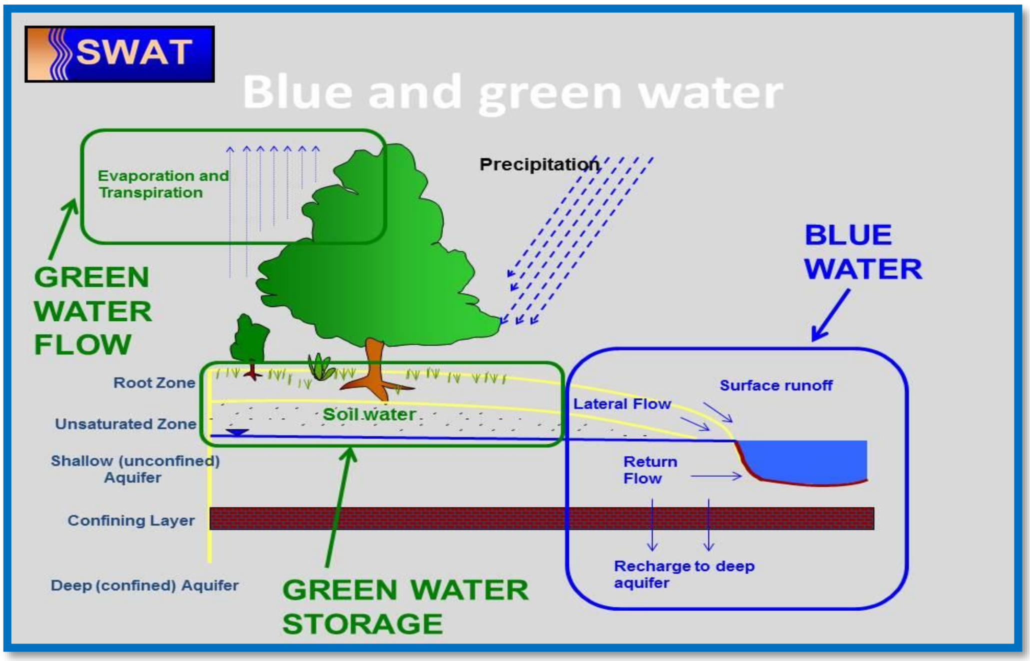
Once the model is successfully calibrated and validated, it can be adapted to generate a range of scenarios. These scenarios encompass potential alterations in climatic conditions, land use patterns, crop distribution dynamics, irrigation efficiency improvements, and changes in water management practices. These scenarios provide valuable insights for planning and policymaking, allowing water managers and policymakers to make more informed and effective decisions regarding watershed management and governance.

Figure 2: Complete Process of the Modelling



Complete hydrological processes are depicted in Figure 3

Figure 3: Complete Hydrological Process

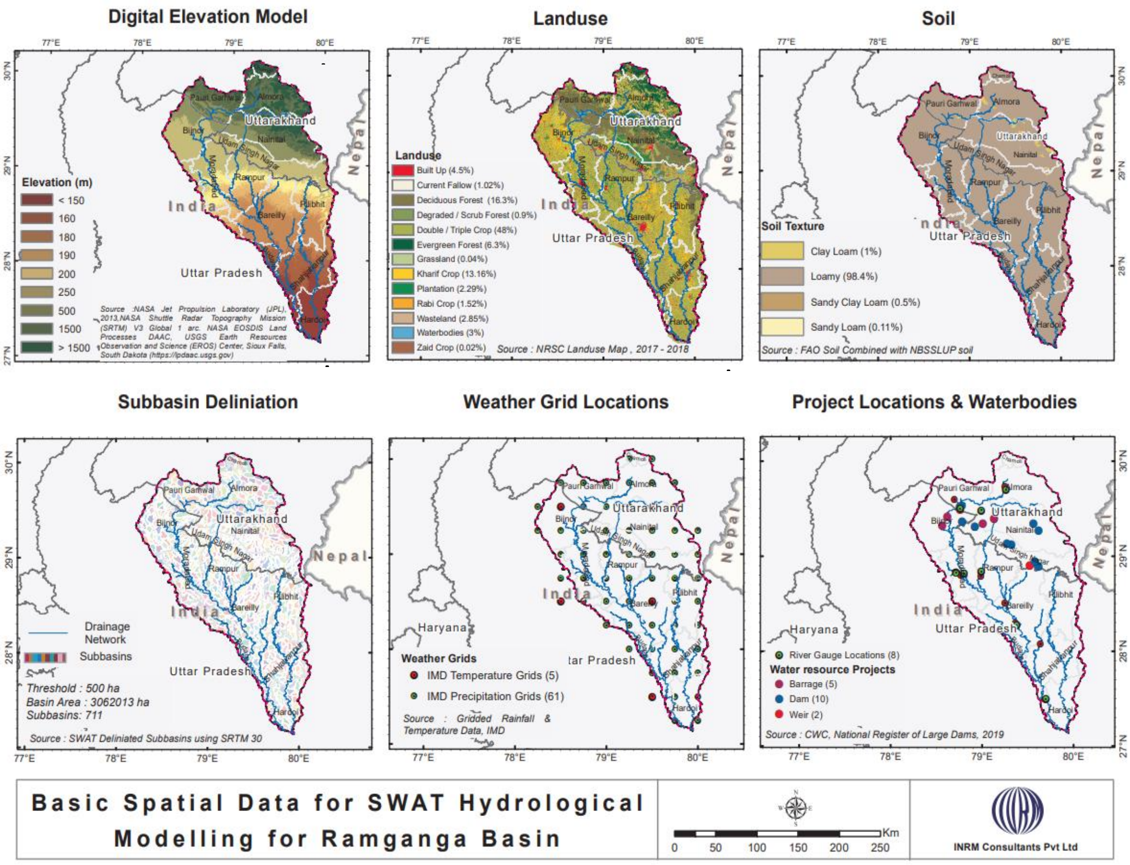


The Ramganga Basin has been successfully delineated using the SWAT model, demonstrating the model's ability to handle large and complex hydrological systems. This extensive basin has been divided into 711 sub-basins and further subdivided into 4,000 Hydrologic Response Units (HRUs), allowing for a detailed representation of the watershed's characteristics and processes. Here's an overview of the key SWAT input layers and data used in this delineation:

- Digital Terrain Model (DTM): The DTM provides critical information about the topography of the basin, allowing the model to account for elevation variations and terrain characteristics that influence water flow and distribution.
- Land Use: Land use data is essential for categorizing and characterizing the different land cover types within the basin, which in turn affects factors like evapotranspiration, runoff, and pollutant transport.
- Soil Data: Soil data are used to define the soil properties and characteristics across the basin, influencing factors such as infiltration rates and water retention.
- Weather Grid Location: The weather grid data provide information on climate and meteorological conditions at specific grid locations, enabling the model to consider the impact of weather patterns on hydrological processes.
- Interventions and Operation Policies: These layers include information about various human interventions and their operational policies within the basin. This could encompass activities related to water resource management and infrastructure.
- Waterbodies: The representation of water bodies is crucial as they play a significant role in water storage and movement within the basin.
- Point and Non-Point Source Contaminations: Data on point source contaminations help the model account for pollutants entering the watershed from specific sources, which is essential for assessing water quality.
- Crop Management Practices: Information about crop management practices, including irrigation, pesticide use, and fertilizer application, is vital for modelling the impact of agricultural activities on the hydrological system.

The integration of these diverse data layers into the SWAT model allows for a comprehensive understanding of the hydrology of the Ramganga Basin. This level of detail and complexity is valuable for assessing the watershed's health, water resource management, and environmental sustainability, and it highlights the versatility of the SWAT model in handling such complex scenarios. SWAT input layers are shown in Figure 4 and are explained in data used section.

Figure 4: Ramganga Delineation & SWAT Hydrological Modelling Input Parameters



3.1 Data Used

Various data used for the modelling purpose is listed below

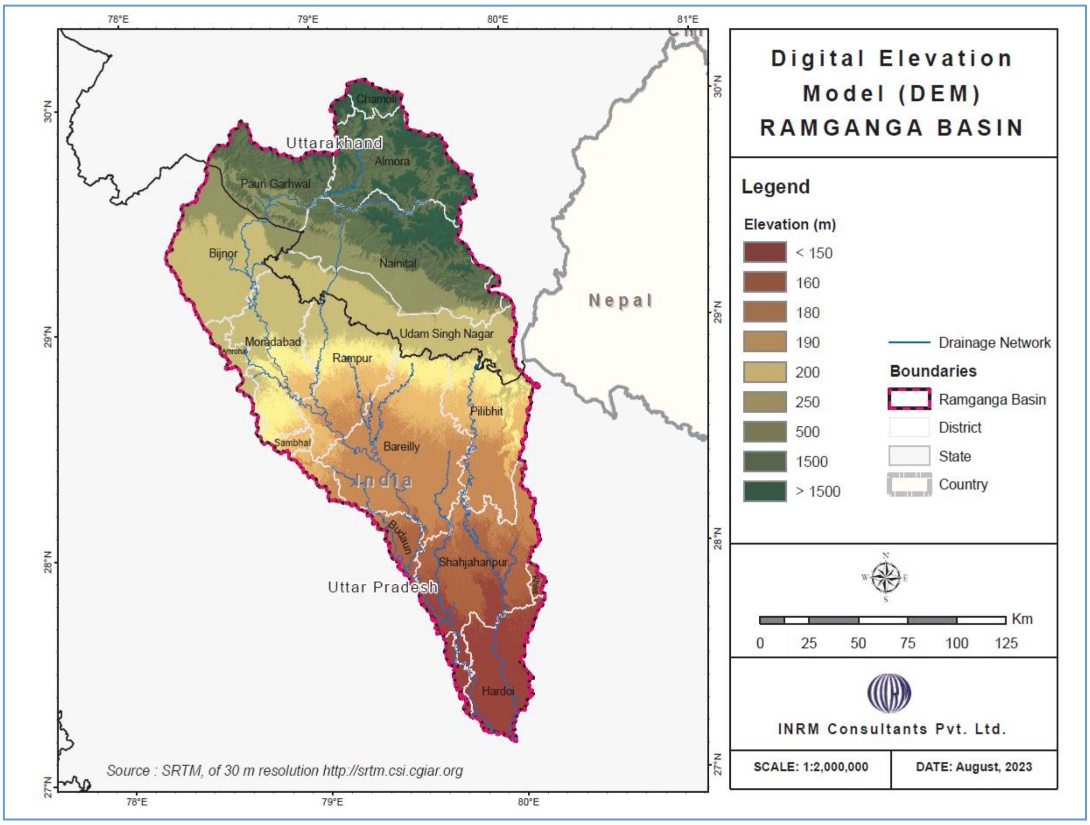
- <u>Terrain</u> – USGS SRTM 30 m resolution DEM - https://www.earthdata.nasa.gov/
- <u>Land Use</u> – Land Use data 2017-2018 (NRSC as received from NWIC)
- <u>Soil</u> – National Bureau of Soil Survey and Land Use Planning (NBSSLUP) + FAO combinations – NBSSLUP data covers 99.2% of the basin, small missing portion is filled by FAO data.
- <u>Weather data</u>
  - <u>Present Scenario</u> – Indian Meteorological Department (IMD) Gridded data: precipitation - 0.25 x 0.25 grid, temperature (min and Max) – 1 x 1 grid (https://imdpune.gov.in/cmpg/Griddata/Rainfall_25_Bin.html)
  - Future Scenario – IPCC AR6 data: precipitation - 0.25 x 0.25 grid, temperature (min and Max) – 0.25 x 0.25 grid (https://www.wdc-climate.de/)
- <u>Interventions (e.g., dams/ barrages/weir etc.)</u>. -info taken from WRIS/NRLD sites) – National Register of Large Dams, 2018 Report (www.cwc.gov.in/national-register-large-dams) and India WRIS (https://indiawris.gov.in)
- <u>Depressions/Waterbodies</u> – NWIC / WRIS / remote sensing – Waterbodies were taken primarily from NWIC geodatabase; addition waterbodies (area) were also taken from India WRIS/Remote sensing/google maps.

- **NPK applied in the agriculture field** (Nitrogen (N), Phosphorus (P), Potassium (K) – District-wise data as compiled by Ministry of Agriculture and Farmers' Welfare under cost of cultivation scheme.
- **Transfer and diversions** – Quantity/Quantity/quantity of diversions is taken from government websites and published reports and literature and in case no data is available, it is indirectly implemented in model.
- **Ramganga Basin Command area and canal network** – NWIC data from Bhuvan.
- **Point source data** – Drain location near Moradabad along with concentration of contamination was received from the UP-PCB. For urban and rural cluster, value was calculated using population and per capita waste generation.

3.2 Terrain (Topography)

Shuttle Radar Topography Mission (SRTM) digital elevation model of 30 m resolution was used to delineate the basin (Figure 5).

Figure 5: Terrain Ramganga Basin



3.3 Land Cover/Land Use

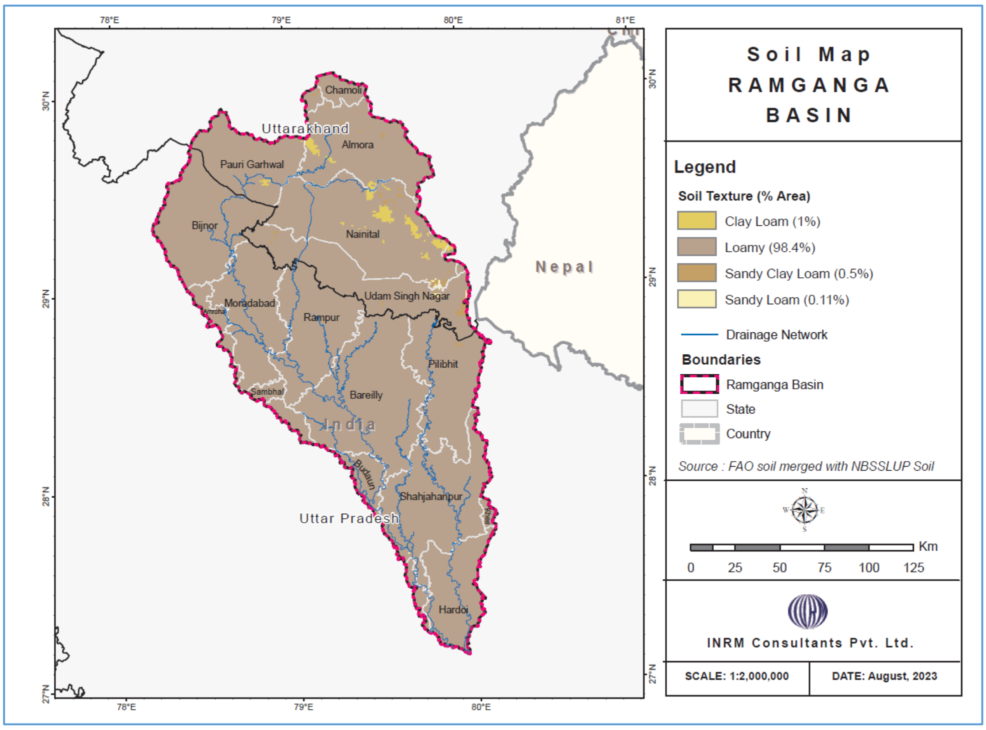
The details are described in Chapter of Ramganga RBM Plan main document. NRSC Map 2017/2018 was used as reference.

3.4 Soil Type

The utilization of soil maps from both NBSSLUP (National Bureau of Soil Survey and Land Use Planning) and FAO (Food and Agriculture Organization) has provided valuable insights into the soil characteristics and distribution within the Ramganga basin. Here's an overview of the soil-related information, as depicted in Figure 6 Understanding the soil composition and its spatial distribution is fundamental for land management, agricultural practices, and water resource planning within the Ramganga Basin. It informs decisions related to crop selection, irrigation strategies, and land use policies, ultimately contributing to sustainable watershed management.

- Soil Texture and Categories: The soil map illustrates the distribution of different soil texture categories across the Ramganga basin. It's worth noting that the predominant soil type in the basin is loamy soils, covering approximately 98.4% of the total area. Loamy soils are known for their balanced mixture of sand, silt, and clay, making them conducive to various agricultural and land use activities.
- Upper Catchment Conditions: In the upper catchment areas of the basin, the presence of hard rock substrates results in shallow soil depths. This geological feature can influence groundwater recharge, runoff patterns, and the overall hydrological behaviour of the region.
- Water Holding Capacity: The soil's water-holding capacity and moisture storage characteristics are highlighted. Surface layers generally exhibit higher water-holding capacity and moisture retention compared to subsoils. This variation has implications for groundwater recharge, plant growth, and soil-water interactions.

Figure 6 : Soils of the Ramganga Basin



3.5 Major Tributaries and Drainage Basins

The details are described in Chapter of Ramganga RBM Plan main document.

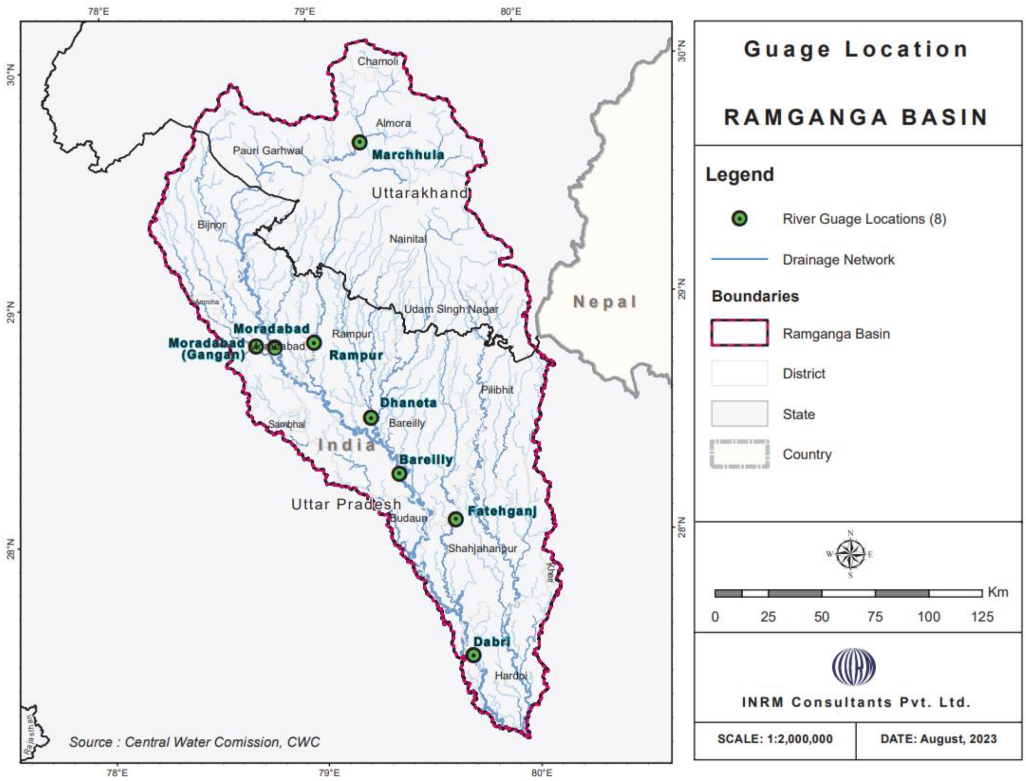
3.6 Hydrological observations in the River Ramganga

For the specific purposes of the Ramganga River Basin Management (RBM) plan, data from eight observation stations were made available. Among these eight stations, three are designated as Gauge Discharge stations, and the remaining five are designated as Gauge Discharge Sediment Quality stations. All data from these eight CWC Hydro observation sites, which were equipped with the necessary information, were used for the calibration and validation of the modelling efforts. However, it's important to note that the remaining were not utilized for the purposes of validation and calibration. Several factors contributed to this decision, which are outlined as follows.

- Continuous data is not available for all these state gauges
- Only a few years of data is available with lot of missing months

Wherever data was available (such as Moradabad, Moradabad (Gangan), Dhaneta, Bareilly, Fatehgarh, Dabri, Marchulla and Rampur), those stations were included in the study for calibration and validation. Gauge locations with data in the Ramganga basin are shown in
Figure 7.

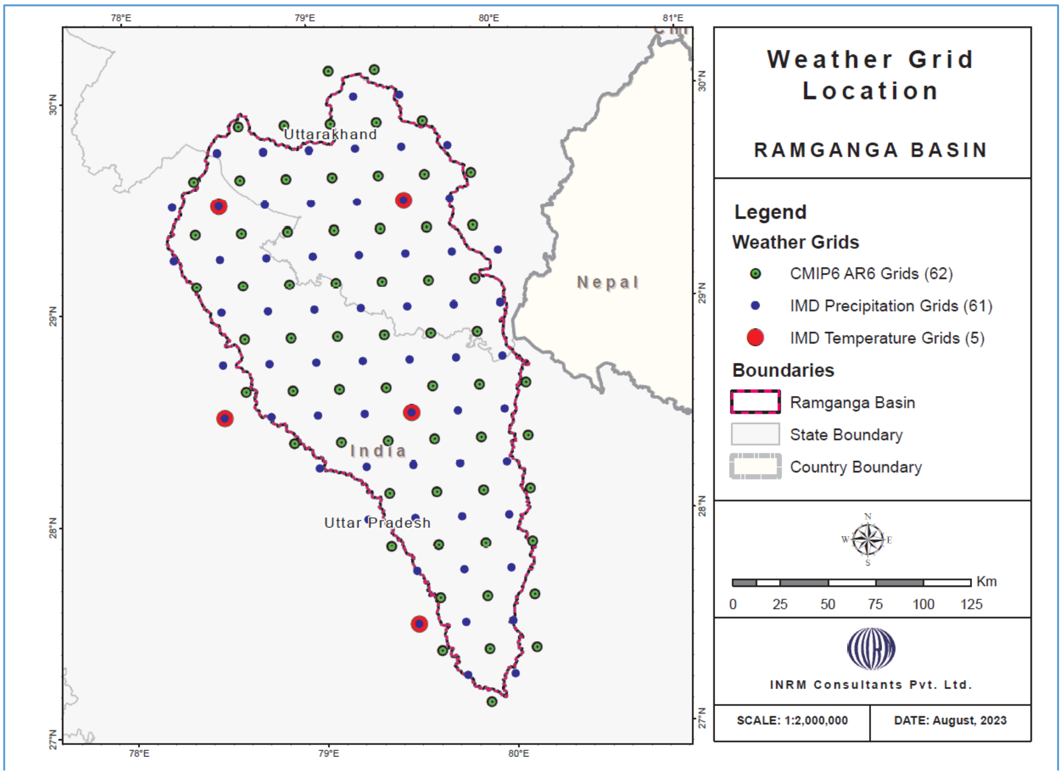
Figure 7 : Gauge Location of the Ramganga Basin



3.7 Meteorological Parameters

IMD gridded data was used for the simulation. IMD gridded rainfall and temperature data were extracted for the Ramganga basin. There were 61 precipitation grids and 5 temperature grids falling within or around Ramganga Basin Figure 8, which have been used in the model simulation. State weather stations can be added in the modelling exercise, to enhance the results, since variability can be captured. Time step of IMD gridded data used for modelling exercise is 1975 to 2020.

Figure 8 : Weather Grid



For climate change runs, there were 62 grids Figure 8, falling in and around Ramganga basins, which were used for the simulation. For climate change runs multi model ensemble data of 13 model was used. In the present study, daily bias-corrected data of precipitation, maximum and minimum temperatures at 0.25° spatial resolution for study area is extracted. The bias-corrected dataset is extracted using Empirical Quantile Mapping (EQM) for the historic (1951–2014) and projected (2015–2100) climate for the four scenarios (SSP126, SSP245, SSP370, SSP585) using output from 13 General Circulation Models (GCMs) from Coupled Model Inter comparison Project-6 (CMIP6).

The IPCC Sixth Assessment Report assessed the projected set of five scenarios that are based on the framework of the SSPs. The names of these scenarios consist of the SSP on which they are based (SSP1-SSP5), combined with the expected level of radiative forcing in the year 2100. Estimated warming in Shared Socioeconomic Pathways in the IPCC Sixth Assessment Report is shown in Table 1 : Estimated warming in Shared Socioeconomic Pathways in the IPCC Sixth Assessment Report and CO_2 concentration in ppm is shown in Figure 9.

Table 1 : Estimated warming in Shared Socioeconomic Pathways in the IPCC Sixth Assessment Report

SSP	Scenario	Estimated warming (2041–2060)	Estimated warming (2081–2100)	Very likely range in °C (2081–2100)
SSP1-1.9	very low GHG emissions: CO_2 emissions cut to net zero around 2050	1.6 °C	1.4 °C	1.0 – 1.8
SSP1-2.6	low GHG emissions: CO_2 emissions cut to net zero around 2075	1.7 °C	1.8 °C	1.3 – 2.4

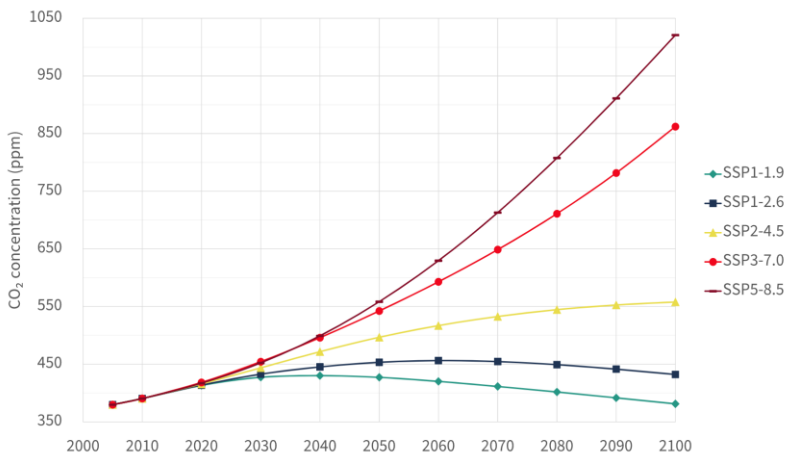
SSP2-4.5	intermediate GHG emissions: CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	2.0 °C	2.7 °C	2.1 – 3.5
SSP3-7.0	high GHG emissions: CO_2 emissions double by 2100	2.1 °C	3.6 °C	2.8 – 4.6
SSP5-8.5	very high GHG emissions: CO_2 emissions triple by 2075	2.4 °C	4.4 °C	3.3 – 5.7

CMIP6 projections are based on the Shared Socio-economic Pathway (SSP) scenarios. Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios with different climate policies. The scenarios are the result of complex calculations that depend on how quickly humans curb greenhouse gas emissions. But the calculations are also meant to capture socioeconomic changes in areas such as population, urban density, education, land use and wealth. Each scenario is labelled to identify both the emissions level and the Shared Socioeconomic Pathway, or SSP, used in those calculations. The scenarios are:

- SSP1: Sustainability (Taking the Green Road)
- SSP2: Middle of the Road
- SSP3: Regional Rivalry (A Rocky Road)
- SSP4: Inequality (A Road divided)
- SSP5: Fossil-fuelled Development (Taking the Highway)

Projected changes are expressed as anomalies according to a historical reference period of 1995-2014. The analysis of two scenarios SSP2-4.5 (middle of the road/moderate emission scenario) and SSP5-8.5 (Fossil-fueled Development/a scenario of comparatively high greenhouse gas emissions) are included in this study. Carbon-di-oxide (CO_2) emissions for all the IPCC AR6 scenarios are shown in Figure 9 Two shortlisted scenarios are elaborated in subsequent sections.

Figure 9: CO2 concentration in ppm in Shared Socioeconomic Pathways in the IPCC AR6 Report



3.7.1 SSP2-4.5, Middle of the Road (Medium challenges to mitigation and adaptation)

This is a “middle of the road” scenario. CO_2 emissions hover around current levels before starting to fall mid-century, but do not reach net-zero by 2100. Socioeconomic factors follow their historic trends, with no notable shifts, wherein social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Environmental systems experience degradation, although there are some improvements and overall, the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

3.7.2 SSP5-8.5 - Fossil-fuelled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation)

The SSP5 scenarios mark the upper end of the scenario literature in fossil fuel use, food demand, energy use and greenhouse gas emissions. This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. This is a future to avoid at all costs. Current CO_2 emissions levels roughly double by 2050. The global economy grows quickly, but this growth is fuelled by exploiting fossil fuels and energy-intensive lifestyles.

3.8 Water Resources Development Projects

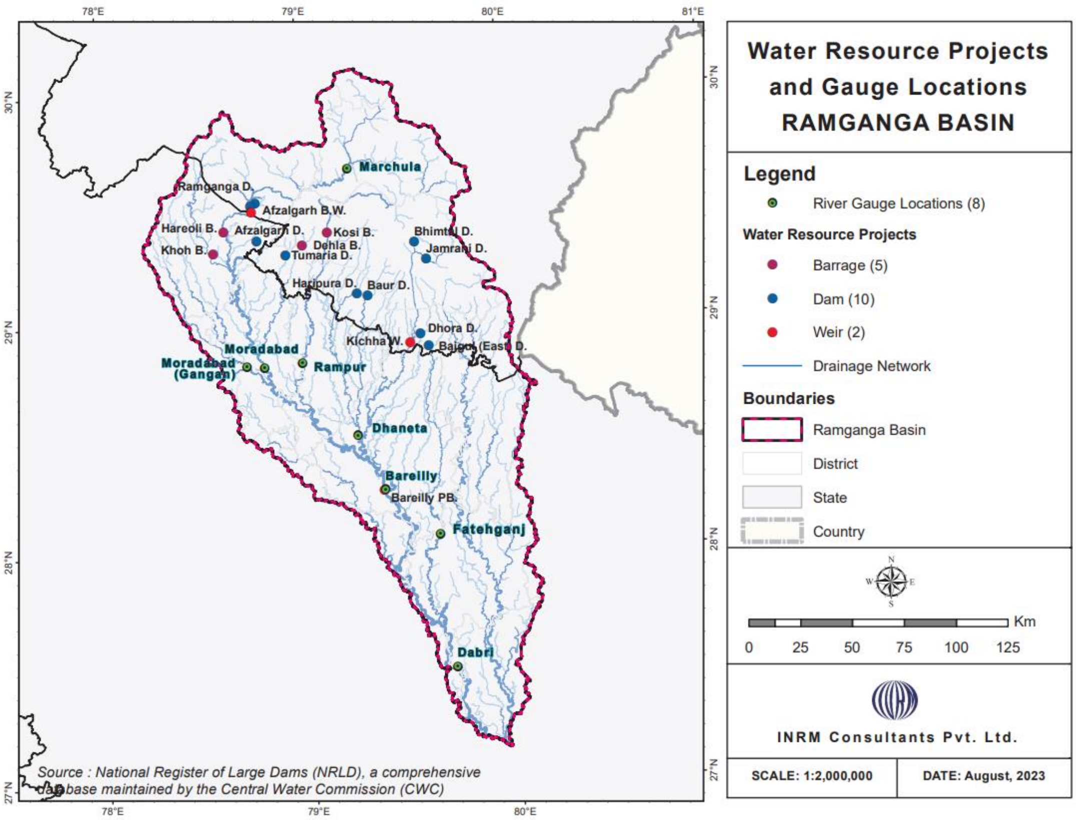
Water resources projects within the Ramganga Basin are broadly classified into two main categories: irrigation projects and hydroelectric projects. These projects are crucial for water resource management and play a significant role in the region's development. Here are some key insights into these projects:

- Irrigation Projects: These projects are designed to manage and distribute water for agricultural purposes. In the Ramganga basin, the focus of pre-planned water resources development primarily revolves around barrage projects. Barrages are structures built across rivers to regulate and divert water for irrigation. Notably, the Kalagarh/Ramganga dam stands out as the major project in the basin for irrigation purposes.
- Hydroelectric Projects: Hydroelectric projects harness the energy of flowing water to generate electricity. While specific details about hydroelectric projects in the Ramganga basin are not provided, they are essential components of the region's water resource infrastructure. These projects contribute to both power generation and overall water management.
- Existing Manmade Structures: The study also considers natural and existing manmade structures within the basin. This includes reservoirs, check dams, and barrages. These structures serve various purposes, such as water storage, flood control, and irrigation.
- Data Sources: Information about the characteristics of dams and water resource projects is obtained from reputable sources, including the National Register of Dams 2018 (NRLD2018), the National Water Informatics Centre (NWIC) database, and the Water Resources Information System (WRIS) website. These sources provide valuable data for the study.

- **Surface Water Bodies**: The Ramganga basin also features various surface water bodies, including lakes, wetlands, and ponds. These water bodies have multifaceted significance in the lives of local communities, serving purposes such as irrigation, drinking water supply, ecological balance, and domestic use.
- **Spatial Distribution**: The projects and interventions are primarily located in the upstream part of the catchment. This distribution pattern can have implications for water availability, flow regulation, and downstream water quality.

The presence of these water resources projects underscores the importance of integrated water resource management in the Ramganga basin. Effective planning, operation, and maintenance of these projects are essential for meeting various water-related needs, sustaining ecosystems, and supporting local livelihoods. All the projects are shown in Figure 10. Mostly all the interventions are present in upstream part of the catchment.

Figure 10 : Major Water Resources Structures of the Ramganga Basin

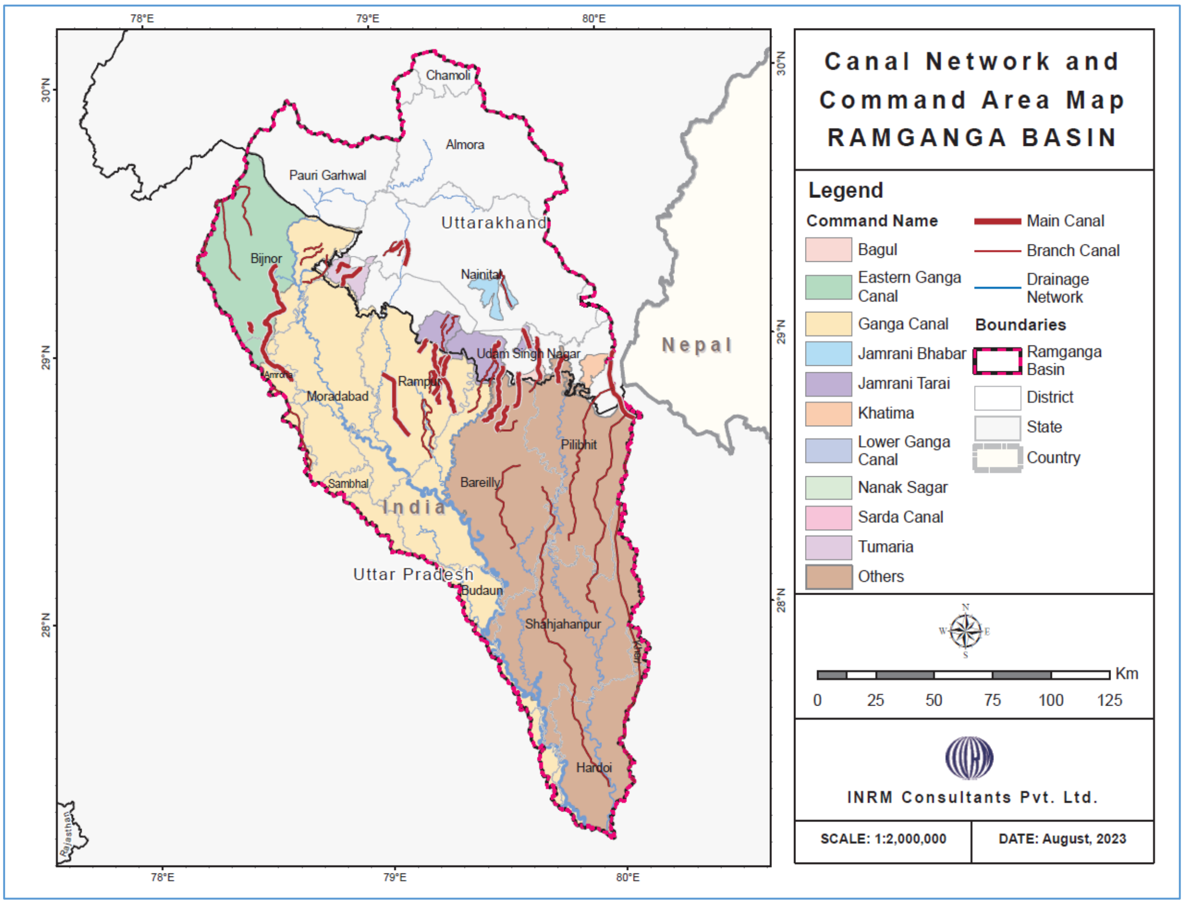


3.9 Ramganga Canal and Command Systems

The command area is the area served by the dam/ project, and gets benefitted by the dam, such as irrigation water, etc. It is an area which can be irrigated from a scheme and is fit for cultivation. In other words, it is the area around a dam which is under its command as an irrigation source. Irrigation of the crop is decided using the canal and command system map of the basin (Figure 11). Ramganga has extensive network of canal and command area. There are lot of interbasin and intrabasin transfers happening in Ramganga basins through network of canals. Lower portion of the Ramganga basin is completely covered into canal network.

These command areas and canal information were used in the hydrological model. All the agriculture land within command area and crops requiring irrigations are provided irrigation from the reservoirs associated with the command area. Agriculture area and crop requiring irrigation outside command are irrigated by groundwater. Command area information of minor projects are unavailable, in such case area near the minor project is irrigated by the water stored in the minor project.

Figure 11 : Canal and Command Systems of the Ramganga Basin



3.10 Ramganga Cropping Pattern

Many river basins in India are experiencing economic water shortage, because it lacks the necessary infrastructure to rejuvenate or recharge the aquifers. Temporal distribution of precipitation, which rarely coincides with demand, is a critical problem in this context[3]. Soil and Water Assessment Tool (SWAT) has been used widely to assess the impact of management practice, and climate and land use changes on water quality and quantity and crop yield[4,5].

[3] Keller, A.; Sakthivadivel, R.; Seckler, D. Water Scarcity and the Role of Storage in Development; International Water Management Institute (IWMI): Colombo, Sri Lanka, 2010.
[4] Gassman, P.W.; Reyes, M.R.; Green, C.H.; Arnold, J.G. The soil and water assessment tool: Historical development, applications, and future research directions. Trans. ASABE 2007,50, 1211–1250.
[5] Arnold, J.G.; Moriasi, D.N.; Gassman, P.W.; Abbaspour, K.C.; White, M.J.; Srinivasan, R.; Santhi, C.; Harmel, R.D.; van Griensven, A.; Van Liew, M.W.; et al. Swat: Model use, calibration, and validation. Trans. ASABE 2012,55, 1491–1508.

The exploration of various scenarios is instrumental in determining the optimal water requirements for agricultural practices. The SWAT model plays a pivotal role in this process by providing a comprehensive analysis of the water utilization dynamics throughout the crop growth cycle. This analysis encompasses several crucial factors, including irrigation, precipitation, groundwater interactions, evapotranspiration, and drainage. Importantly, the model ensures a robust and credible evaluation of water use by taking into account the daily variations in soil moisture levels. SWAT's capabilities extend to estimating and simulating actual evapotranspiration (ET) over the entire duration of crop growth, considering a range of conditions that may be optimal or suboptimal. This comprehensive assessment aids in making informed decisions regarding water management and allocation, ultimately contributing to sustainable agricultural practices.

The modelling process in the Ramganga Basin includes the integration of major crops grown in the region, along with their corresponding management practices. This valuable information is sourced from the district agriculture contingency plans. All the major crops grown in the basin in Kharif and Rabi seasons are taken from the district agriculture contingency plans. Irrigation of the crop was decided using the canal and command system map of the basin (Figure 11). Invariably, two crops are grown in the entire Ramganga catchment (1 in Rabi and 1 in Kharif).

Main Kharif crops grown in the Ramganga Basin are Rice, Maize. Sugarcane being year-long crop is grown throughout the year. Main Rabi crops grown in Ramganga basin are wheat, Millet. Annual yield of the crops is also validated with the district and state averages. Average annual yield of each crop has been compared and validated with modelling output. Comparison of the simulated and average yield of the Ramganga basin is given in Table 2. Results shows good match with the observed data. Further it can be fine-tuned with the information is provided by the state agencies.

Table 2: Crop Yield Comparison

Crop	Model (t/ha)	State Average (t/ha) (UK+UP)
Pearl Millet	1.99	1.83
Corn/Maize	2.44	2.01
Rice	1.6	1.35
Wheat	2.54	2.10
Sugarcane Biomass	7.35	6.44
Note: All values are average over 50 years simulation for entire Ramganga Basin		

3.11 NPK Data for Non-Point Source Pollution

Within the Soil and Water Assessment Tool (SWAT) framework, NPK data encompasses information regarding the levels and dynamics of nitrogen (N), phosphorus (P), and potassium (K) in soils. These macronutrients are crucial for plant growth and are pivotal components in agricultural and environmental modelling within SWAT. The data received for total NPK usage was organized by district and crop, facilitating its implementation into the model. However, in instances where such data was unavailable for certain districts, neighboring districts' data were utilized to simulate non-point source pollution. This data serves as a foundational element for further risk assessment and analysis.

The significance of NPK data in SWAT extends to its role in simulating nutrient dynamics in soils, predicting crop growth, evaluating the consequences of agricultural practices on water quality, and facilitating informed decision-making regarding land use and nutrient management. This data is instrumental in modelling and managing the intricate relationships between agriculture, nutrient dynamics, and environmental considerations.

3.12 Point Source input from Municipal waste

In the Soil and Water Assessment Tool (SWAT) model, the term "point source inputs from municipal waste" typically refers to the discharge of treated or untreated wastewater originating from municipal sewage treatment plants or other specific sources within urban areas, into nearby rivers or streams. These inputs carry significant implications for water quality and the health of aquatic ecosystems. By integrating these point sources inputs from municipal waste into the SWAT model, it becomes possible to gain a deeper understanding of the environmental impact caused by wastewater discharges into local water bodies. This information, in turn, enables informed decision-making regarding wastewater treatment and management practices.

In this specific modelling context, point source input data from urban settlements was incorporated into the model. This input was based on factors such as per capita waste generation and contributions from urban and rural clusters from selected drains in Moradabad. Such data helps refine the model's accuracy in representing the effects of urban wastewater discharge on the hydrological and ecological dynamics of the studied area.

3.13 Scenarios for Flow Regime Change Analysis

One of the primary and deeply concerning issues is the continuous degradation of the hydrological conditions in river basins. This deterioration often results from excessive groundwater extraction and the establishment of diversions without considering the Environmental Flows. The Ramganga Basin is not exempted from these challenges. To restore the hydrological equilibrium of a basin, it's imperative to have access to historical information predating water resource development, which is typically unavailable. Nonetheless, the creation of such historical data is achievable solely through hydrological modelling and simulation, and this approach has been embraced in the current study.

A set of scenarios has been created to assist in the selection of strategies for enhanced planning and management at the basin level. These scenarios were generated through the utilization of the hydrological simulation model, SWAT. Using the SWAT hydrological model, four distinct flow scenarios were developed for the Ramganga Basin, each representing various flow conditions resulting from significant human interventions, climate change impacts, and other relevant factors.

<u>Scenario 1 – Natural Flow Regime</u>: Pre-development flow (Natural or Virgin flow) is a flow which tells the basin potential. In natural flow no interventions were implemented, and all agriculture practices were under rainfed condition. Natural flow condition is generated by removing the major human interventions (e.g., dams/ barrages/diversions) in the model and removing irrigation practices. All other parameters were the similar as the present scenario.

<u>Scenario 2 – Present Flow Regime</u>: Current regime (Present), represents the existing scenario where in all the irrigation practices with their source is applied. Also, all the interventions and abstractions were implemented. All the point and non-point pollutants were incorporated in the model. It best represents the current existing scenario.

<u>Scenario 3 – Climate Change Regime</u>: The SWAT model ran using the intergovernmental Panel on Climate Change Assessment Report (IPCC AR6) data, 13 model ensemble data. Model is simulated for two

scenarios SSP2-4.5 and SSP5-8.5 for three time slices (mentioned below). Baseline period taken for modelling is from 1995 to 2014.

- SSP2-4.5 (middle)
  - Baseline (BL) 1995-2014
  - Near Term (NT) 2021-2040
  - Mid Term (MT) 2041-2060
  - Long Term (LT) 2081-2100
- SSP5-8.5 (high)
  - Near Term (NT) 2021-2040
  - Mid Term (MT) 2041-2060
  - Long Term (LT) 2081-2100

Grid-resolutions for the climate projection are 0.25°x0.25° and 62 weather grids data for temperature and precipitation have been used. The outputs of the climate change scenarios have been analyzed with respect to the possible impacts on the runoff, precipitation, and actual evapotranspiration.
Scenario 4 – Pristine Flow Regime: Pristine flow regime is similar to natural flow regime, only difference is that the water intensive crops were replaced by less water-intensive crops and other parameters same as Natural scenario. Sugarcane, and rice were replaced by millets and maize from agricultural land.

3.14 Model Validation & Calibration

As river basins and watersheds are unique and cannot be replicated, standard practice in hydrologic research involves partitioning the observed data into distinct time intervals or geographic regions for the purposes of calibration and validation. One perspective supports the inclusion of both wet and dry periods within these calibration and validation periods to ensure that the model is capable of performing effectively under a wide range of conditions.

Given that SWAT input parameters are tied to specific processes, it is crucial to maintain them within a reasonable range of uncertainty. The initial step in the calibration and validation process of SWAT involves identifying the most sensitive parameters for a particular watershed or sub-watershed. These parameters are chosen by the user based on their professional judgment or the outcomes of sensitivity analysis. Sensitivity analysis can be executed either through manual adjustments of parameters or through automated calibration using available model tools. Sensitivity analysis aims to assess how the model's output responds to alterations in its inputs (parameters). It is essential to identify the pertinent parameters and determine the level of precision required for calibration.

3.15 Model Performance

Statistical parameters namely regression coefficients (R^2) and Nash Sutcliffe coefficient (NS) were used to assess the model efficiency on monthly SWAT hydrologic streamflow predictions.

It was found that the model has strong predictive capability with Coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), Percent bias (PBIAS) and RMSE parameter. Statistical model efficiency criteria fulfilled the requirement of r2 > 0.6 and ENS > 0.5 which is recommended by SWAT developer (Santhi et. al., 2001). This showed the model parameters represent the processes occurring in the watershed to the best of their ability for the available data and may be used to predict watershed response for various outputs. The model validation results for monthly flow shown in Figure 5 indicates generally a good fit between measured and simulated output.

3.15.1 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[6]). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as

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

Where Yi^{obs} is the i^{th} observation for the constituent being evaluated, Yi^{sim} is the i^{th} simulated value for the constituent being evaluated, Y^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations. NSE ranges between −∞ 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 indicate that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance[7].

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 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[8], Van Liew et al., 2003[9]). R^2 is oversensitive to high extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data (Legates and McCabe, 1999[10]).

3.15.2 Model Evaluation Statistics (Error Index)

Percent bias (PBIAS): Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999). PBIAS is calculated as,

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

Where PBIAS is the deviation of data being evaluated, expressed as a percentage.

RMSE-observations standard deviation ratio (RSR): RMSE is one of the commonly used error index statistics. RSR standardizes RMSE using the observations standard deviation, and it combines both an error

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[6] 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

[7] 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

[8] 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

[9] 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

[10] 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

index and the additional information recommended by Legates and McCabe (1999). RSR is calculated as the ratio of the RMSE and standard deviation of measured data as,

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2}\right]}$$

RSR incorporates the benefits of error index statistics and includes a scaling/normalization factor, so that the resulting statistic and reported values can apply to various constituents. The lower RSR, the lower the RMSE, and the better are the model simulation performance.

3.16 Results & Discussions

Several scenarios have been created to facilitate the identification of strategies for enhanced planning and management at the basin level. These scenarios have been generated employing the hydrological simulation model known as SWAT. Utilizing the SWAT hydrological model, four distinct flow scenarios have been formulated for the Ramganga Basin. These scenarios represent a range of flow conditions influenced by significant human interventions, the presence or absence of certain factors such as climate change, and other pertinent variables.

In order to generate the above-mentioned scenarios for Ramganga basin, the first requirement was to calibrate and validate for the SWAT model for the present flow regime / business as usual scenario. Figure 12
show the calibration and validation results for the SWAT model at 5 stream flow measurement locations, where continuous data was available. The observations and simulations at the 5 gauging stations come to satisfactory agreement, with an R^2 or NSE and an absolute PBIAS. The calibration and validation results demonstrate that the SWAT model is generally capable of simulating the stream flow of the catchment accurately. Also, apart from flow validation, crop yield validation was also done. In addition to flow and crop yield comparison, Evapotranspiration comparison also falls under satisfactory range. Remote sensing data were compared with the ET simulated by the model.

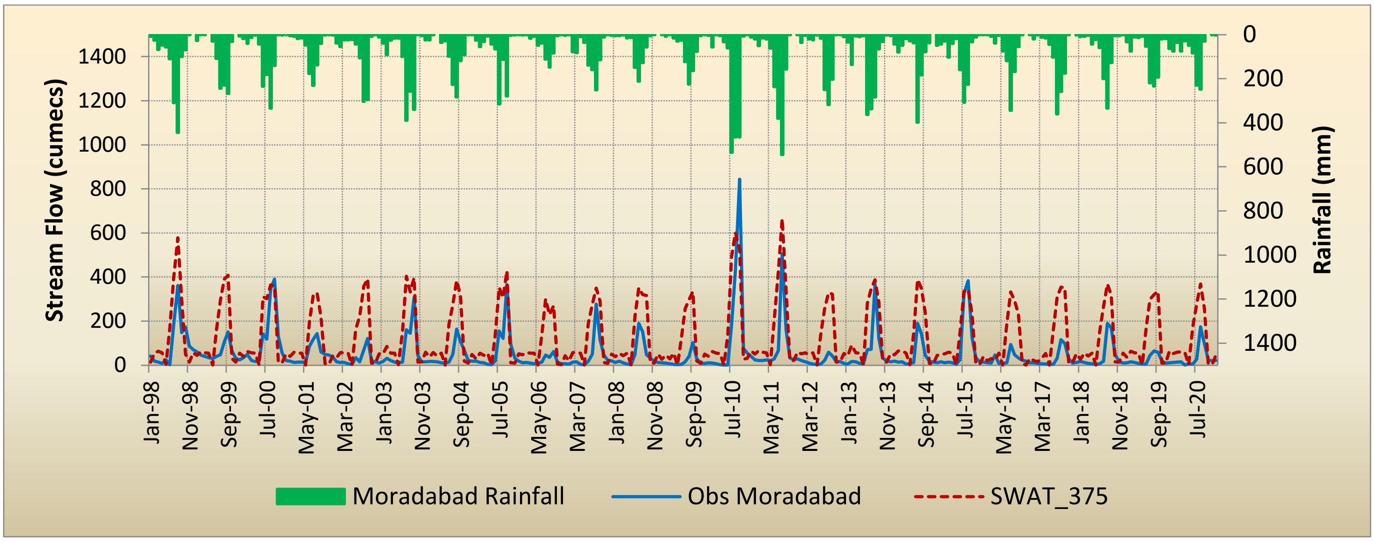
3.16.1 Present Flow Regime

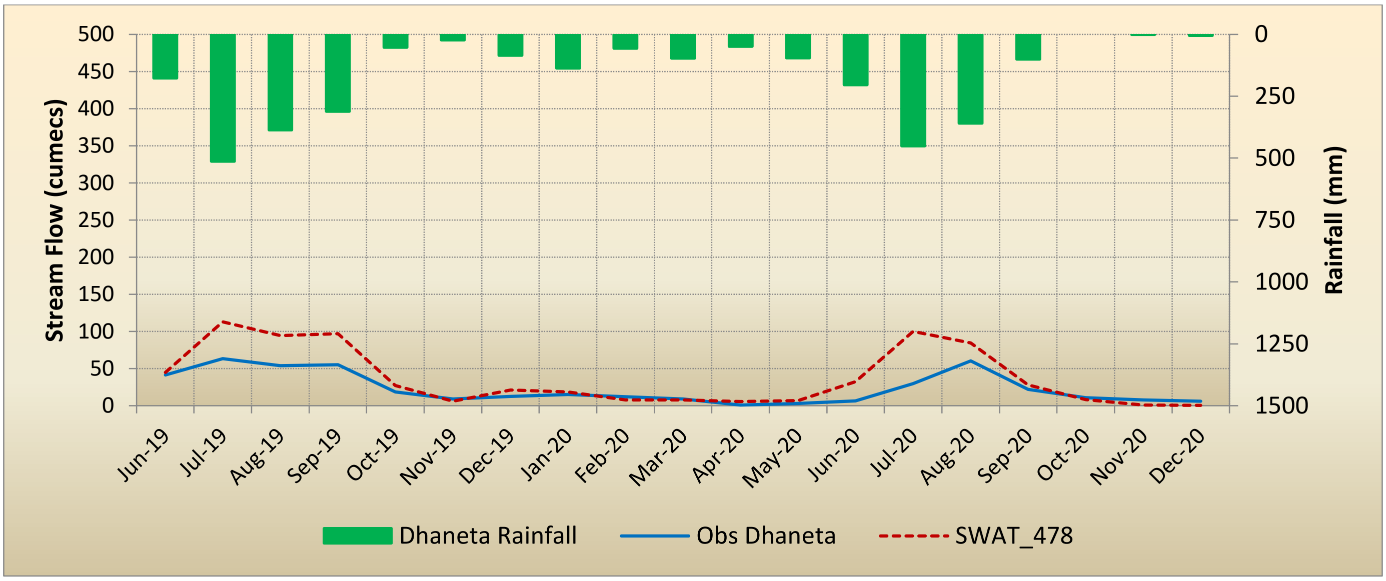
In this particular scenario, the model is subjected to calibration and validation to accurately represent the current real-world conditions. This scenario encompasses the actual implementation of all aspects such as cropping patterns, crop management, irrigation practices, interventions, water diversions, transfers, point source pollutants, and non-point pollutants (NPK) as they exist in reality. Monthly time-series model validation, is conducted using observed data from all the Central Water Commission (CWC) gauges within the Ramganga basin that have available data.

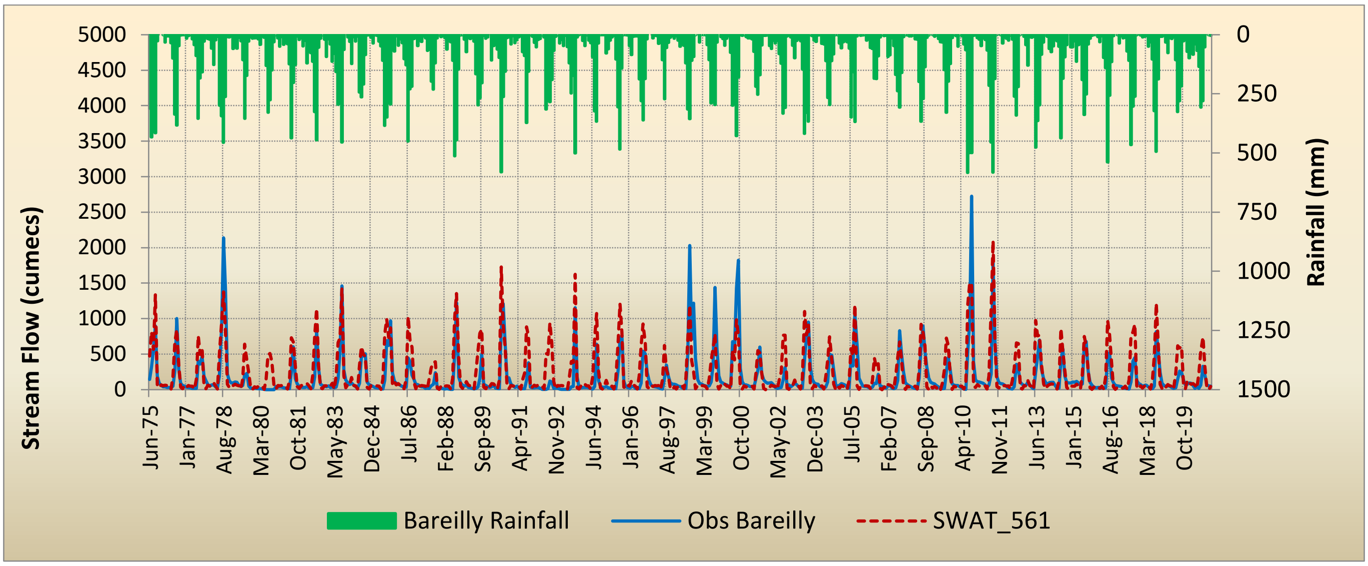
Once the model has undergone calibration and validation, the same model is subsequently employed to generate additional scenarios, including those related to the natural regime and climate change. Additionally, the calibrated model serves as input for groundwater modeling efforts. The validation process indicates that the simulated results align well with the observed data, affirming the model's ability to replicate the hydrological characteristics of the basin. It is important to note that observed data is typically more readily available for the monsoon period. A comparative visualization of observed versus simulated data for the main Ramganga is presented in Figure 12
. Present flow conditions established through calibrated and validated model incorporating.

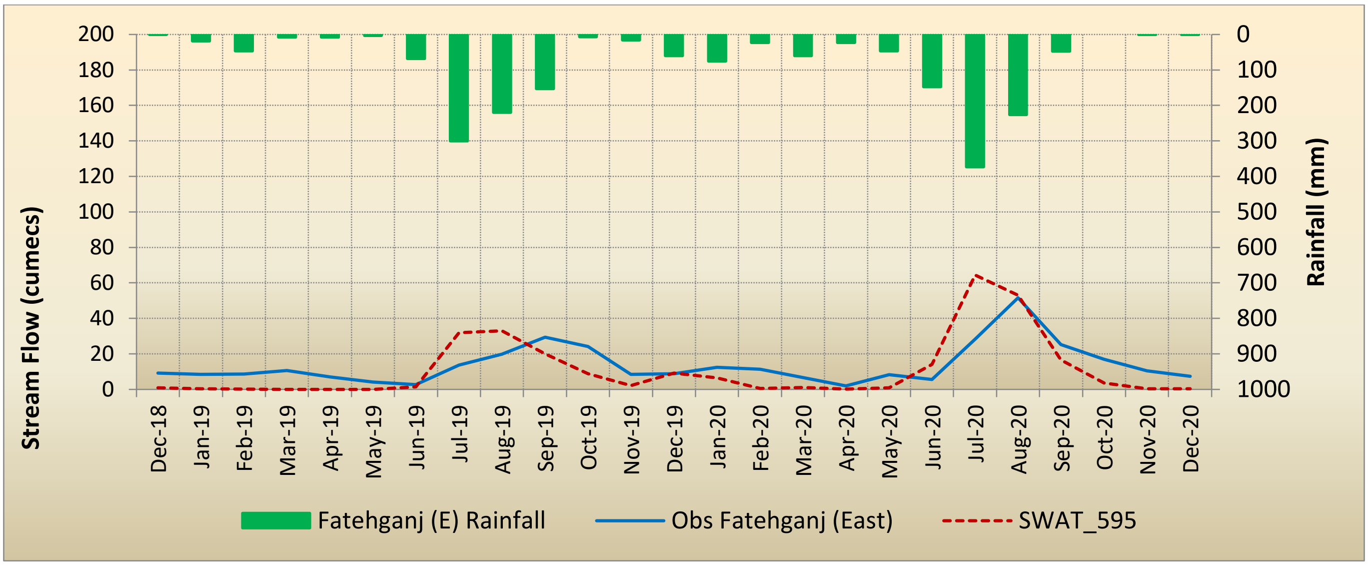
- All major interventions (e.g., dams/ barrages/diversions etc. -info from WRIS/NRLD sites), and
- Management practices (cropping pattern (double/triple crops), irrigation schedules as per district handbook, NPK doses as per district average data, point source pollutants from major drains and from pullulated clusters)

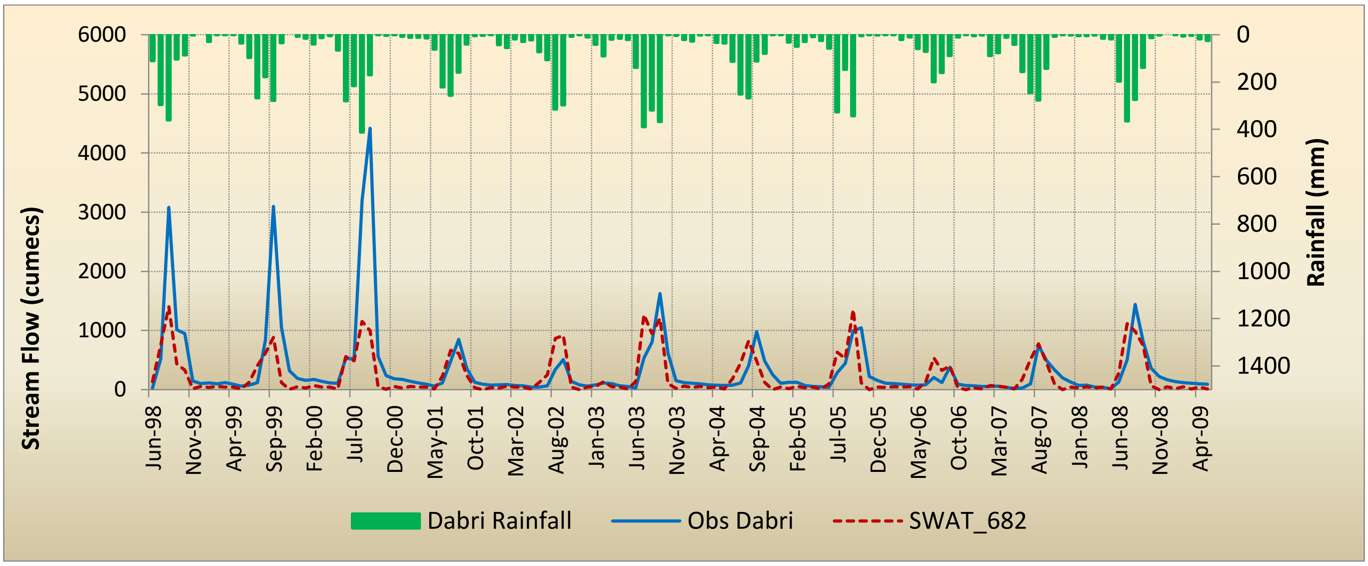
Figure 12 : Model Comparison on Main Ramganga






Stream Flow (cumecs)
Rainfall (mm)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
250
500
750
1000
1250
1500
Jun-75
Jan-77
Aug-78
Mar-80
Oct-81
May-83
Dec-84
Jul-86
Feb-88
Sep-89
Apr-91
Nov-92
Jun-94
Jan-96
Aug-97
Mar-99
Oct-00
May-02
Dec-03
Jul-05
Feb-07
Sep-08
Apr-10
Nov-11
Jun-13
Jan-15
Aug-16
Mar-18
Oct-19
Bareilly Rainfall
Obs Bareilly
SWAT_561


Stream Flow (cumecs)
Rainfall (mm)
200
180
160
140
120
100
80
60
40
20
0
0
100
200
300
400
500
600
700
800
900
1000
Dec-18
Jan-19
Feb-19
Mar-19
Apr-19
May-19
Jun-19
Jul-19
Aug-19
Sep-19
Oct-19
Nov-19
Dec-19
Jan-20
Feb-20
Mar-20
Apr-20
May-20
Jun-20
Jul-20
Aug-20
Sep-20
Oct-20
Nov-20
Dec-20
Fatehganj (E) Rainfall
Obs Fatehganj (East)
SWAT_595


Stream Flow (cumecs)
Rainfall (mm)
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
1400
Jun-98
Nov-98
Apr-99
Sep-99
Feb-00
Jul-00
Dec-00
May-01
Oct-01
Mar-02
Aug-02
Jan-03
Jun-03
Nov-03
Apr-04
Sep-04
Feb-05
Jul-05
Dec-05
May-06
Oct-06
Mar-07
Aug-07
Jan-08
Jun-08
Nov-08
Apr-09
Dabri Rainfall
Obs Dabri
SWAT_682

3.16.2 Natural Flow Regime

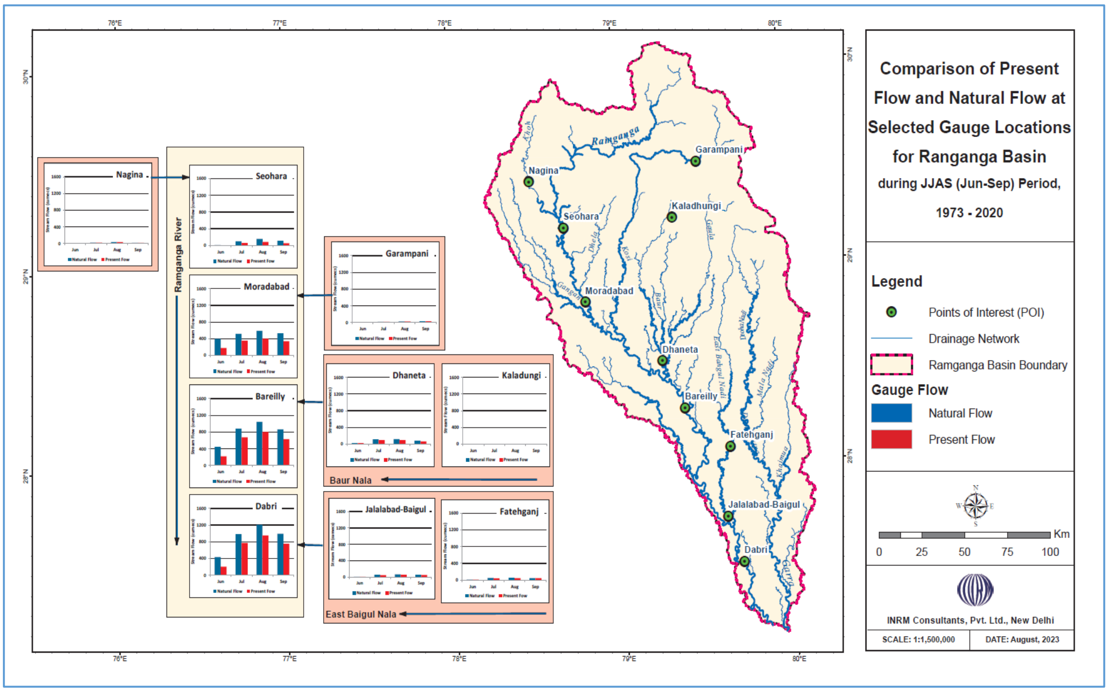
Anthropogenic activities such as river regulations have substantially changed the water balance of the natural catchment. Conducting studies to better understand the intricate watershed processes and how topography, land use, soils, and climate interact with one another is crucial for achieving this goal. The information presented above is essential for obtaining important water balance elements such surface runoff, groundwater, and evapotranspiration (ET), as well as for determining the basin's real potential and future development planning. Natural flow regime simulation is essential for determining the basin's actual potential. The study also establishes that there has been a substantial reduction in overall water resource availability with respect to natural scenario, but to fulfill the demand, over exploitation of groundwater is taking place in parts of the Ramganga basin. This information sets the yardstick for the restoration of the hydrological and environmental health of the basin and can lead to better management of water resources.

The Ramganga River Basin today proposes substantial water resource development projects. Therefore, it is pertinent to evaluate the hydrological health of the basin, before imposing any additional stress on the already stressed system. Thus, it is important to understand the situation of the basin in its "pristine" state. Such simulation of basin during its pristine state is also essential to determine the reference hydrology against which alterations in the surface runoff and other hydrological components in the basin can be measured. The analysis of the basin in its pristine state helps in understanding the extent to which the basin has been already exploited and also gives an insight to viable options that can be formulated to restore the basin close to its initial state.

The developed SWAT model provides the opportunity to generate scenario that can help in understanding the water resource availability under the Natural Flow Regime or Virgin or pre-development condition. Calibrated model of SWAT is used as base model in this scenario. Therefore, in order to develop Natural Flow Regime scenario, it was assumed that there has been no irrigation happening within the catchment and all the projects such as reservoirs and canal diversions were removed from the calibrated SWAT model. This scenario assumes that all the farming areas are rainfed. Comparison of flow with all scenarios are shown in Figure 17 to Figure 20 in the form of Flow Duration Curve (FDC). Long term annual and monthly model comparison for observed and simulated is shown on map (Figure 21 and Figure 22) for better understanding.

To achieve the natural scenarios, the major human interventions are removed (e.g., dams/ barrages/diversions) in the model. Apart from removing the interventions, irrigation practices are also removed. All other parameters are the same as the present scenario. Comparison of present and natural flow is shown in Figure 13.

Figure 13 : Comparison of Present flow regime and Natural Flow Regime at selected Gauge locations



3.16.3 Climate Change Regime

As the demand for water resources continues to surge, there is an increasing pressure to utilize them judiciously. Water, in addition to being a precious resource, is inherently complex. Its behavior is influenced by a range of factors, including the dynamic nature of weather and the spatial variability of landmass, both of which contribute to the dynamic responses of watersheds to natural and artificial water inputs. The potential repercussions of climate change on water resources are a subject of paramount concern for hydrologists, water managers, and policymakers.

To address these concerns, runoff simulations for future climatic scenarios were conducted using the Soil and Water Assessment Tool (SWAT) with the aid of projected bias-corrected statistical downscaling models. For the generation of climate change scenarios, data from the Intergovernmental Panel on Climate Change Assessment Report (IPCC AR6) were employed, involving 13 ensemble models. The complete dataset was segmented into four distinct time intervals, and two future scenarios were simulated to provide insights into the potential impacts of climate change on water resources.

Climate change stands out as one of the most pressing challenges confronting humanity today. Driven primarily by human activities, it poses a direct threat to our essential food and water supplies and, indirectly, to global security. The rise in atmospheric concentrations of carbon dioxide and other greenhouse gases is anticipated to bring about significant alterations in hydrological patterns. This resulting global warming is poised to have profound repercussions for the management of water resources.

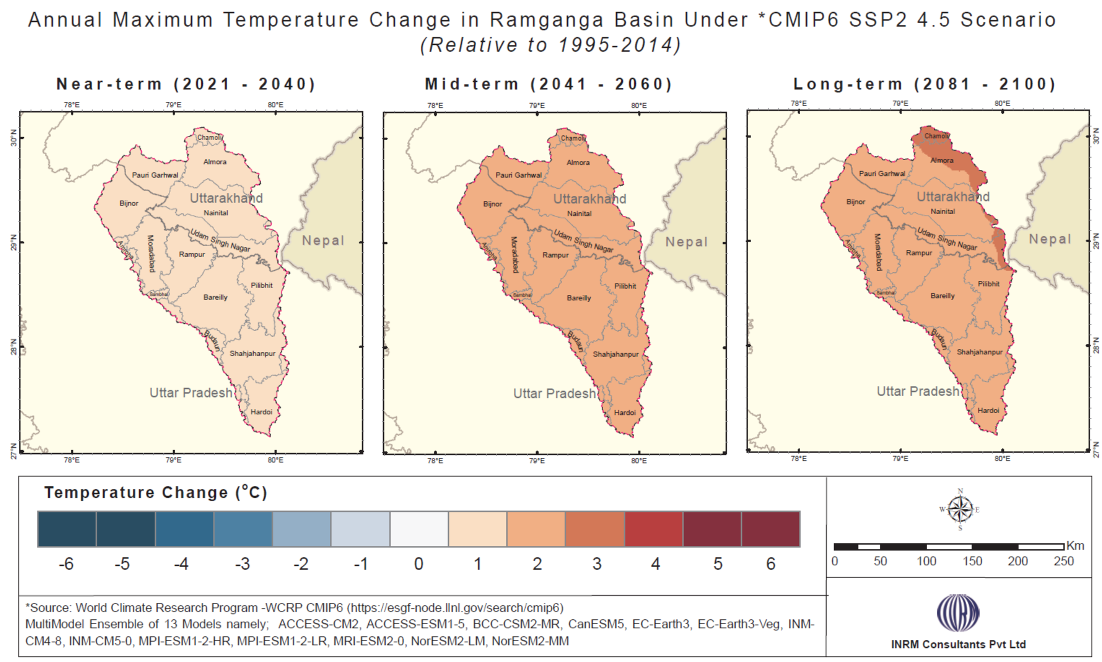
This particular scenario aims to assess the potential effects of climate change on streamflow within a river basin situated in the humid tropical region of India. It is widely recognized that climate variability and change will reshape regional hydrological conditions, leading to a diverse array of impacts on water resource systems.

The climate change data reveals notable trends. Under the AR6 IPCC SSP2-4.5 scenario, it is projected that the maximum temperature will experience an increase of approximately 1.0°C in the near-term, whereas in the mid-term and long-term, the increase is anticipated to be around 2.0°C across the entire Ramganga basin. Conversely, in the SSP5-8.5 scenario, the projected temperature change is more pronounced when compared to the SSP2-4.5 scenario. Specifically, the average annual maximum temperature is expected to rise by about 1.0°C in the near-term, 2.0°C in the mid-term, and a substantial 4.0°C in the long-term under the SSP5-8.5 scenario, as illustrated in Figure 14. This widening temperature range is poised to exert additional pressures on the basin.

Average annual minimum temperature for IPCC AR6 SSP2-4.5 scenario is projected to increase by about 1.0°C towards near-term, about 2.0°C towards mid-term and by 3°C towards long-term while for IPCC AR6 SSP5-8.5 scenario it is projected to increase by about 1.0°C towards near-term, about 2.0°C towards mid-term and 5.0°C towards long-term for Ramganga basin. Thus, projected temperature increases in long-term is higher than that of near-term and mid-term. Minimum temperature is showing higher projected change towards all the time series as compare to maximum temperature for both climate scenarios (Figure 15).

Figure 14 : Projected changes in average annual maximum temperature in Near-term, Mid-term and Long-term with respect to baseline in SSP2-4.5 and SSP5-8.5 scenarios

IPCC AR6 SSP2-4.5 Scenario



IPCC AR6 SSP5-8.5 Scenario

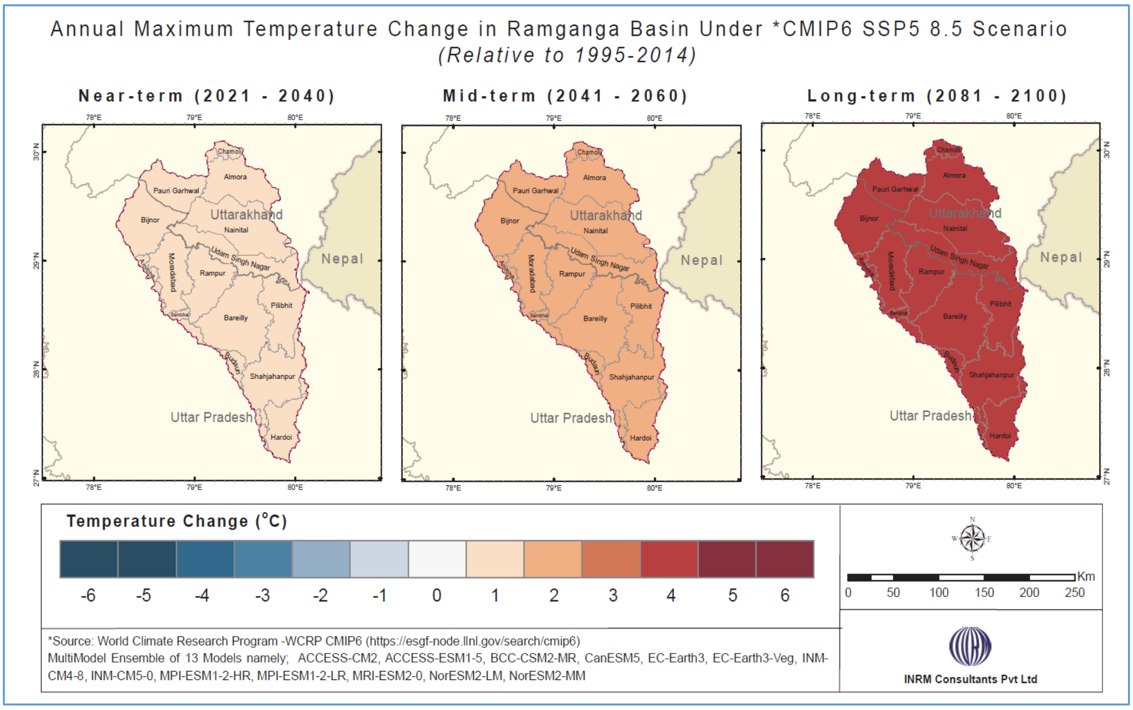
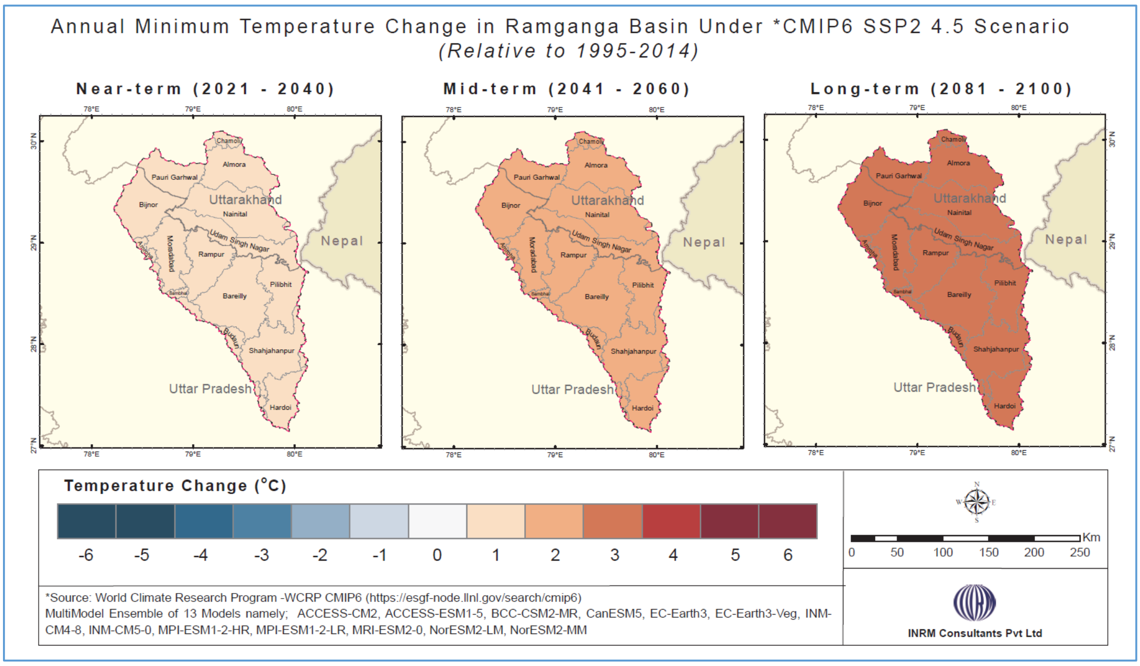
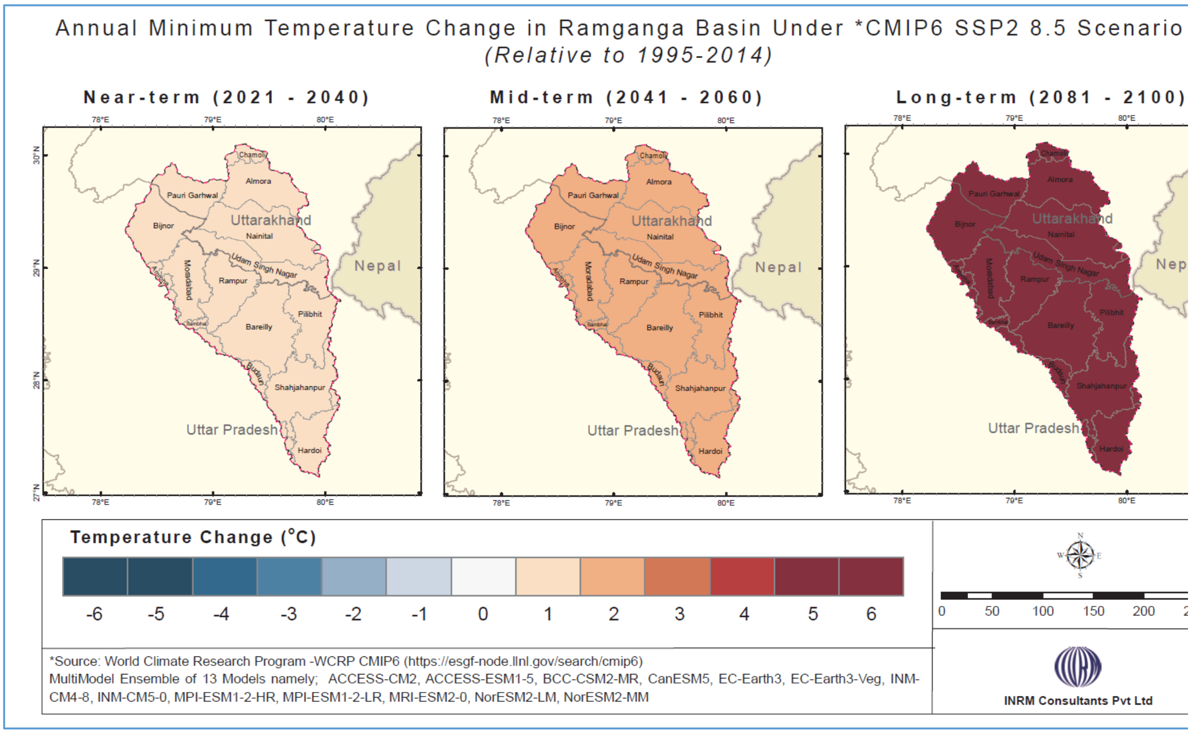


Figure 15 : Projected changes in average annual minimum temperature in Near-term, Mid-term and Long-term with respect to baseline in SSP2-4.5 and SSP5-8.5 scenarios

IPCC AR6 SSP2-4.5 Scenario



IPCC AR6 SSP5-8.5 Scenario

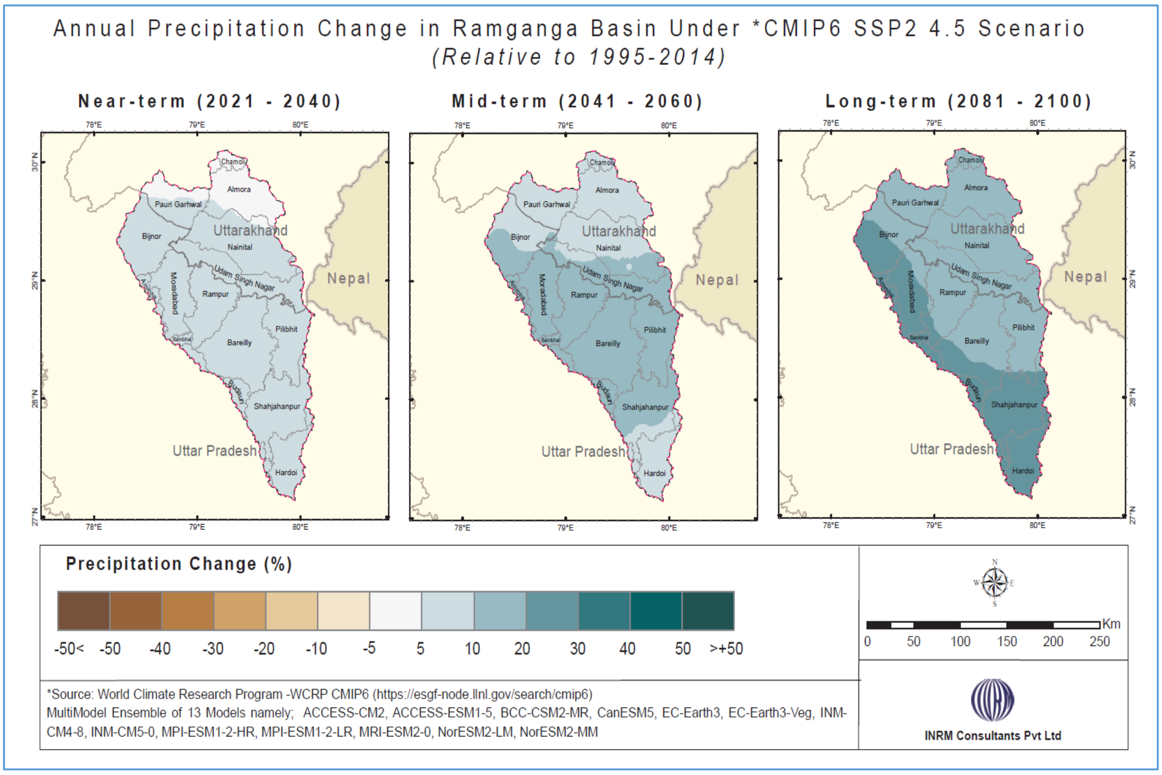


The average annual rainfall projections for the IPCC AR6 SSP2-4.5 scenario indicate an increase ranging from about 5% to 10% in the near-term, approximately 10% to 20% in the mid-term, and a significant increase of about 30% to 30% in the long-term for the Ramganga basin. In contrast, under the IPCC AR6 SSP5-8.5 scenario, rainfall is projected to increase by about 10% in the near-term, approximately 20% in the mid-term, and a substantial 50% increase in the long-term for the same basin. Consequently, it is evident that the percentage of projected rainfall increase ranges from moderate to very high in the future for both climate scenarios, as depicted in Figure 16.

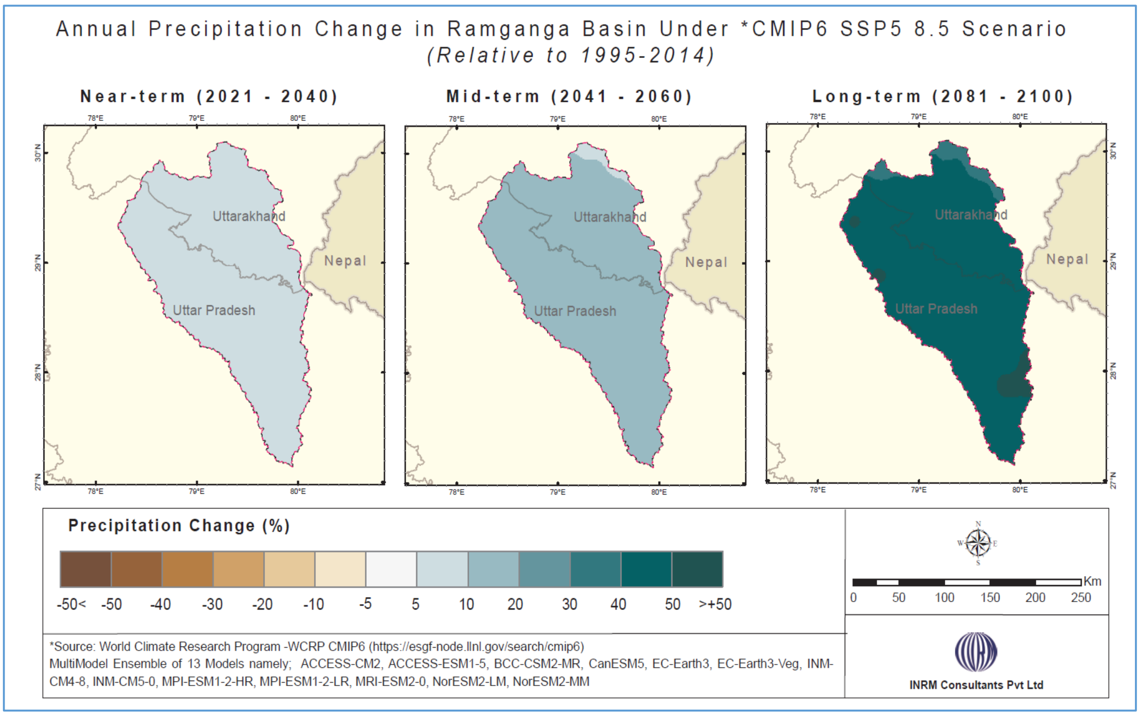
Furthermore, it is worth noting that the situation is anticipated to worsen under the SSP5-8.5 scenario. Analysis of climate change data indicates that under the SSP5-8.5 scenario, rainfall is projected to increase by a remarkable 50% across the entire Ramganga basin in the long-term. This substantial increase in precipitation could potentially lead to flash floods, particularly as the number of rainy days has decreased, and the intensity of 1-day maximum rainfall has increased in the basin.

Figure 16 : Projected changes in average annual precipitation in Near-term, Mid-term and Long-term with respect to baseline in SSP2-4.5 and SSP5-8.5 scenarios

IPCC AR6 SSP2-4.5 Scenario



IPCC AR6 SSP5-8.5 Scenario



Based on the changing climate, IPCC AR6 data was used to simulate the impact of climate change on water balance of the basin. Climate change simulation outputs shall help the watershed managers, decision and policy makers to make timely corrective and appropriate decision.

3.16.4 Nutrient Study

This segment of the study outlines the simulation approach employed to determine the fate and concentration of nutrients within the Ramganga river basins using the SWAT model. Diffuse pollution, primarily stemming from agricultural activities, presents a significant threat to water quality. Nutrient levels are estimated through the nutrient cycles integrated into the model. The study focuses on analyzing the nutrient balance within this basin. The nutrient component of the SWAT model incorporates inputs from agriculture, transportation via runoff and groundwater, plant consumption, and mineralization processes occurring in the soil.

The primary objective of this research is to comprehend the long-term dynamics of water and nutrients within the Ramganga catchment using the SWAT model and to quantify nutrient loads. However, due to the scanty data availability at block level, and crop-wise data on fertilizer consumption (NPK) and corresponding water quality data, calibrating and validating the nutrient content proved challenging.

Nitrogen (N) is an extremely reactive element and exists in various dynamic forms. It may be introduced to the soil through fertilizer, manure or residue application, biological fixation, or rainfall. Within the SWAT model, there are five distinct N pools in the soil. Two of these pools contain inorganic forms of N, while the remaining three contain organic forms. Nitrogen is primarily transported in the nitrate and organic N forms, which can be carried by surface runoff, lateral flow, or percolation.

Fertilizer application was integrated into the model setup, and it was observed that the average fertilizer application aligns with the district data received from both states. In addition to Total N and Total P concentrations, several other parameters such as nitrate, ammonia, pesticides, etc., can be included in the study.

3.17 Scenario Comparison

The changes in flow patterns can be attributed to various factors, primarily the demands for irrigation, as agriculture is the predominant activity in the basin. Additionally, the development of water resource structures to meet irrigation needs, hydropower generation, and flood control has contributed to these changes. Figure 17,

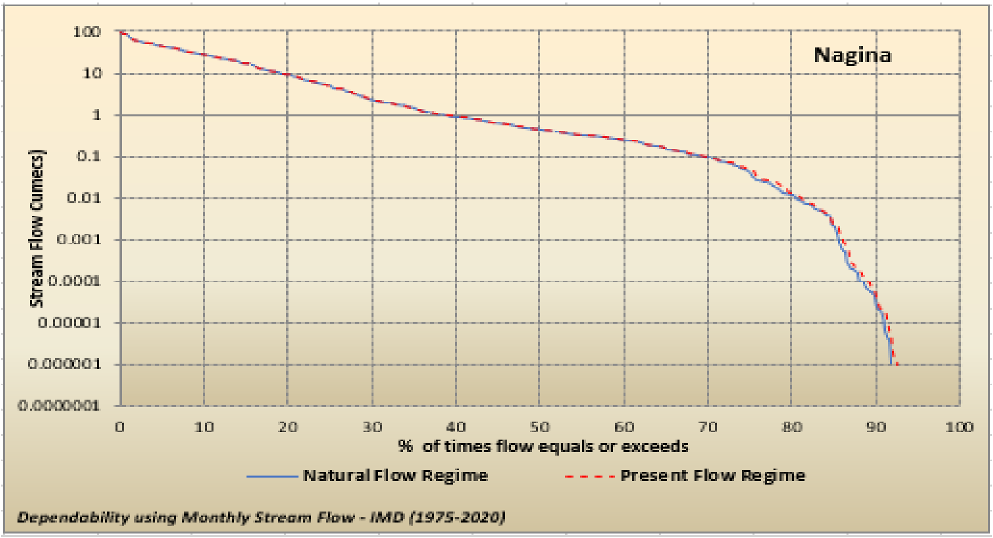
Figure 18, Figure 19, and Figure 20, provide clear evidence of the overexploitation of water resources in these basins. The Flow Duration Curve (FDC) has been extensively utilized in hydrological studies, including water supply, irrigation planning, hydropower, river and reservoir studies, and the enhancement of low flows. The FDC illustrates the variation in streamflow by graphically representing the distribution of the flow regime.

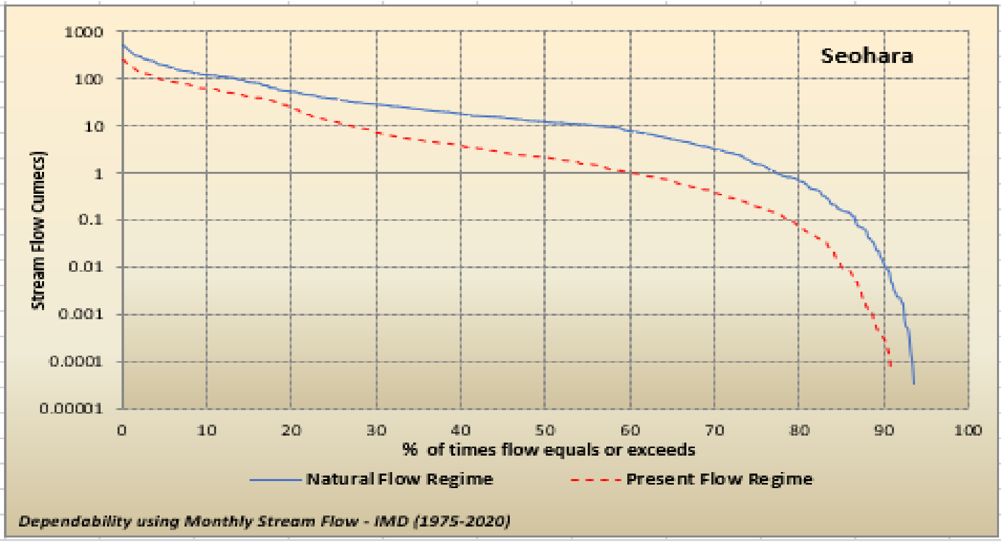
FDCs are generated by plotting surface runoff from the SWAT model or observed runoff at various gauge stations against different levels of dependability where the flow is expected to be equalled or exceeded. The analysis of FDC at 11 locations is depicted in Figure 17 to Figure 20.

A Flow Duration Curve (FDC) is essentially a representation of the flow regime's cumulative distribution function over a specific time interval, such as daily, weekly, or monthly streamflow. These curves have numerous applications, including hydropower planning, water-quality management, sedimentation studies in rivers and reservoirs, habitat assessment, wetland inundation mapping, instream flow evaluations, water resource allocation, low and flood frequency analysis, flood damage assessment, and the selection of optimal water resource projects. FDC is a valuable tool in water management because it displays the full spectrum of flows, encompassing low flows and flood events.

In this study, long-term flow duration curves have been developed for natural, present, and no groundwater scenarios using daily flow data from each site. These FDCs provide a comprehensive representation of the flow regime characteristics for the Ramganga basin. The shape of the constructed FDCs varies at each site, influenced by factors such as precipitation, watershed conditions, and meteorological variables. The FDCs clearly demonstrate that the Ramganga basin cannot sustain flow throughout the year, leading to the extraction of groundwater to meet the basin's increasing demands. The present flow exceeding natural flows indicates that additional water is extracted from groundwater to meet irrigation and other basin demands, with some of it returning to the river as return flow. Figure 17, Figure 18, Figure 19, and Figure 20 further illustrate that in areas where there is no intervention in the upstream catchment, natural and present flow levels are nearly equal.

Figure 17 : FDC Comparison at various locations in Ramganga Basin




Seohara
Stream Flow Cumecs)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0
10
20
30
40
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60
70
80
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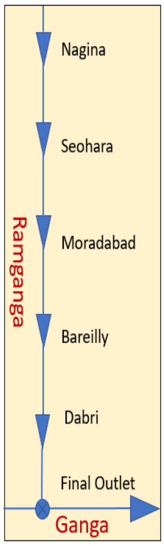
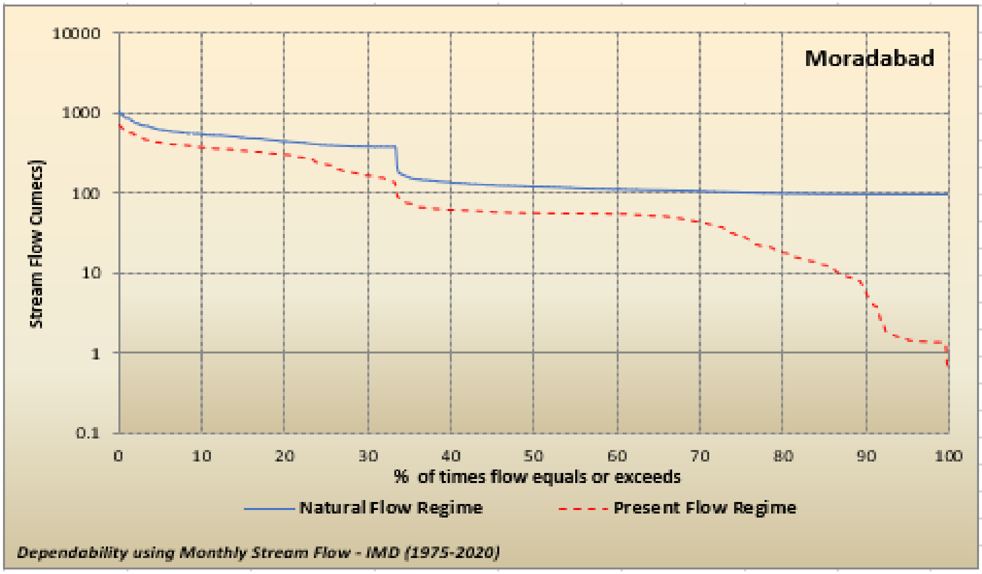
100
% of times flow equals or exceeds
Natural Flow Regime
Present Flow Regime
Dependability using Monthly Stream Flow - IMD (1975-2020)


Nagina
Seohara
Moradabad
Bareilly
Dabri
Final Outlet
Ramganga
Ganga


Moradabad
Stream Flow Cumecs)
10000
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100
10
1
0.1
0
10
20
30
40
50
60
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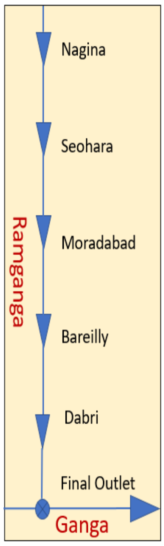
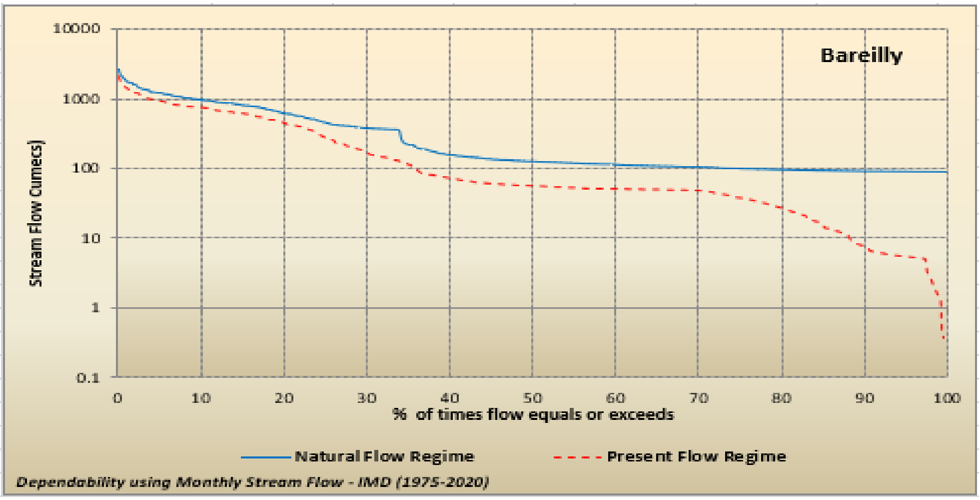
80
90
100
% of times flow equals or exceeds
Natural Flow Regime
Present Flow Regime
Dependability using Monthly Stream Flow - IMD (1975-2020)


Nagina
Seohara
Moradabad
Bareilly
Dabri
Final Outlet
Ramganga
Ganga


Bareilly
Stream Flow Cumecs)
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0.1
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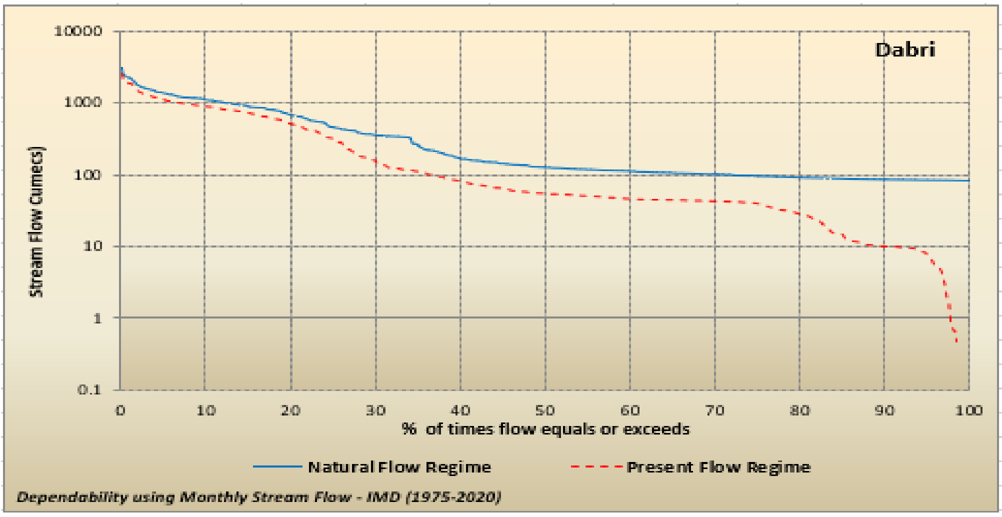
100
% of times flow equals or exceeds
Natural Flow Regime
Present Flow Regime
Dependability using Monthly Stream Flow - IMD (1975-2020)


Dabri
Stream Flow Cumecs)
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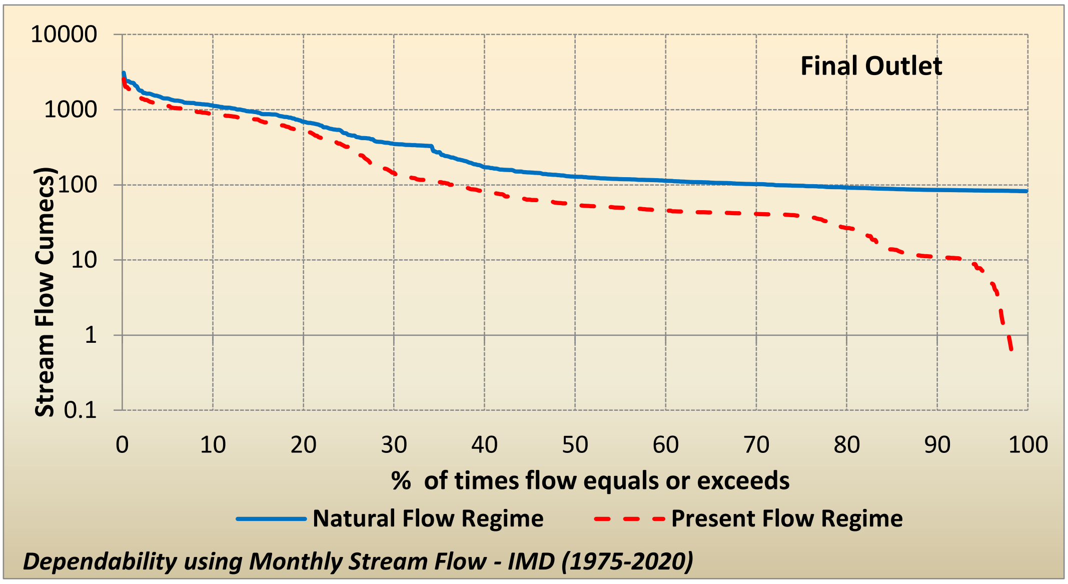
% of times flow equals or exceeds
Natural Flow Regime
Present Flow Regime
Dependability using Monthly Stream Flow - IMD (1975-2020)


Final Outlet
Stream Flow Cumecs)
10000
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100
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1
0.1
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100
% of times flow equals or exceeds
Natural Flow Regime
Present Flow Regime
Dependability using Monthly Stream Flow - IMD (1975-2020)

Figure 18 : FDC Comparison at various locations in Kosi Basin

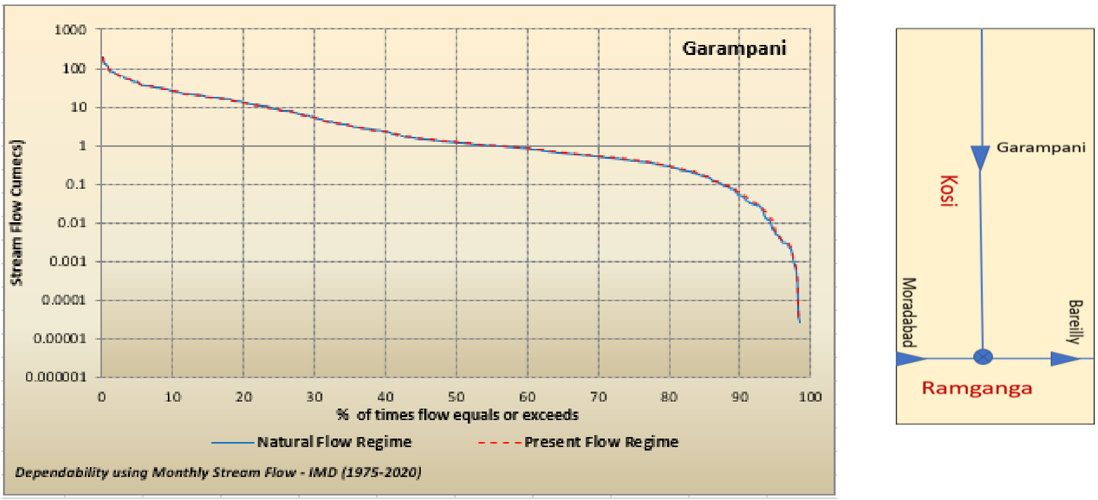


Figure 19 : FDC Comparison at various locations in Baur Nala Basin

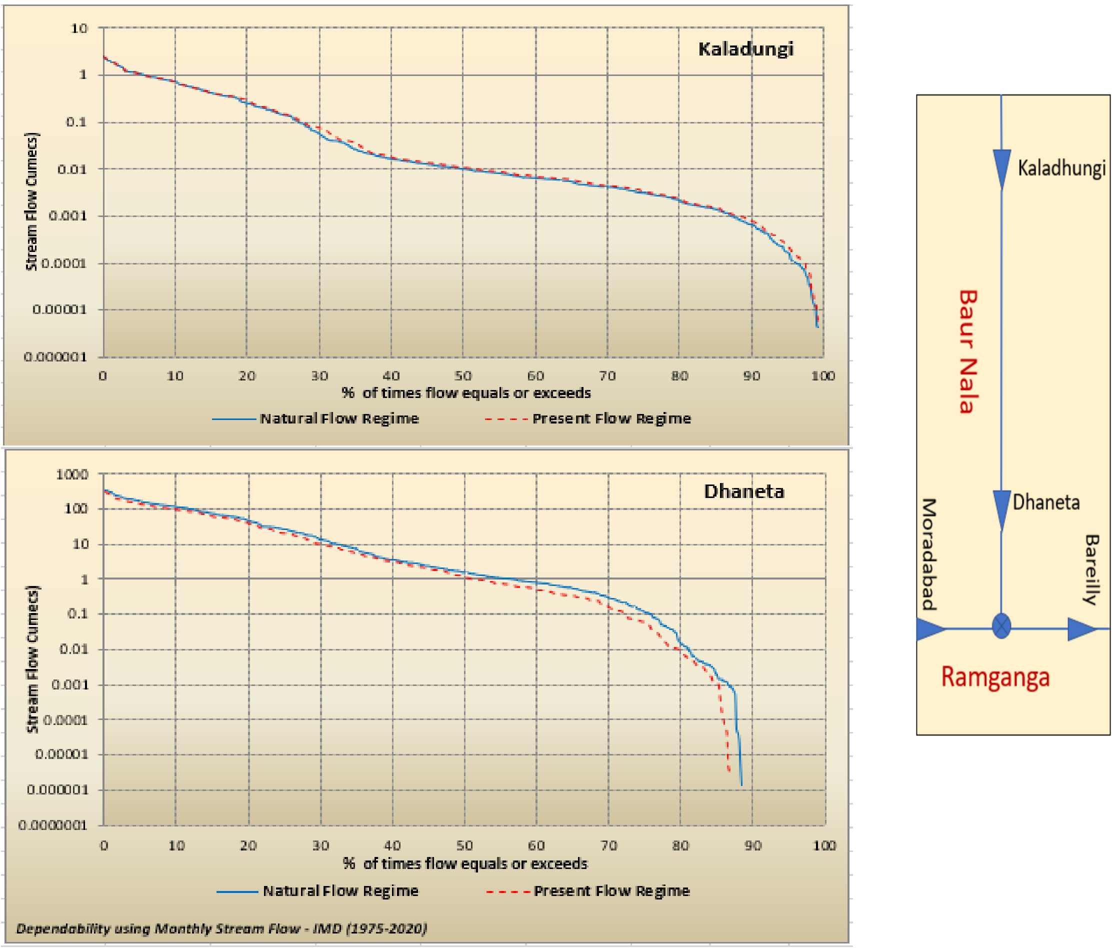
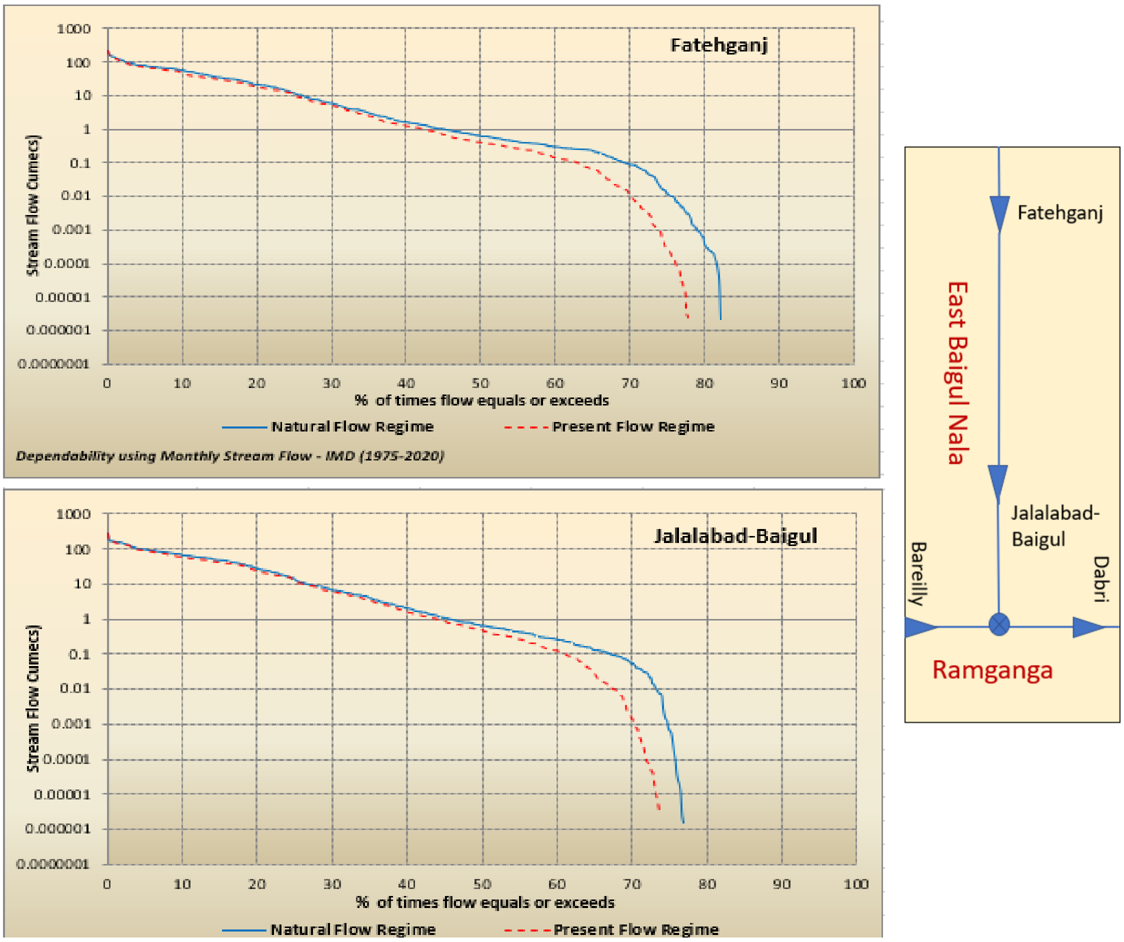
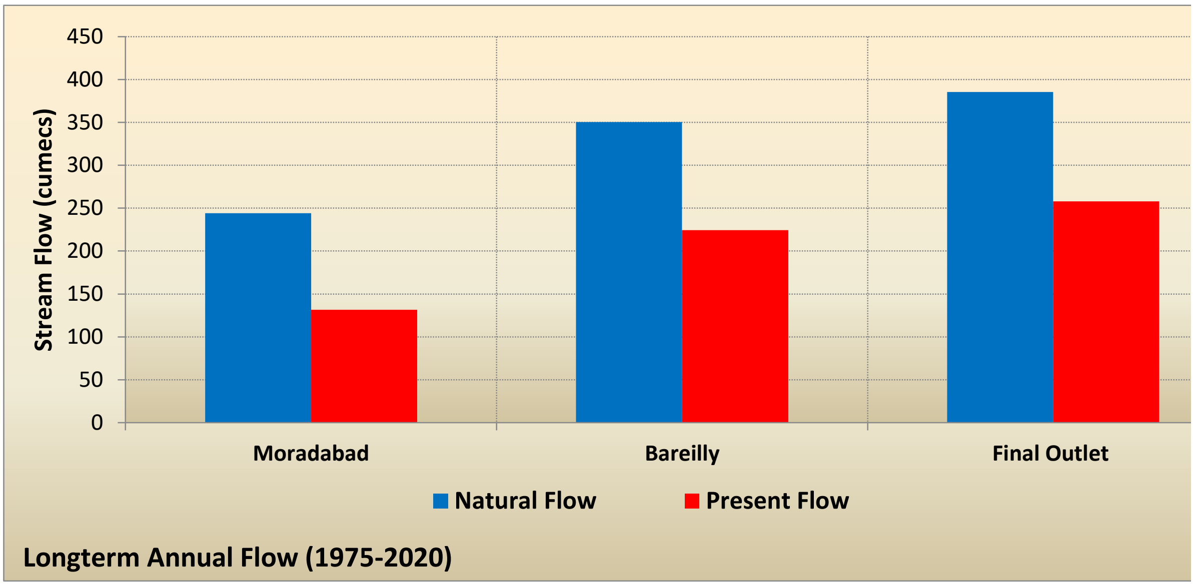


Figure 20 : FDC Comparison at various locations in East Baigul Nala Basin



In addition to the Flow Duration Curve, the study also aggregated long-term annual and monthly flow data at Moradabad, Bareilly, and the final outlet of the Ramganga basin. Comparisons between the current flow regime and the natural flow regime are depicted in Figure 21 and Figure 22 respectively. It becomes evident from the long-term average annual flow data of the Ramganga basin that the natural flow exceeds the current flow regime at Moradabad, Bareilly, and the final outlet of the Ramganga basin. Figure 22 provides a representation of the monthly distribution of flow for both the natural and present scenarios at Moradabad, Bareilly, and the Ramganga Basin's final outlet.

Figure 21 : Long Term Average Annual flow of the Ramganga Basin



Long term mean monthly flow at Moradabad, Bareilly and Final outlet is shown in Figure 22

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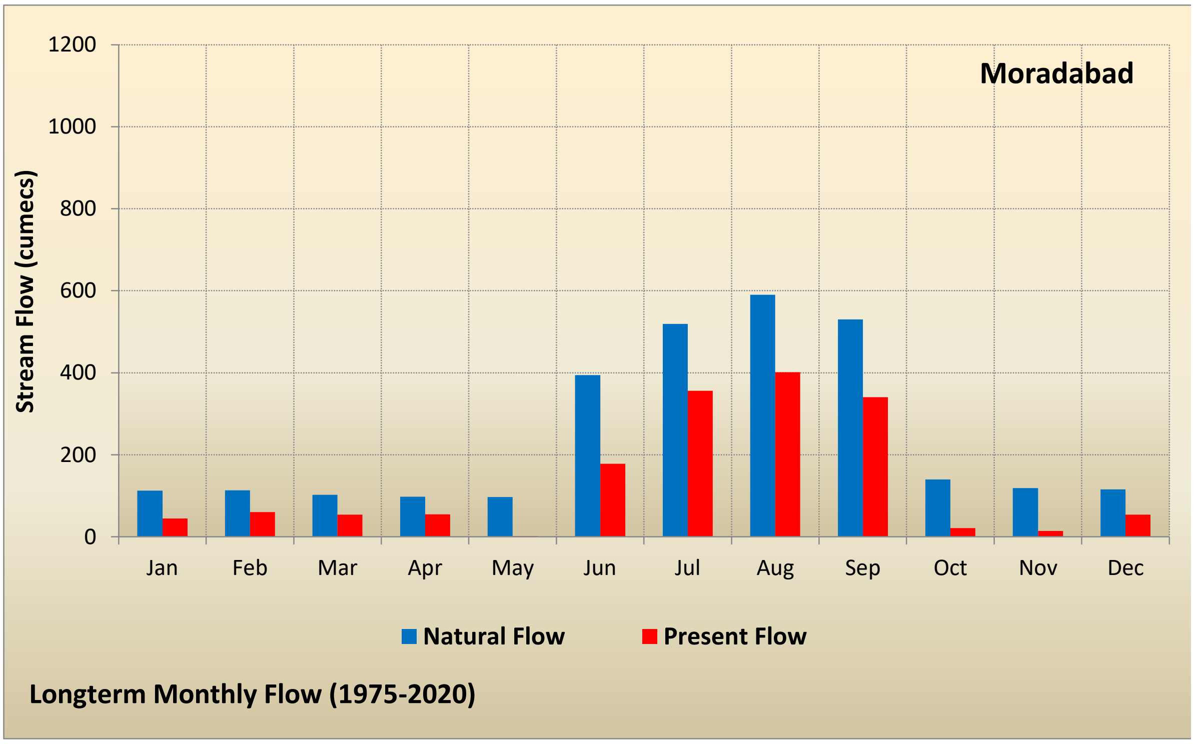
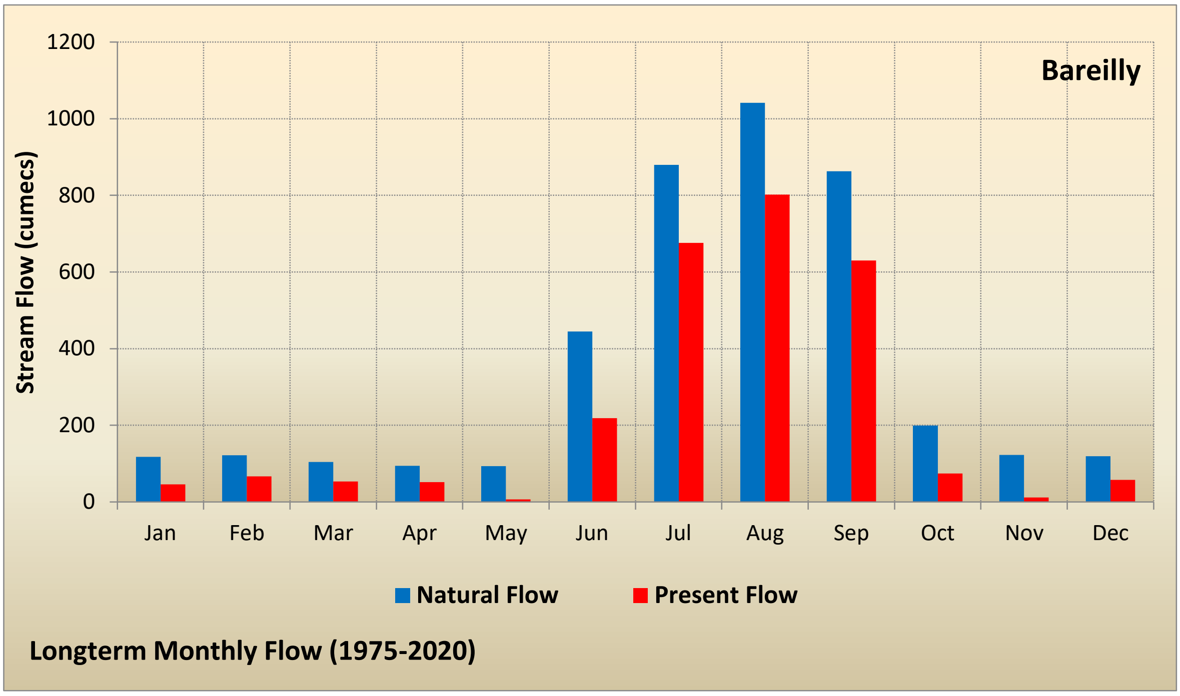
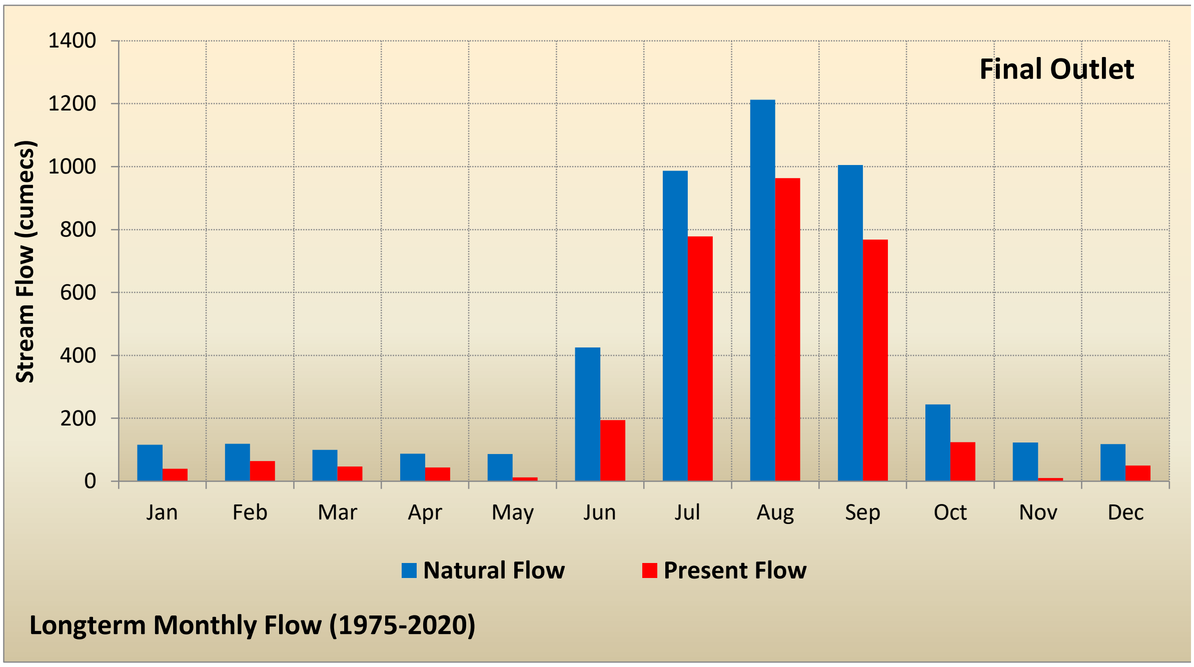
Figure 22 : Long Term Mean Monthly flow of the Ramganga Basin







4 GROUNDWATER MODELLING

Groundwater is a crucial resource for the entire world. The importance of the groundwater in coming decades is going to be even more critical with current surface water resources suffering on the account of exploitation and quality concerns. Surface water and groundwater resources are interconnected. To design sustainable water resource development strategies, decision-makers need comprehensive knowledge on these relationships.

Groundwater models are crucial for the development and management of groundwater resources as well as for predicting the outcomes of management actions. A conceptual model's fundamental elements include the region's physical boundaries and hydrological boundaries of the region (Bear et al., 1992). Simulating groundwater flow through numerical modelling makes it possible to foresee how changes in the hydrologic environment would affect the subsurface flow. However, in order to do so, it is necessary to define precisely the region's physical boundaries, the water fluxes into and out of area. Usually, Groundwater is recharged by irrigation and precipitation and removed from the system through pumping for industrial, agricultural, or domestic purposes. Evaporation, transpiration, subsurface flow, and stream flow are also extracted from the groundwater. Rivers can be a source of input or output depending on their nature, i.e., losing or gaining streams. The current study aims to study the groundwater in the Ramganga river basin thorough numerical modelling. Groundwater modelling for the entire Ramganga basin was carried out using SWAT output in USGS open source MODFLOW 6 groundwater model.

Groundwater models may be used to predict the effects of hydrological changes (like groundwater pumping or irrigation developments) on the behavior of the aquifer and are often named groundwater simulation models. Groundwater models are used in various water management plans. For groundwater modelling Open source USGS ModelMuse is used for groundwater modelling using SWAT output as input to the model. In absence of fence diagram, basic aquifer characteristics were fixed using the CGWB district reports. In case of missing data in CGWB report, a few assumptions were made taking values from neighboring districts and literatures. Groundwater aquifer is shown in Figure 23
and complete groundwater modelling process is shown in Figure 24.

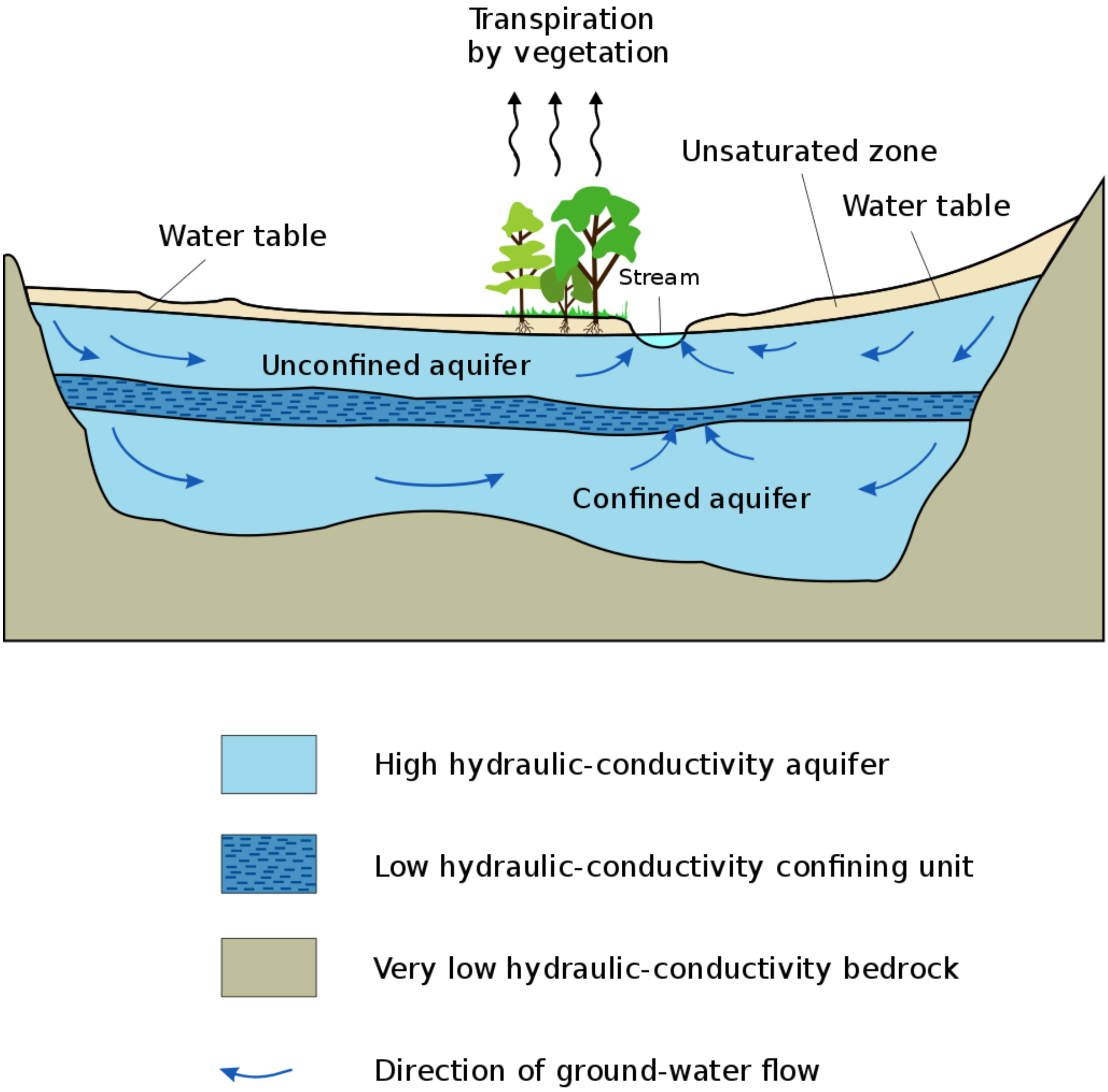
ModelMuse uses MODFLOW 6 in the background. MODFLOW 6 presently contains two types of hydrologic groundwater models,

- The Groundwater Flow (GWF) Model and
- The Groundwater Transport (GWT) Model.

The GWF Model for MODFLOW 6 is based on a generalized control-volume finite-difference (CVFD) approach in which a cell can be hydraulically connected to any number of surrounding cells. Users can define the model grid using

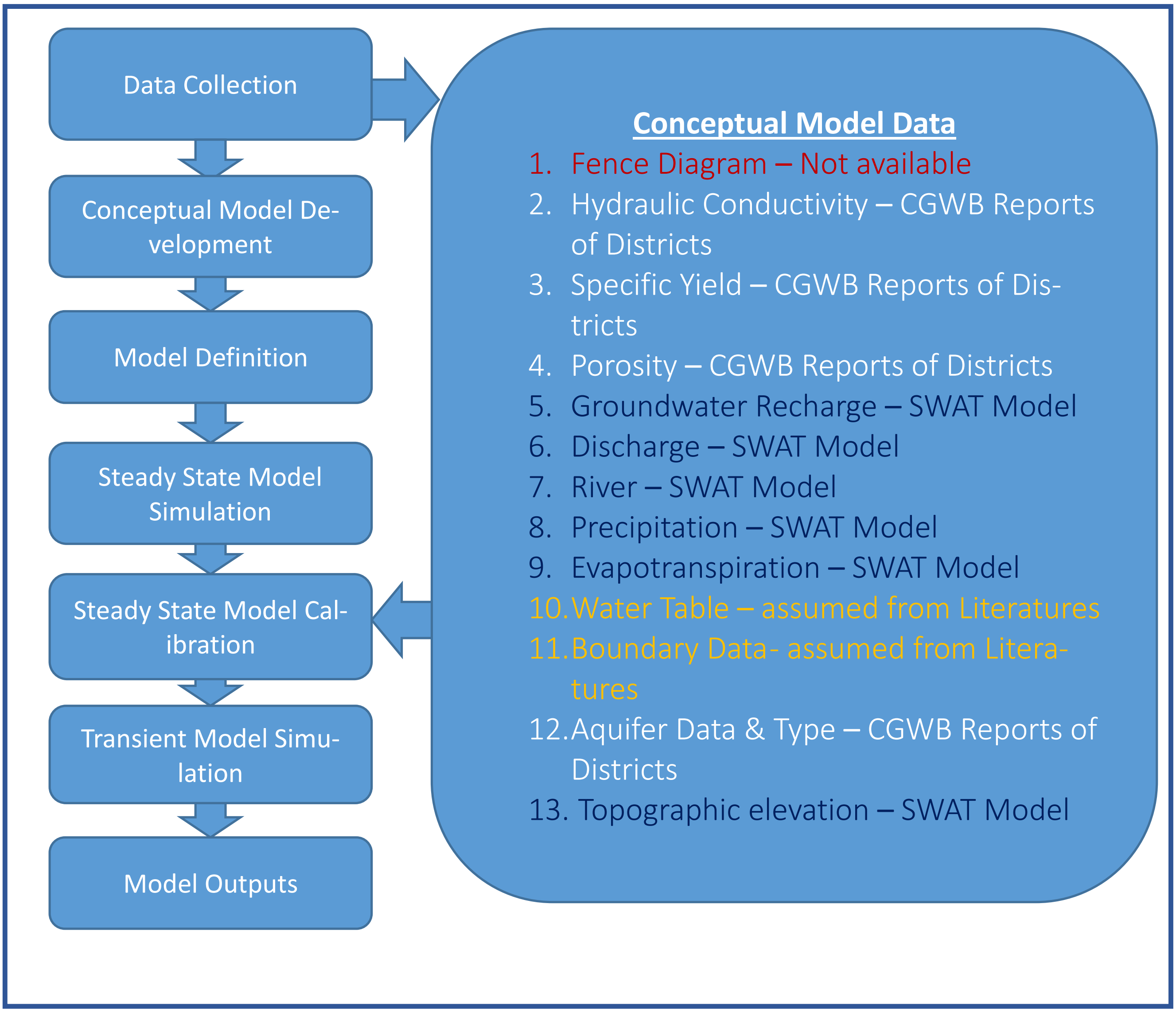
- a regular MODFLOW grid consisting of layers, rows, and columns
- a layered grid defined by (x, y) vertex pairs

Figure 23 : Groundwater Aquifer



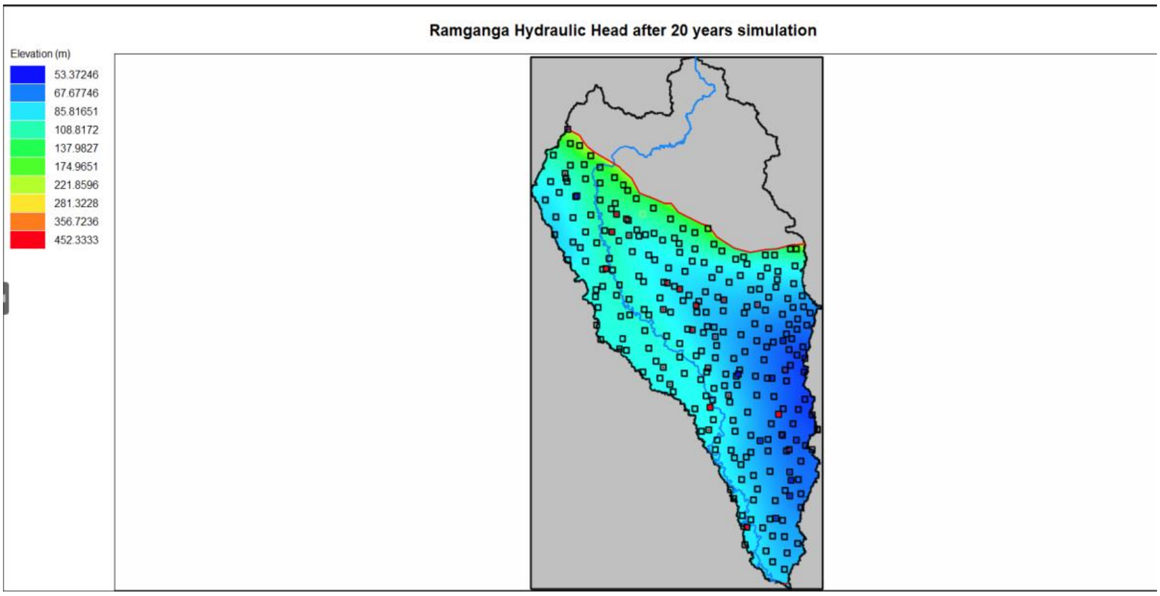
All the parameter used as an input to groundwater model is taken from SWAT hydrological model. Aquifer characteristics are defined using CGWB reports. In absence of fence diagram, aquifer depth, water table etc., are taken from literatures. Complete groundwater hydrological process and data used along with source is shown in Figure 24.

Figure 24 : Complete Groundwater Modelling Process along with Data Source



The groundwater model was simulated for a duration of 20 years, spanning from 2000 to 2020, utilizing the outputs generated by SWAT. Figure 25 depicts the groundwater hydraulic head after 20 year simulations.

Figure 25 : Drawdown in Ramganga aquifer after 20 year simulation



5 DATA GAPS AND ASSUMPTIONS

The SWAT hydrological models, while valuable tools, are not without their imperfections. Any deficiencies in their structure, parameterization, or initialization can be addressed through observations. It is highly advantageous to supplement observed data with additional information and incorporate indirect observational techniques to enhance model accuracy. The observed data often come with a significant degree of uncertainty and may not provide continuous records. Notably, the observed data for stream flow lack information on low flows, and the available data from state gauges are limited.

Due to these data gaps and the absence of continuous, long-term data series, certain gauges could not be utilized for model calibration and validation. In the absence of actual data, some proxy data were employed for model validation. For instance, in ungauged subbasins, crop yield and evapotranspiration were utilized for validation and calibration purposes.

In addition to the challenges with flow data, there is also limited access to pesticide, nutrient, chemical, and fertilizer application data at the block and farm levels. The presence of these data gaps and the unavailability of certain data make it challenging to replicate the current real-world scenario accurately. Furthermore, data on groundwater abstraction at the block level is also lacking. The data gaps and assumptions associated with the available data are summarized in the following bullet points:

- Interventions (e.g., dams/ barrages/weir etc.) taken from India WRIS/NRLD, 2018. There are a few major/medium/minor structures, which are present within the basin, but details/characteristics/releases/operations/diversions data of such structures are missing. In case of non-availability of the data, official reports/literature/publications were referred. In case of non-availability of data on official sites also, those interventions were implemented with blank / no data.

- ➢ There is a lot of **inter/intra basin transfers** happening within Ramganga basin, In case of known transfer amount, actual numbers are included/implemented. Else indirectly transfer were included, by utilizing the water for irrigation in the command area.
- ➢ **Drinking water diversions** were implemented, wherever information was available on official sites about the source and quantity.
- ➢ **Cropping pattern** –Cropping pattern were taken from the latest district handbook available on the website. In case the cropping pattern changes over the years, same is not included in the study. (https://agricoop.nic.in, https://agcensus.nic.in, https://www.icar.org.in, https://www.farmer.gov.in/handbooks.aspx)
- ➢ **Irrigation source** – All the commands are irrigated from the dam/barrage/weir associated with it. In case the amount of diversion was not known, irrigation was done directly from the source dam (parent dam). If the agriculture area is outside the command area, then irrigation is done from groundwater.
- ➢ **NPK doses** are taken as per aggregated data for a district. In case of missing district data, neighboring district data was used.
- ➢ **Command of Sarda and Ganga canals** are within the Ramganga Basin, the same is implemented as a command with outside source. But the actual amount transferred is not known, therefore crop requirement is considered as the amount transferred into the Basin.
- ➢ Transferring of water from Dam to barrage and then to command is not implemented. Directly water from Dam is used for irrigation in the command area, this is done so because transfer amount from Dam to barrage is unknown at many places. This is termed as indirectly implemented of transferring of water into command area.
- ➢ **Actual daily/monthly releases from all dams (operation rule)** (e.g., Kalagarh) are not known, hence it is assumed that release shall happen once dams are filled (Spilling).
- ➢ **Non-point pollution** is implemented using crop wise fertilizer and pesticide data provided at district level. However, some of the district has missing data and in such a case neighboring district data is used.
- ➢ **Point source pollution** is implemented, using urban and rural clusters population data and per capita formula. In addition, all the drains draining into Ramganga River near Moradabad town are also implemented in the model. All the pollutants information provided are implemented. However, there is scope of refinement.

6 CONCLUSION

Water requirements are undergoing significant changes due to rapid economic and population growth, leading to increased demand for expanded water supplies. Irrigation, which constitutes the largest share of water usage, continues to be a vital component of local and state economies. Another pressing demand for water arises from growing concerns for environmental and recreational values, areas that may not be legally protected or receive as much public attention in terms of water allocation. These shifts in demand, coupled with the fact that water resources are already fully allocated in many parts of the basin, pose challenges for effective river basin management.

Managing a river basin requires addressing multiple objectives and employing a variety of water management strategies to ensure sustainable development of water resources. A GIS-based framework known as the Programme of Measures (POM) tool serves as a valuable tool for identifying the most feasible and cost-effective management scenarios. This tool facilitates the efficient assessment of numerous options, evaluates the cost-effectiveness of various combinations, and includes features for exporting data to more comprehensive process-based river basin models. This comprehensive approach provides watershed managers and policymakers with a holistic view of all available options and their potential outcomes.

The study's findings highlight that the basin is highly managed, featuring numerous interventions, transfers, diversions, and planned projects. To meet the growing water demand, groundwater is being over-exploited in certain sub-systems of the basin. The flow duration curves (FDCs) illustrate that the Ramganga basin struggles to maintain a consistent flow throughout the year, especially in its upper reaches and just downstream of the dam. However, Moradabad city benefits from a significant flow in the river due to the confluence of numerous tributaries and drains. While the basin is extensively irrigated under the canal command system, groundwater extraction is necessary to meet the basin's increasing demands.
In conclusion, this study provides valuable insights for river managers and water professionals who must navigate the trade-offs between human water use and the preservation of riverine ecosystems. It can be integrated into an optimized management system aimed at maximizing available water resources while ensuring the sustainability of the ecosystem.