ARCP Final Report



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Assessment of Climate-Induced Long-term Water Availability in the Ganges Basin and the Impacts on Energy Security in South Asia

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Project Overview

Project Duration	:	2 years
Funding Awarded	:	US$ 40,000 for Year 1; US$ 35,000 for Year 2
Key organisations involved	:	Institute for Global Environmental Strategies (IGES), Japan (Dr. Xin Zhou, Dr. Bijon Kumer Mitra, Dr. Brian Johnson, Dr. Diego Silva Herran) Central University of Rajasthan (CURAJ), India (Dr. Devesh Sharma) Bangladesh University of Engineering and Technology (BUET), Bangladesh (Professor G.M. Tarekul Islam) Center of Research for Environment, Energy and Water (CREEW), Nepal (Dr. Rabin Malla)

Project Summary

The Ganges basin provides essential water for drinking, irrigation, industrial use and cooling of power generation facilities. Changes in the water availability induced by global climate change will impact on economic development as well as human life in this basin and beyond. Water competition among major consumers will become fiercer in the Ganges basin in the coming decades as the three major South Asian developing countries, Nepal, India and Bangladesh focus more on poverty eradication, industrial development, food security and universal energy access for achieving their long-term social and economic development goals. These factors combined will exacerbate the existing level of water stress that has been experienced in some sub-basins of the Ganges. As one of the largest water consumers, the energy sector will thus face a big challenge in ensuring sufficient water to maintain stable operations of the existing and planned thermal power plants in the future. Quantitative knowledge on the spatial distribution of water supply, water demand, water supply-demand balance and energy water requirement is crucial to energy feasibility planning and effective water resource management. However, few studies on these practical issues can be found in existing literature.

This project, entitled "*Assessment of Climate-Induced Long-term Water Availability in the Ganges Basin and the Impacts on Energy Security in South Asia*", is funded by the Asian-Pacific Network for Global Change Research (APN). The project aims to inform decision makers, relevant stakeholders and energy project investors about future water availability under climate change conditions, as well as water supply-demand balance and water risks for existing and planned power plants from the present to 2050. We developed a novel approach on an integrated assessment of the water-energy nexus by using various modelling techniques (hydrological modelling, water demand projections) together with first-hand data collection from power plant field surveys. Three case studies were conducted for India, Bangladesh and

Nepal. The case study in India covering four selected sub-basins, namely Chambal, Damodar, Gandak and Yamuna, provides a detailed assessment on future water availability, water demand, water supply-demand balance and the water risks for existing and planned thermal power plants at the sub-basin and district levels. To enable effective communications with the target audience, a free on-line web tool, Water-Energy Nexus Assessment for India, was developed to help explore and visualise the spatial data and the results on maps. Through multi-stakeholder consultations in the kick-off workshops and the final workshops held in the three countries, the objective of this project, the major results and key messages have been effectively communicated with relevant policy makers from the development and planning ministry, energy sector and water supply and management department, etc., as well as academia and other stakeholders (e.g., project investors). This project has contributed to strengthening the science-policy interface in the area of water-energy nexus for the Ganges basin.

Keywords: Water-energy nexus, integrated assessment, Ganges basin, water supply and demand balance assessment, water stress for thermal power generation

Project outputs and outcomes

Project outputs include:

- An integrated assessment of the water-energy nexus at the sub-basin level, including water supply assessment, water demand assessment, water supply-demand balance assessment and water stress assessment for future thermal power generation;
- A free on-line tool providing spatial visualisation results on water supply, water demand, water supply-demand balance, and water stress for existing and planned thermal power plants at the district level for four selected sub-basins in India (accessible at IGES website *https://www.iges.or.jp/en/index.html*);
- Stakeholder consultation workshops through which the objective, methodology, results and key messages were effectively communicated with relevant stakeholders in Nepal, India and Bangladesh.

Project outcomes:

- Relevant governmental officials, particularly from the national planning organisation and the energy development sector, were for the first time informed about the spatial distribution of the water supply-demand balance at the district level.
- Relevant planning officials, energy planners and investors became highly aware of the potential water risks, both current and future, faced by existing and planned thermal power plants located in the water-stressed regions.
- Relevant planning officials, energy planners and investors were informed about the potential sites where water surpluses exist for consideration of future new energy projects, particularly thermal power plants.
- Relevant energy planners, project developers and investors were informed about the substantial impacts of the selection of proper technologies of power generation and types of cooling system on sustainable water use.

Key facts/figures

- For India, from the supply side, the overall water availability will increase in the future in the four sub-basins, particularly in Chambal, Damodar and Gandak. However, the water availability in Yamuna will decrease in the far future (2071-2100).
- Water availability will vary from month to month depending on the physical conditions such as precipitation, evapotranspiration and surface runoff, etc. The water availability in Damodar and Gandak in both the dry and the wet seasons will increase; however, it will decrease in Chambal and Yamuna in the dry season in the future. At the district level, the water availability in most of the districts in the four sub-basins will increase.
- From the demand side in India, future water demand will increase due to population growth, industrial development and the increase in power generation and irrigation. Out of the four sub-basins, Chambal will have the smallest water demand and Yamuna will have the largest water demand. In all the four sub-basins, irrigation water demand will dominate followed by domestic water demand and this trend will continue until 2050. Damodar has the highest energy water demand followed by Gandak where the energy water demand will greatly increase due to many planned new installations.
- For the water supply-demand balance at the sub-basin level in India, Chambal and Damodar will have water surplus in the future. Chambal will have the largest water surplus among the four sub-basins. Yamuna and Gandak will face serious water deficit in the future, particularly the Yamuna sub-basin.
- At the district level, most of the districts in Chambal and Damodar will have water surplus. However, most of the districts in Gandak and Yamuna will face water deficit in the future. Particularly in Gandak, many new thermal power installations are planned, operation of which will face severe water shortage.
- Many of the existing power plants are located in water-stressed areas and many new thermal power plants are planned to be built in the areas under high or moderate water stress. Specifically, most of the existing power plants and planned power plants in Yamuna and Gandak, a few plants in the upper part of Chambal and a few plants in the middle and right part and the lower part of Damodar will face high risk of water shortage. On the other hand, most of the districts in the middle and lower part of Chambal and the districts located in the upper part of Damodar can be selected as appropriate locations for new thermal power plants.
- For Bangladesh, from the supply side, the Ganges flows will increase significantly in the future, especially during the pre-monsoon (April to May) and the monsoon months (June to September). There will be a decrease of the inflows during the post-monsoon period (October-November). Winter flows may likely increase in the future due to the increase in winter precipitation (December- February) under climate change.
- From the demand side in Bangladesh, the power sector will become the largest water consumer if power plants are to be equipped with the open-loop cooling system. However, if power plants are to be installed with the close-loop cooling system, a significant amount of water can be saved. Selection of proper cooling systems for thermal power generation has a critical influence on the total water demand and the level of water stress in the country. Relevant policy makers, investors and the energy project developers should be highly aware of the substantial impacts of the selection of the

power generation technologies and the type of the cooling systems on sustainable water use.

Potential for further work

The present study can be further developed in the following areas. First, the Ganges basin includes 19 sub-basins across the borders of Nepal, India and Bangladesh. The present study only conducted a detailed case study for four sub-basins within India and a case study for Bangladesh covering the whole sub-basins within the border of Bangladesh. An extended study covering all 19 sub-basins can be developed in the future to provide a fuller picture of the water-energy nexus in the Ganges basin. In addition, the case study in India provided a very detailed assessment at the district level for the four sub-basins which can be extended to all 19 sub-basins. The calibration and validation of the SWAT model for the assessment of water supply at the sub-basin level are very limited in the present study and should be improved further by using the monitoring data or other reference data from secondary sources. The dissemination of the present study is limited through stakeholder consultation workshops and the IGES website and could be extended through relevant outreach events and publication in relevant journals.

Publications

Mitra, B. K., Zhou, X., Sharma, D., Jhonson, B., & Herran, D. S. (2018). *Integrating spatial variability of water resources in long-term power infrastructure planning: An illustration from Ganga River Basin*. Paper presented at Nexus 2018: Water, Energy Food and Climate, 16-18 April 2018, North Carolina.

Mitra, B. K., Zhou, X., & Islam, G. M. T. (2018). *Managing water-energy nexus for sustainable power infrastructure planning in Bangladesh*. Presentation at the Workshop on Harnessing of Climate-Water-Energy Nexus for Resource Security in the Ganges River Basin, 18 November 2018, Bangladesh University of Technology, Dhaka.

Islam, G. M. T., Mitra, B. K., Zhou, X., & Hosain, M. S. (2018). *Water resource availability in Ganga basin of Bangladesh*. Presentation at the Workshop on Harnessing of Climate-Water-Energy Nexus for Resource Security in the Ganges River Basin, 18 November 2018, Bangladesh University of Technology, Dhaka.

Mitra, B. K., Zhou, X., Sharma, D., Jhonson, B., & Herran, D. S. (2018). *Impact of spatial variability of water supply and demand on sustainability of thermal power generation in four sub-basins of Ganga*. Presentation at the Workshop on Harnessing of Climate-Water-Energy Nexus for Resource Security in the Ganges River Basin, 20 November 2018, Central University of Rajasthan, India.

Sharma, D., Mitra, B. K., & Zhou, X. (2018). *Water availability in selected sub-basins of Ganga*. Presentation at the Workshop on Harnessing of Climate-Water-Energy Nexus for Resource Security in the Ganges River Basin, 20 November 2018, Central University of Rajasthan, India.

Mitra, B. K. (2018). *Tracing synergies and trade-offs across water-energy nexus: Practical benefits and challenges*. Presentation at the Symposium on Towards Sustainable Development of Semi-arid Area in India: From the View Point of Food-Water-Energy Nexus. 21 December, Aoyama Gakuin University, Tokyo.

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We sincerely thank Dr. Hiroaki Shirakawa who helped develop the Water-Energy Nexus Assessment web tool. This free on-line tool greatly enhanced the ability to present high-volume spatial data, which would otherwise be challenging to include in a written report. As a handy tool, it helps strengthen communication with the target audience.

1. Introduction

Water, energy and food are fundamental resources to support human survival, economic growth and sustainable development. Rapid urbanisation and population growth are placing increasing pressures on these resources, the shortage of any one of which could lead to social and political instability, geopolitical conflicts and human health hazards and cause irreversible environmental damages both within individual countries and beyond national borders.

Resources are intrinsically interdependent on each other for both supply and demand sides. Water is required for extracting fuels and refining and processing the raw materials which are finally transformed into different forms of energy such as natural gas, liquid fuels or electricity. On the global scale, approximately 8% of the total withdrawn water is used for energy generation (Bhattacharya and Mitra, 2013). In some developed countries it accounts for about 40% of the total withdrawn water (World Economic Forum, 2011; Huston et al., 2004). Large water demand will continue to grow particularly in the emerging countries like China, India and Brazil due to the increasing energy demands from rapid economic development. These three countries combined will account for 30% of the global total energy consumption over the next 40 years (World Energy Council, 2010). Similarly, energy is an important input to enable modern water supply and wastewater treatment. Hence, insecurity in individual sectors can become more serious when such issues are considered together. Until recently, a surge in demand for water and energy has typically been addressed through sectoral approaches, which ignore the intrinsic interactions among various resources. This needs to be addressed by taking into account the interlinkages among resources and integrating such into relevant national and regional development plans.

South Asia is one of the major regions in the world with rapid economic development and population growth, as well as with a large poverty-ridden population, high energy demand and limited availability of water and energy. As a result, resource conflicts are prominent issues in this region, which are considered threatening to the long-term growth pattern. On the one hand, South Asia is one of the driest regions in the world. On the other hand, the existing power generation is dominated by coal-based and gas-based thermal power plants, which are water intensive facilities (Mitra and Bhattacharya, 2012). The portfolio of energy mix will stress future water availability among various end users. In fact, some cases of water conflicts have already been reported in South Asia (The Times of India, 2011; UNEP Finance Initiative, 2010; NDTV, 2013). This situation has the potential to degrade even further if the impacts from long-term climate change are taken into account.

There are few systematic analyses which address these issues from the perspective of the interactions between energy security and water availability that will be impacted from climate change in South Asia. The study conducted by Mitra and Bhattacharya (2012) is one of the few quantitative studies of the water-energy nexus in this region. Their estimates show that the water demand from Indian power plants will grow to 225 billion cubic meters by 2050 if the power plants are equipped with open-loop cooling systems. This indicates that water availability could threaten the reliability of existing operations as well as the physical, economic and environmental viability of future projects. Given the location-specific nature of water resources, understanding the water and energy relationship at the river basin and sub-basin levels, or even at particular sites, is crucial for ensuring future energy security in the region, particularly for transboundary river catchment.

The Dublin Conference on Water and Environment in 1992 and the United Nations Conference on Environment and Development pointed out that resource management should be considered throughout the river basin to avoid negative social, economic and environmental impacts, which is particularly important for transboundary river basins.

The Ganges basin is a strategic river basin in South Asia. It has the second largest catchment area and is the most populated area in the world. It is home to more than 500 million people, which will increase to 1 billion by 2050. More than 30% of the water resources in the region are provided by this basin. **Figure 1** shows the location of the Ganges River with its 19 sub-basins. The basin connects three South Asian countries: Nepal, India and Bangladesh. Population growth together with rapid economic development will place great pressure on water resources. The Ganges basin is defined as a water-stressed area, the issue of which could degrade further in the near future. In addition, water-intensive economic activities such agriculture and power generation are expected to increase.

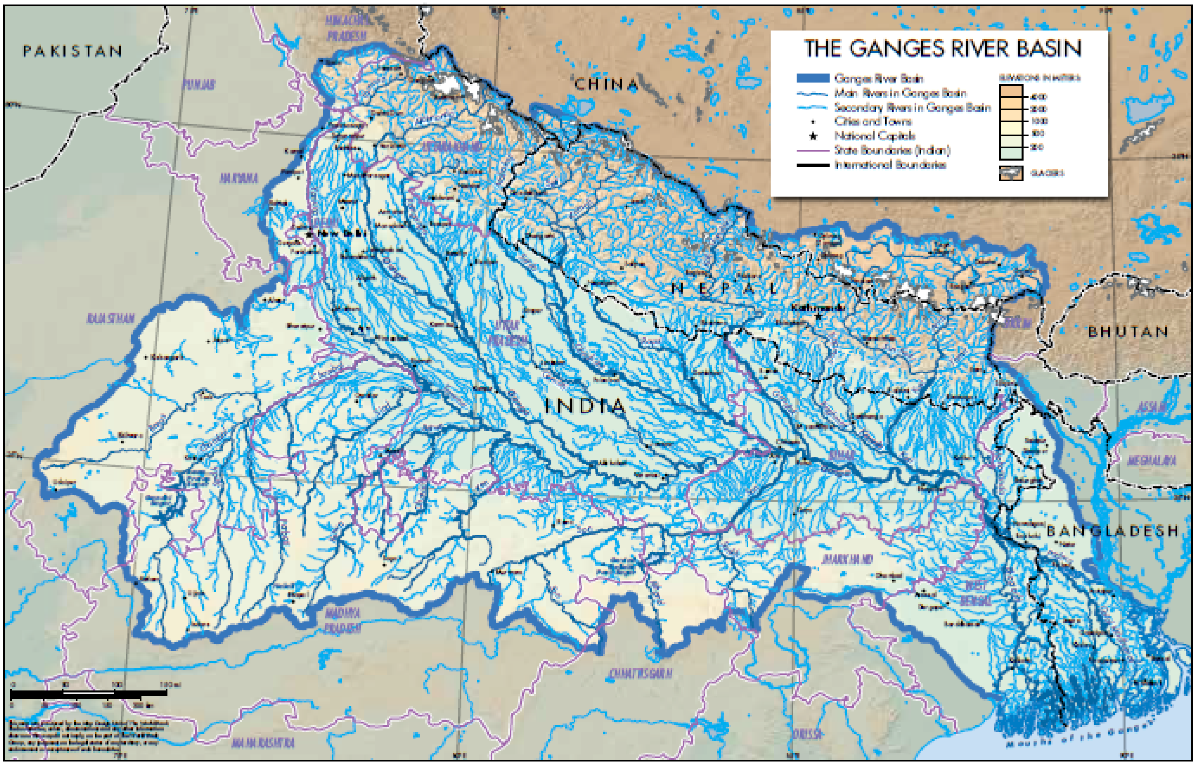


Figure 1 Map of the Ganges basin (World Bank 2014)

The Ganges basin supplies water to thermal power plants with a capacity of more than 50 GW, accounting for over 40% of the total capacity in the region. Massive upstream hydropower developments impact downstream water supply and cause water scarcity in some parts of India and Bangladesh, particularly in the dry season. Thermal power is the major type, covering 73% of the total installed capacity, followed by hydro power. Out of the total installed capacity of thermal power plants, 92% uses coal. Therefore, the Ganges basin is a strategic area in South Asia. Its sustainable use is of great importance for regional development.

This project, funded by the Asia Pacific Network for Global Change Research (APN), is entitled “Assessment of Climate-induced Long-term Water Availability in the Ganges Basin and

Impacts on Energy Security in South Asia”. The objective is to inform decision makers and investors on the water supply and demand balance/deficit under the long-term impacts from climate change up to 2050 and water stress for future energy supply. This will enable effective energy planning and water management and help reduce the risk of investment in water-constrained areas.

The outputs of the project include:

(i) An integrated assessment of water-energy nexus at the sub-basin level, including water supply assessment, water demand assessment and water stress assessment for future thermal power generation;
(ii) A free on-line tool providing spatial visualisation of water supply, water demand, water supply and demand balance/deficit, and water availability for existing and planned thermal power plants at the district level for India (accessible at IGES website *https://www.iges.or.jp/en/index.html*);
(iii) Stakeholder consultation workshops through which the objective, methodology, results and key messages were conveyed to relevant stakeholders in the three countries.

Case studies were conducted in three riparian countries of the Ganges basin, namely Nepal, India and Bangladesh at different levels of detail and using different methodologies particularly to assess future water demand. The case study for India is the most detailed, which provides a full assessment that includes three components, i.e., water supply assessment based on the Soil and Water Assessment Tool (SWAT), water demand assessment for agriculture, livestock, households and industry based on various methodologies, and water stress assessment for future thermal power plants at the district level for four selected sub-basins – Chambal, Damodar, Gandak and Yamuna.

The case study for Bangladesh was conducted at the single sub-basin level, including water supply assessment based on SWAT, water demand assessment mainly based on literature review at the sub-basin level and water stress assessment for overall thermal power generation in the sub-basin.

The case study for Nepal is the least detailed and is mainly based on a literature review. The energy supply in Nepal is mainly based on hydro, which is not relevant for the assessment of water stress for thermal power plants. The major purpose of including the Nepal case study is to enable discussions on cross-border cooperation in the context of water-energy nexus among the three countries. On the one hand, abundant water resource in Nepal provides potential opportunities to invest in hydro power expansion, which enables cross-border electricity transmission to India and Bangladesh to help address the big gaps in energy supply and demand in these two countries. On the other hand, large-scale hydro power development in Nepal as an upstream country may impact downstream water supply in India and Bangladesh, in particular in the dry season, which may worsen the situation of water shortage for existing and future power plants. The synergies and trade-offs between the upstream and downstream countries in the context of water-energy nexus is very relevant for this project. Due to the differences in the three case studies, we include the two case studies of India and Bangladesh in the main body of this report and Nepal’s case study in Appendix 1.

Section 2 provides the overall analytical framework of this project, including the water supply module, the water demand module, the energy module and water-energy nexus assessment for thermal power generation, as well as power plant surveys, stakeholder consultations and the web tool developed for the spatial visualisation of the research results. Section 3 presents the results of the two case studies in India and Bangladesh with discussions. For each case study, specific methodologies for water supply assessment and water demand assessment are provided, followed by associated results. Section 4 summaries the conclusions and policy implications and Section 5 discusses the future direction of this research.

2. Methodology

2.1 An integrated assessment approach

Various approaches were used to implement this project. First of all, we developed an integrated approach which combines various modelling techniques to assess the water-energy nexus from the perspective of energy supply security under the long-term impacts from climate change.

Second, one of the key parameters for future water demand projection is water use intensity of thermal power generation based on different technologies, including fuels (coal, gas and oil) and the cooling systems (close-loop, open-loop and dry cooling systems). Due to limited available literature in this area particularly for South Asia and the importance of this parameter, we conducted field surveys of about 15 power plants located in different places in India and Bangladesh, respectively, and used various technologies as well as questionnaire surveys through our local collaborators to obtain first-hand data.

Third, to achieve the objective of this project, which is to inform the decision makers and investors on the spatial distribution of water stress particularly from the long-term energy supply security perspective, we conducted stakeholder consultation meetings in the three countries to communicate with relevant stakeholders on the research purpose and methodologies and collected feedbacks on their concerns and needs at the kick-off meetings, and conveyed the research results and key messages at the final workshops (see Appendices 2 - 7).

Finally, to enable policy makers and investors to explore the data, relevant assessments and results, we developed a free on-line tool for spatial visualisation of water supply, water demand, water supply-demand stress and water availability for future thermal power generation for India at the district level for four sub-basins, Chambal, Damodar, Gandak and Yamuna.

2.2 Analytical framework

We developed an integrated approach which links various modelling techniques, including hydrological modelling based on SWAT, water demand assessment for major water consumers (agriculture, domestic sector and industry) based on various techniques, and energy technology scenario analysis for existing and future thermal power generation. The analytical framework (see **Figure 2**) includes a Water Supply Module, Water Demand Module, Water Supply-Demand Assessment, Energy Module and Water-Enter Nexus Assessment.

Under the Water Supply Module, based on the results from the General Circulation Models (GCM) (IPCC, 2007), i.e., future climate change under the Intergovernmental Panel on Climate

Change (IPCC) Representative Concentration Pathways (RCP) 4.5 and RCP 8.5 for the time period of 2020-2050 for the Ganges sub-basins, future water supply (in billion cubic meters, BCM) is projected using a hydrological model, SWAT.

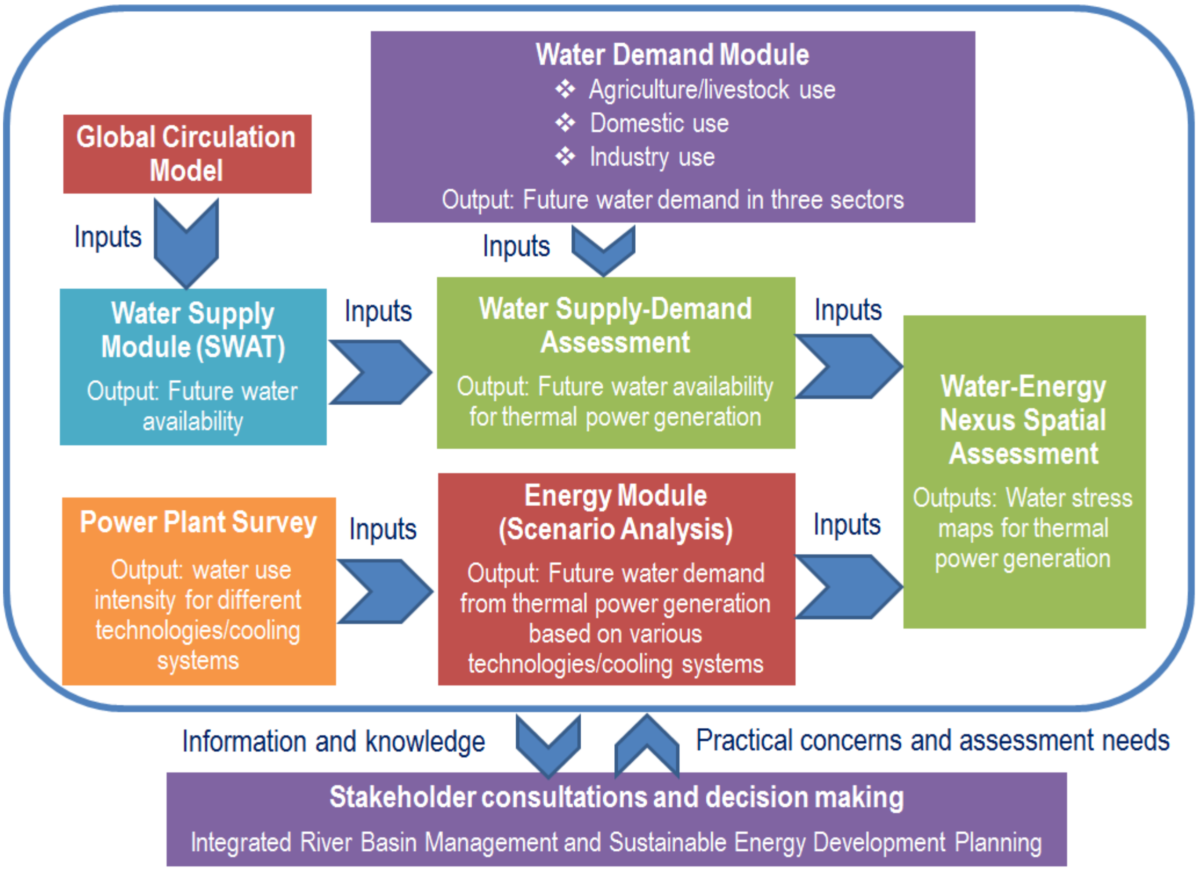


Figure 2 Overall analytical framework

Under the Water Demand Module, future water demand of three major sectors – agriculture/livestock, domestic sector and industry (manufacturing, commercial and services) – is estimated for the Ganges sub-basins based on various methodologies taking into account population growth, income levels, economy development and activity expansion, etc., up to 2050. Since the methodologies used for water demand projection for India and Bangladesh are different, detailed methodologies used for the projections of the three sectors are introduced in Sections 3.1 and 3.2, respectively. Adding up the water demand from the three major sectors is the total water demand excluding the water demand from thermal power generation which is estimated in the Energy Module.

Based on the outputs from the Water Supply Module, i.e., future water availability under climate scenarios RCP 4.5 and RCP 8.5, and the outputs from the Water Demand Module, i.e., water demand from the three sectors, water supply and demand balance at the sub-basin level or at the district level can be assessed by subtracting the future water demand of the three sectors and the environmental water use (estimated as 1.23% of total water demand) from future water supply. Any surplus in water supply can be considered for future thermal power generation. Further water stress assessment for future thermal power generation is conducted under the spatial Water-Energy Nexus Assessment. A deficit in water supply implies there will be no water available for the proper operation of existing power plants nor for new capacity installations.

Under the Energy Module, water demand from future thermal power generation (including both existing installations and planned new installations) is estimated. Information on i) the location of existing installations and planned new installations; ii) the types of technologies used for each installation (both existing and planned), including different power generation technologies (coal-fired, gas-fired, oil-fired, hydro and other renewables) and the cooling systems (open-loop, close-loop and dry cooling, etc.), and iii) total annual electricity generation of each installation is collected. To obtain first-hand data on the water intensity (in m^3/MWh) of different technologies (combination of power generation technologies and cooling systems), power plant field surveys and questionnaire surveys were conducted. Based on the type of technology used, the water intensity of the particular type of technology and the total annual electricity generation as well as future water demand from each installation is estimated. Total water demand from thermal power generation at the sub-basin or district level is obtained by summing up individual demands in the respective locations.

Based on the outputs from the Water Supply-Demand Assessment, i.e., water surplus/deficit for existing and new planned thermal power generation at the sub-basin or district levels, and the outputs from the Energy Module, i.e., total water demand from thermal power generation at the same sub-basin or district levels, water stress for future thermal power generation for each location (sub-basin or districts) can be assessed. For locations in which water supply is in deficit after balancing the water supply and water demand from three sectors, the operation of existing and planned thermal power installations in the locations will be constrained by water availability. Furthermore, for the locations with water supply surplus but not enough to satisfy the water demand from existing or planed thermal power generation within the locations, the operation of these installations will also be threatened by water constraints. The results of the water stress assessment for each location are provided in maps and can be visualised through the on-line spatial analysis tool. For those areas under water stress, alternative power generation technologies or alternative cooling methods that can sustain thermal power generation under water constraints are provided.

3. Results & Discussion

3.1 Case study in India

The catchment area of the Ganges lies between longitudes 73°30’ to 89°0’ E and latitudes 22°30’ to 31°30’ N connecting three South Asian countries, i.e. India, Bangladesh and Nepal. The Ganges catchment area is approximately 1,087,300 km^2, which covers 52% of the area of South Asia and 30% of the area of India (World Bank, 2014). The Ganges is very important to the riparian countries, particularly India, which occupies 76% of the total catchment area.

The Ganges is defined as a water-stressed river basin and the problem is expected to become more critical in the near future with the expected increase in water-intensive economic activities such as agriculture and power generation. Rapidly growing urbanisation is also a big concern for the Indian areas located in this river basin. In India, more than 600 million people live in this basin and 50 major cities are located in this region (World Bank, 2015).

Water of this basin is used for various purposes including irrigation, domestic use, industrial use and hydropower generation. Among the users, agriculture alone accounts about 90% of total water use (Sinha, 2014). According to the Ministry of Water Resources of India, the average water resource potential of the Ganges is 525,020 Million Cubic Metres (MCM), of which only 250,000 MCM is utilisable water. Of the utilisable water, 56,451 MCM is already sanctioned for various hydropower projects in the basin and the rest of the utilisable water 193,549 MCM is for other users. A significant amount of the water is being diverted for various industrial purposes. Approximately 50,000 MW of thermal power capacity is installed in the Ganges basin that is located in Indian territories, which extract millions of cubic meters of water from the surface water system (Sinha, 2014).

Power generation, 73% of which is provided by thermal power generation technologies, demands huge amounts of water from this basin. **Table 1** shows the installed capacity of different power utilities located in the Ganges basin (as of 31 March 2015). Geographically, Uttar Pradesh has the largest installed capacity, followed by Rajasthan and West Bengal.

Table 1 Installed capacity of power utilities in Indian states located in the Ganges basin (in MW)

	Thermal			**Nuclear**	**Hydro**	**Renewables**	**Total**
	Coal	**Gas**	**Sub-total**				
Bihar	2,516	-	2,516	-	129	114	2,760
Jharkhand	2,405	-	2,405	-	201	20	2,626
West Bengal	8,084	100	8,184	-	1,248	132	9,564
DVC	7,161	90	7,251	-	193	-	7,444
Delhi	5,002	2,366	7,368	122	822	21	8,333
Haryana	6,528	560	7,088	109	1,457	137	8,790
Himachal Pradesh	152	62	214	34	3,422	724	4,393
Rajasthan	9,401	825	10,226	573	1,719	4,386	16,904
Uttar Pradesh	11,678	550	12,228	336	2,168	990	15,722
Uttarakhand	400	69	469	22	2,442	244	3,177
Total	**53,325**	**4,623**	**57,948**	**1,196**	**13,802**	**6,768**	**79,714**

Source: Central Electricity Authority, 2015.

According to Gosain et al. (2011), the impacts of climate change and climate variability on water resources are likely to affect irrigated agriculture, installed power generation, environmental flows in the dry season and higher flows during the wet season, thereby causing severe droughts and floods in urban and rural areas. The increasing pressures induced by climate change on water resources will threaten the livelihoods of 85% of the population of this basin that relies on agriculture and will also negatively affect the basin's sustainable development.

The case study for India provides a detailed assessment that includes three components, i.e., water-energy nexus including water supply assessment based on SWAT, water demand assessment for agriculture, livestock, households and industry based on various methodologies, and water stress assessment for future thermal power plants. The assessment of the water-energy nexus was conducted at the district level for four selected sub-basins, Chambal, Damodar, Gandak and Yamuna.

3.1.1 Selection of the sub-basins

It has been realisvved that water availability may challenge the reliability of the operation of existing power plants as well as the physical, economic and environmental viability of future power plant projects. Considering the location-specific nature of water resources and climatic scenarios, it is necessary to quantify the linkages between water and energy at an appropriate hydrologic level, such as the river basin or sub-basin level.

Due to differences in the locations, which are closely related to the natural endowment such as local climate, terrain, soil type, etc., as well as differences in the demographics and social and economic development, the selection of the sub-basins within the Ganges basin is important in order to assess the water availability and water demand situation in detail. The Ganges basin is divided into 19 sub-basins, as shown in **Figure 1**. As an outcome of the project kick-off workshop held in Jawaharlal Nehru University, New Delhi, 20 April 2015, it was decided that considerations from both the supply side and the demand side of water resources should be taken into account (see **Figure** 3). The following criteria are used for the selection of the sub-basins in this project.

i) Water supply side: Water is used for various processes of power generation such as cooling, ash disposal and other domestic uses. Water availability is directly linked with the stability of power generation. For water supply, two variables are considered for the selection of the sub-basins, i.e., precipitation and water yield.

ii) Water demand side: Except for power generation, which consumes substantial quantities of water, there are three other major water use sectors – agriculture (irrigation and livestock), domestic sector and industrial sector. Agriculture is the largest water consumer, particularly for irrigation. Therefore, irrigation water requirement is used as an indicator for the selection of the sub-basins. This is directly linked with the land area for agriculture and crop patterns. For domestic use, water requirement is proportional to the size of the population and per capita water consumption. Industrial water depends on the number of industrial units as well as types of industries and their water requirement.

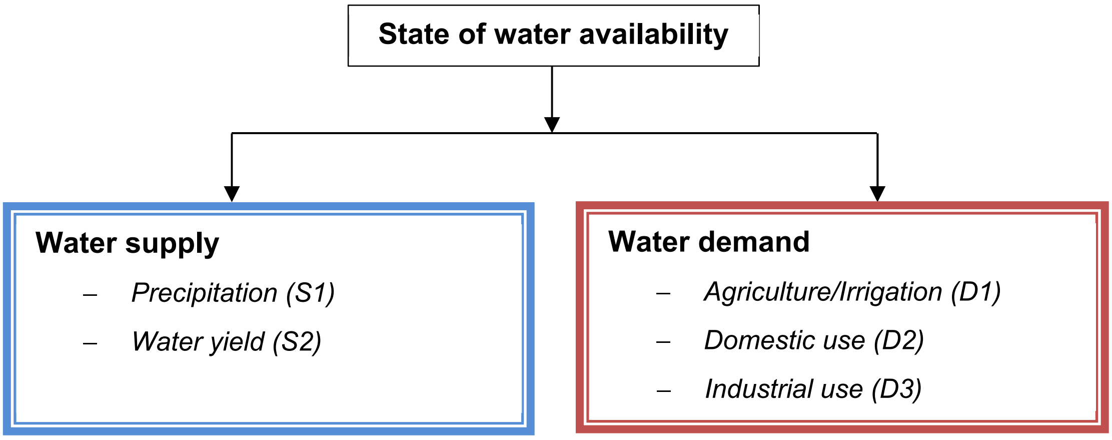


Figure 3 Criteria for the selection of the sub-basins

The following steps are used for the selection of the sub-basins:

(i) Preparation of the precipitation map and the water yield map (see **Figure 4** and **Figure 5**) based on the water system modelling report for the Ganges basin (INRM consultant, undated). Nineteen sub-basins are categorised into five levels based on the amount of precipitation and the amount of water yield, respectively. Level 1 indicates the highest supply, i.e., the highest precipitation or the highest water yield, while Level 5 indicates the lowest supply, i.e., the lowest precipitation or the lowest water yield.

(ii) Preparation of the demand side-related maps for population density, irrigation water demand and number of industries in each of the sub-basins based on the five-level classification. For each sub-basin, Level 1 links with the highest demand and Level 5 links with the lowest demand (see **Figure 6**, **Figure 7** and **Figure 8**). Population density and the irrigation demand maps are taken from the water system modelling report for the Ganges basin (INRM consultant, undated). The map for the industrial sector is prepared using the secondary data collected from various reports and the data from the Ministry of Micro Small and Medium Enterprises.

(iii) Preparation of the composite supply map based on the average level of precipitation and water yield for each sub-basin based on the results from Step (i) and the composite demand map based on the average level of population density, irrigation water demand and number of industries for each sub-basin based on the results from Step (ii) (see **Figure 9**). For details, please see also **Table 2**.

(iv) Preparation of the demand/supply ratio map based on the results from Step (iii) (see **Figure 10**). For details, please see **Table 2**.

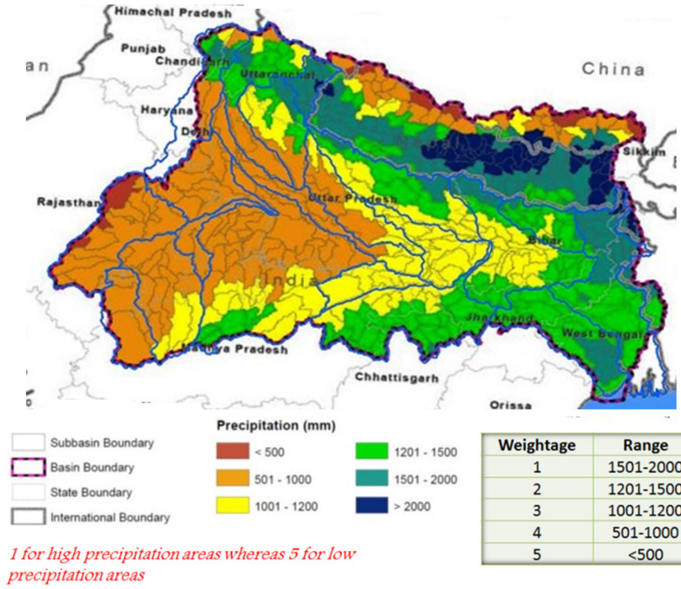
(v) Based on the demand/supply ratios and taking into account the location of the existing thermal power plants in the sub-basins (see **Figure 10**), four sub-basins are selected (see **Figure 11**) including:

a) Chambal sub-basin: Categorised as the area with low water supply, low water demand and a few existing thermal power plants;

b) Yamuna sub-basin: Categorised as the area with low water supply but high water demand;

c) Gandak sub-basin: Categorised as the area with high water supply but low water demand which can be considered for future power plant development;

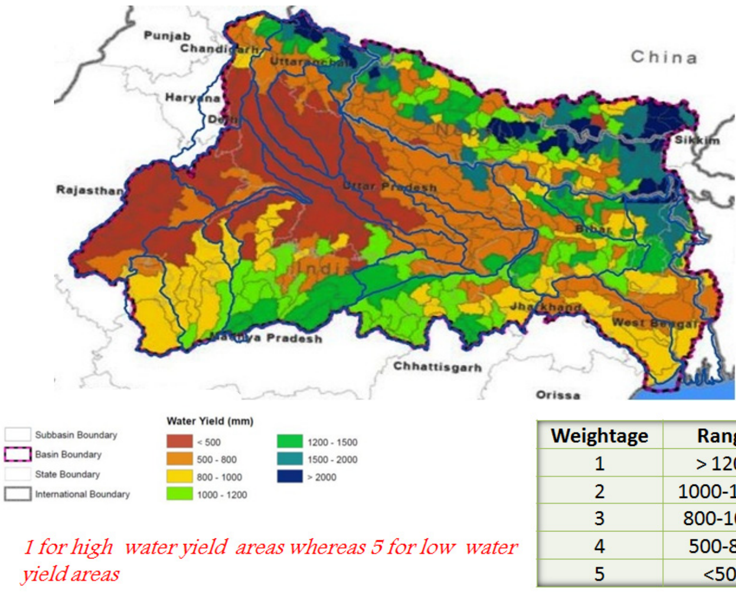
d) Damodar sub-basin: Categorised as the area with moderate water supply and moderate water demand but with many existing thermal power plants.



Weightage	Range
1	1501-2000
2	1201-1500
3	1001-1200
4	501-1000
5	<500

Figure 4 Precipitation distribution in the Ganges Basin

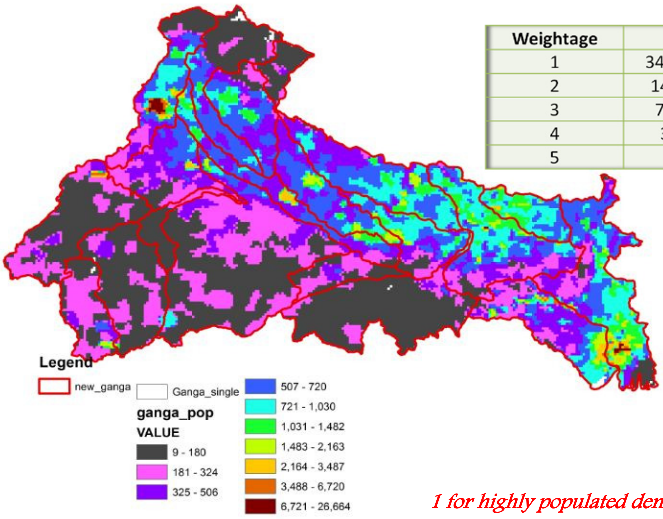
Note: Modified from the water system modelling for the Ganges basin (report prepared by the INRM consultant, undated).



Weightage	Range
1	> 1200
2	1000-1200
3	800-1000
4	500-800
5	<500

Figure 5 Water yield distribution in the Ganges basin

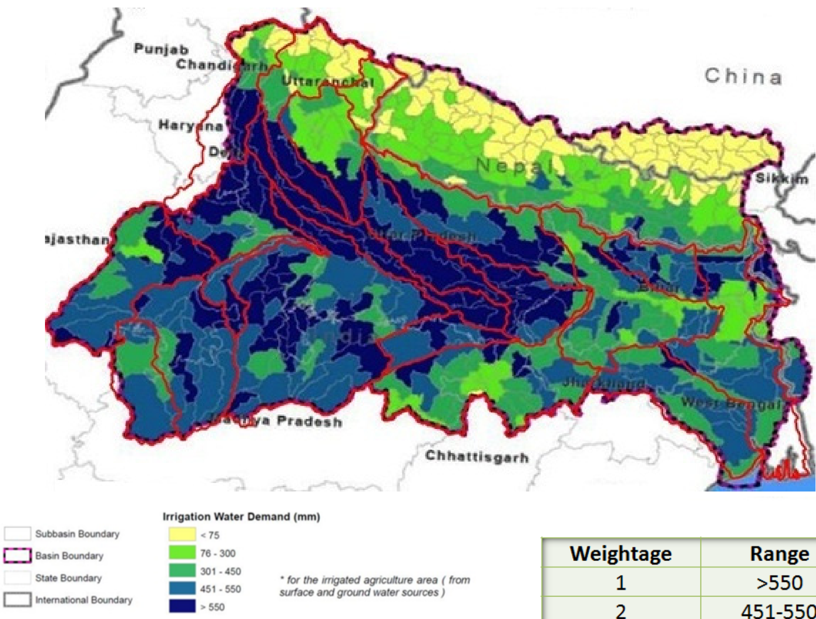
Note: Modified from the water system modelling for the Ganges basin (report prepared by the INRM consultant, undated).



Weightage	Range
1	3488-26664
2	1448-3487
3	721-1482
4	325-720
5	9-180

1 for highly populated density area whereas 5 for low population density area

Figure 6 Population density in the Ganges Basin



1 for high irrigation demand area whereas 5 for low irrigation demand area

Weightage	Range
1	>550
2	451-550
3	301-450
4	76-300
5	<75

Figure 7 Irrigation water demand in the Ganges basin

Note: Modified from the water system modelling for the Ganges basin (report prepared by the INRM consultant, undated).

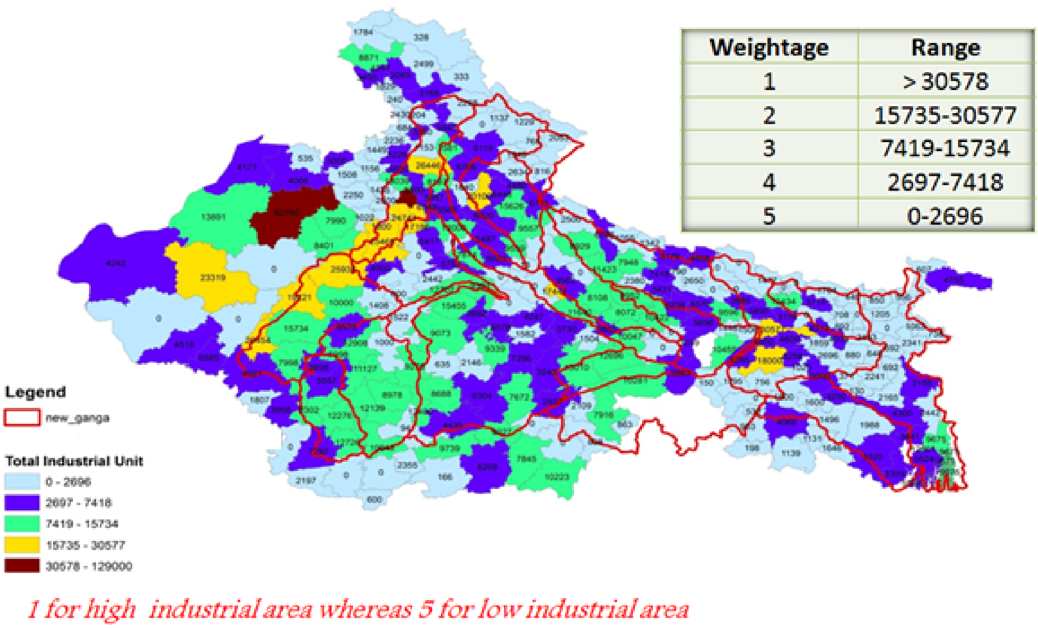


Figure 8 Number of industries in the Ganges basin

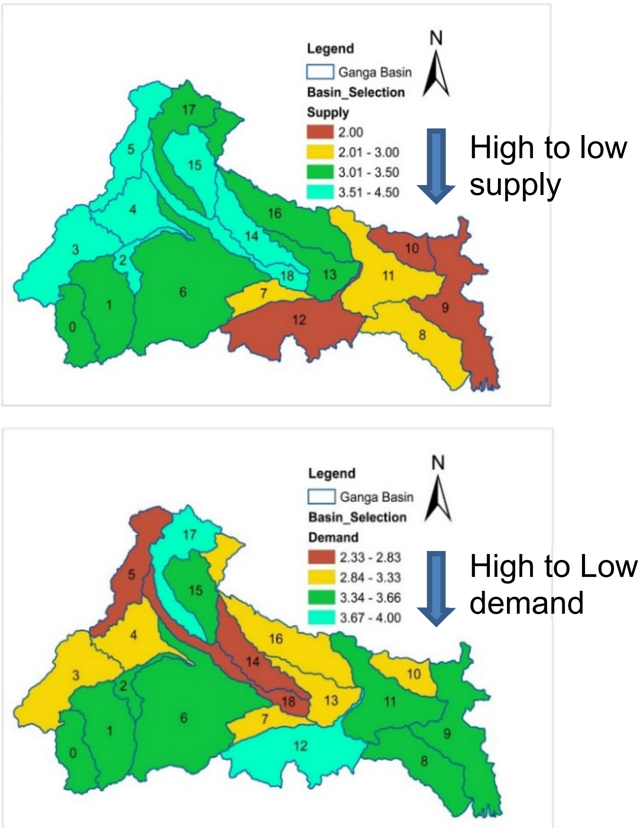


Figure 9 Demand and supply patterns in the Ganges basin

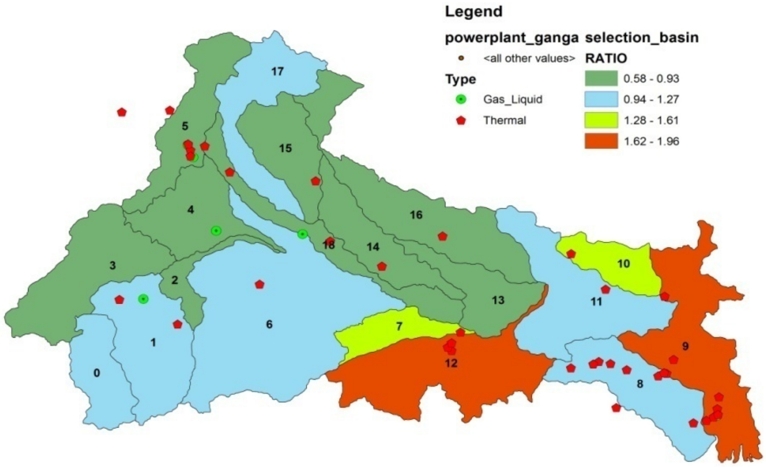


Figure 10 Demand-supply ratio in the Ganges basin

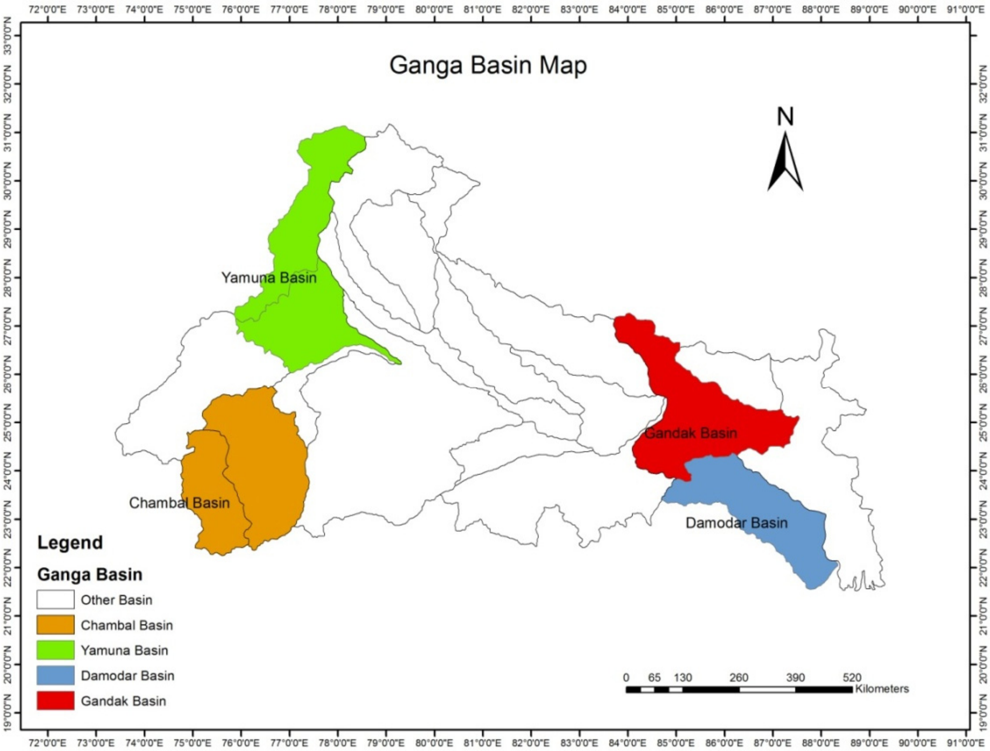


Figure 11 Four sub-basins selected for this project

Table 2 Supply and demand-side indicators for the selection of the sub-basins

ID	Sub-basin	Supply			Demand				Demand /Supply ratio
		PRECP	WYLD	Supply Average	Industry	Population	Irrigation	Demand Average	
0	Chambal Upper	4.0	3.0	3.5	3.5	5.0	2.5	3.7	1.05
1	Kali Sindh	4.0	3.0	3.5	3.3	5.0	2.0	3.4	0.98
2	Chambal Lower	4.0	4.0	4.0	3.8	5.0	2.0	3.6	0.90
3	Banas	4.0	5.0	4.5	2.5	5.0	2.0	3.2	0.70
4	Yamuna Middle	4.0	5.0	4.5	4.0	4.5	1.5	3.3	0.74
5	Yamuna Upper	4.0	4.0	4.0	3.0	3.0	1.0	2.3	0.58
6	Yamuna Lower	4.0	3.0	3.5	4.0	4.5	2.0	3.5	1.00
7	Tons	3.0	2.0	2.5	3.3	4.8	2.0	3.3	1.33
8	Damodar	2.0	4.0	3.0	4.5	3.5	2.5	3.5	1.17
9	Bhagirathi and others (Ganga Lower)	2.0	2.0	2.0	4.5	3.0	3.0	3.5	1.75
10	Kosi	2.0	2.0	2.0	4.5	3.0	2.0	3.2	1.58
11	Gandak and others	3.0	3.0	3.0	4.0	3.5	3.5	3.7	1.22
12	Sone	2.0	2.0	2.0	4.0	4.8	3.0	3.9	1.96
13	Ghaghara Confluence to Gomti confluence	3.0	4.0	3.5	3.5	4.3	1.5	3.1	0.88
14	Gomti	4.0	5.0	4.5	4.0	3.5	1.0	2.8	0.63
15	Ramganga	3.0	5.0	4.0	3.5	4.0	3.0	3.5	0.88
16	Ghaghara	3.0	4.0	3.5	4.0	3.5	2.0	3.2	0.90
17	Ramganga Confluence	3.0	4.0	3.5	4.5	4.5	3.0	4.0	1.14
18	Upstream of Gomti confluence to Muzaffarnagar	4.0	5.0	4.5	4.0	3.5	1.0	2.8	0.63

Note: The supply average is the mean of the values of precipitation (PRECP) and water yield (WYLD). The demand average is mean of the values of three major demand sectors, i.e., industrial sector, domestic sector and agriculture/irrigation, represented by the indicators of number of industries, population density and irrigation water demand. The demand-supply ratio is calculated by dividing the demand average by the supply average.

Chambal sub-basin

The Chambal sub-basin is located between latitudes 22°27' N and 27°20' N and longitudes 73°20' E and 79°20' E. The area lies within the semi-arid zone of north-western India overlapping the borders of Madhya Pradesh (MP) State, Rajasthan State and Uttar Pradesh (UP) State covering 24 districts (Department of Water Resources, Rajasthan, undated). Banas and Mahi Basins lie to the west and Gambhir and Parbati Basins lie to the north. On its south, east and west, the Chambal sub-basin is bounded by the Vindhyan mountain ranges and on the north-west by the Aravallis.

There are four distinct seasons in the Chambal sub-basin. Annual precipitation ranges from 356 mm to 1,270 mm and the mean annual rainfall is about 797 mm. Out of the rainfall, 93% comes during the four monsoon months (from June to September). The mean average temperature in different months is: January, 15 - 20 °C; April, 27.5 - 32.5 °C; July, 27.5 - 32.5 °C and October, 25 - 27.5 °C. The average annual potential evaporation is 1,763 mm.

Forests occupy only 8.8% of the geographical area of the Chambal sub-basin, while arable land area constitutes 75%. Out of the total arable land area of 10.14 million hectares, nearly 71.4% is cultivated annually (Department of Agriculture). Agriculture depends solely on rainfall and normal practices are used to raise Kharif crops like bajra, jowar and maize during the monsoon months and wheat, barley and other Rabi crops during the Rabi season, making use of the moisture in the soil and winter rainfall. Wheat and barley are grown on 25% of the total cultivated area annually.

Damodar sub-basin

The Damodar basin lies between latitudes 22°15’ N and 24°30’ N and longitudes 84°30’ E and 88°15’ E and spreading over an area of about 23,370 km^2 in Jharkhand and West Bengal states. The basin is bounded by the Santhal Paragana district in the north, Hazaribag and Palamau districts in the west, Ranchi, Purulia and Bankura districts in the south and Hooghly and Howrah districts in the east and southeast. It covers six districts of Jharkhand and five districts of West Bengal. The three-fourths of the basin representing the upper catchment belong to Jharkhand State while the low-lying flood plains lie in West Bengal State (Jana & Majumder, 2010).

The Damodar sub-basin is located in the warm sub-tropical zone and its climate is influenced by the Bay of Bengal monsoon. Rainfall is irregular and about 85% of total annual rainfall occurs in the rainy season (from June to September) and the remaining 15% occurs in the winter season (from October to December). Annual rainfall varies from 765 mm to 1,607 mm with an average of 1,200 mm. Evaporation is maximum during summer with 21 mm and minimum in winter in monsoon with 2.5 mm with 70% humidity. In summer, the average high temperature is 43 °C and the low temperature is 30 °C. In winter, the average high temperature is around 25 °C and low temperature is 10 °C.

The River Damodar originates in the hills of the south-east corner of the Palamu district of Bihar at an elevation of 600 m and outfall in River Bhagirathi in West Bengal near Calcutta. The right bank tributaries of River Damodar are Sapahi, Bhera, Isri and Gowai, while the left bank tributaries are Bokaro, Konar, Jamunia and Barakar. The major Dams of the Damodar basin are Tilaiya, Konar, Maithon Panchet Dams and Durgapur Barrage. Flood reserve capacity is 1,292 MCM (NIH, 1998-99).

There are six thermal and three hydro power plants in the Damodar sub-basin, with a total capacity of 5,857 MW, of which 5,710 MW is from thermal power capacity and 147.2 MW from hydro power capacity.

Gandak sub-basin

The Gandak sub-basin is bounded in the north by the Himalayas, in the south by the River Ganges, in the east by the Burhi Gandak basin and in the west by the Ghagra basin. River Gandak, known as Kalie or Krishna Gandaki in the upper reaches, rises in the glacial area of southern Tibet at altitude of 7,620 m near the Tibet Nepal border to the south-east of Dhaulagiri at latitudes 29°18” N and longitude 83°85” E. After receiving a number of tributaries including

Mayangadi, Bari and Trisuli, Gandak debouches into the plains of West Champaran district of Bihar at Triveni (Valmikinagar). At this point two more tributaries, Panchand and Sarhad, join the river. Thereafter, the river flows in a southerly direction and forms the boundary between Uttar Pradesh and Bihar for about 45 km. It then flows through Bihar and finally joins the River Ganges opposite Patna (India-WRIS, undated).

The catchment area of River Gandak is trapezoidal in shape up to Triveni. Out of its total catchment area of 45,731 km^2, 5,687 km^2 is in Tibet, 30,882 km^2 in Nepal, 1,874 km^2 in UP, and 7,288 km^2 in Bihar. It runs a course of 380 km in Tibet and Nepal and about 250 km in India.

Yamuna sub-basin

The catchment of the upper Yamuna above Tajeawla extends over 82 km in the north-south direction and 98 km in the east-west direction. Geographically, the area lies between latitudes 30°31' N and 31°30' N and longitudes 77°0' E and 78°30' E. It covers the Dehradun, Tehri and Uttar Kashi districts in Uttarakhand and the Nahan (Sirmour) and Shimala districts in Himachal Pradesh (HP) and to a small extent in the Ambala district of Haryana. The catchment presents a great diversity of climate conditions mainly because of different elevations. The mountain ranges influence the climate through their indirect orographic effects such as rain shadow of individual mountain ranges.

The broad land use patterns in the upper Yamuna catchment shows that non-agriculture lands constitute over 86% of the total area with more than half of it covered by forest and the rest by pastures and hilly areas, etc.

3.1.2 Water availability assessment for the sub-basins

3.1.2.1 Hydrological Model

The hydrological model, SWAT, was used for assessing the water availability at the sub-basin level. SWAT is a physically-based, semi-distributed and basin-scaled hydrological model that runs on a daily time basis. SWAT was developed to predict the impacts of land management practices and can simulate the climate change impacts on watersheds. In SWAT, basins are divided into multiple sub-watersheds, which are further divided into hydrologic response units (HRUs) characterised by homogeneous land use, slope and soil type. The overall hydrological balance is simulated for each HRU including precipitation, potential evapotranspiration, evapotranspiration, soil water, lateral sub-surface flow, and water yield (Arnold et al., 1998; Srinivasan et al., 1998).

The hydrological cycle is simulated by the SWAT model based on the water balance equation:

$$SW_t = SW_0 + \Sigma_i (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})$$

where: SW_t - final soil water content after t days (in mm); SW_0 - initial soil water content (in mm); R_{day} - amount of precipitation on day i (in mm); Q_{surf} - amount of surface runoff on day i (in mm); E_a - amount of evapotranspiration on day i (in mm); W_{seep} - amount of percolation and bypass flow exiting the soil profile bottom on day *i* (in mm); Q_{gw} - amount of return flow on day *i* (in mm); *t* - time (days).

SWAT is used to predict future water availability in the selected four sub-basins. **Figure 12** presents the methodology for assessing the impacts of future climate change on water availability. A bias-correction technique (delta change method) is applied to the precipitation and temperature projections of the GCMs to correct existing bias, improve the quality of the datasets and reduce the uncertainty in the future projection of water availability. The bias-corrected projections are used to run the hydrological model for the assessment of the climate change impacts on water availability based on the future climate change scenarios.

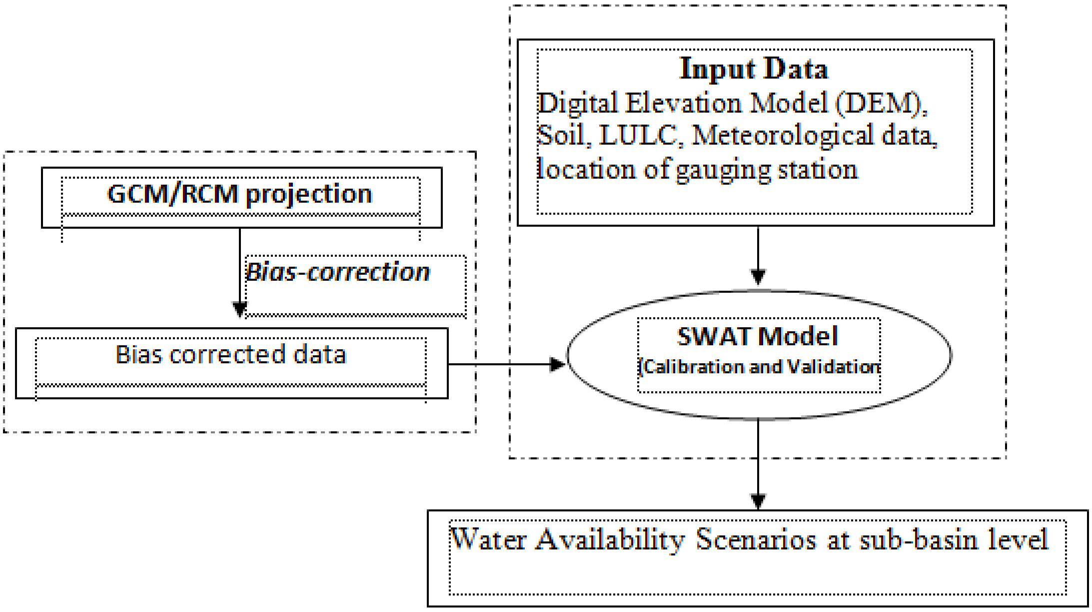


Figure 12 Hydrological model for the selected sub-basins

Note: GCM - General Circulation Model; RCM- Regional Circulation Model; LULC- Land use and land cover

Required data including Digital Elevation Model (DEM), soil map, land use and land cover (LULC) data, meteorological data and climate model projections on temperature and precipitation is shown in **Table 3**.

Table 3 Data used for the SWAT model

Data Required	Data source
Digital Elevation Model (DEM)	SRTM 90 X 90 m resolution
Land use and land cover	National Remote Sensing Centre (NRSC) 100 m X 100 m resolution
Soil	Food and Agriculture Organization (FAO) gridded raster data 6500 m X 6500 m
Weather data	Precipitation of 0.5 degree (IMD) Temperature of 1 degree (IMD) Relative humidity, solar radiation, wind grid weather data http://globalweather.tamu.edu/
Future climate from GCM	MRI-CGCM3 model http://pcmdi9.llnl.gov/

MRI-CGCM3 is a general circulation model, an updated version of the MRI-CGCM2 series developed by the Meteorological Research Institute (MRI). MRI-CGCM3 is composed of atmosphere-land, aerosol, and ocean-ice models, and is a subset of the MRI's earth system model MRI-ESM1 (Yukimoto et al. 2012). The atmospheric component of the MRI-AGCM3 is interactively coupled with an aerosol model to represent direct and indirect effects of aerosols with a new cloud microphysics scheme. MRI-CGCM3 is used for conducting basic experiments for pre-industrial control. The spatial resolution of this climate model is 1.12148° x 1.125°. Two climate scenarios of RCP 4.5 and RCP 8.5 of this model (see **Table 4**) are used for the assessment of the climate change impacts on water resources in this study.

Table 4 Climate change scenarios RCP 4.5 and RCP 8.5

Climate change scenarios	Description
RCP 4.5	Stabilisation without overshooting pathway leading to 4.5 W/m^2 and stabilisation after 2100
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100

Generation of the future datasets for the four sub-basins are considered for five decadal periods (2011-2020, 2021-2030, 2031-2040 and 2041-2050) and the historical period of 1976-2005.

One of the major limitations of the existing method for water availability assessment is that the SWAT model is not calibrated due to the lack of discharge data for the sub-basins. However, the model does not require much calibration according to Gosain et al. (2005) and Mishra et al. (2017). Another limitation is that future water availability of the sub-basins is simulated based on a single GCM model, i.e., MRI-CGCM3.

3.1.2.2 Methods of downscaling water availability assessment to the district level

In this project, water availability is defined as the volume of water available for use in a specific area, which can be obtained by multiplying the water yield by the area of the spatial unit. Water yield (in mm) projection from the SWAT model is provided at the HRU and sub-basin levels. On the other hand, water demand of major sectors can be projected at the district level based on the statistical data available at various administrative levels. To conduct the assessment with better spatial resolution, for the case study in India, we selected the district level as the basic spatial unit for both the supply side and the demand side assessment. To provide water supply assessment at the district level, the results on the water availability from the SWAT model at the HRU level need to be further downscaled to the district level. The following steps are used for the downscaling:

(i) Identification of all districts located within the border of each HRU in the respective sub-basins;
(ii) Calculation of the area of each district;
(iii) Using the water yield result of the relevant HRU from the SWAT model as the representative value for the district located within the HRU;
(iv) Volume of water availability is estimated by multiplying the water yield by the area of the district.
(v) In the case that one district is located across more than one HRU, calculation of the water availability of the district is conducted based on the land area covered within each of the relevant HRUs using the Geographical Information System (GIS) tool and the water yield of each respective HRU and summing up the results.

3.1.3 Water demand estimation

Estimation of the water demand for five sectors (domestic sector, irrigation, livestock, industrial sector and energy sector) under the current and future scenarios are mainly dependent on the secondary information. As most of the secondary information for the above mentioned sectors is available at the district level, water demand at the state or sub-basin level is estimated based on the percentage of area of the district covered within the border of a specific sub-basin.

3.1.3.1 Domestic water demand estimation

Domestic water use was estimated at the district level by multiplying the population by the different water use rates per capita for urban and rural areas. In the urban areas, per capita water use is often higher than in the rural areas due to better water infrastructure in the cities and resource- intensive lifestyles of the urban households. Therefore, for the present study, per capita water demand for urban and rural areas is considered as 150 litres per capita per day (lpcd) and 70 lpcd, respectively (Van Rooijen et al., 2009). District-level population data were taken from the census (2001 and 2011) and used to project future population using the arithmetic increase method for all the sub-basins. For urban areas, the average value is used considering metropolitan areas and cities with populations over 1 million. Similarly, the average value of villages and towns is used for the rural areas. For the future case, population projections are estimated using the arithmetic increase method. With this method, the average increase in population per decade is calculated based on the past census data, which assumes that the population is changing at a constant rate.

3.1.3.2 Irrigation water demand estimation

Irrigation water requirement is calculated at the district level for major cereal crops for the four sub-basins. Based on these estimated data, percentage changes in the crop water requirement are calculated. The detailed procedure is described as follows:

(i) Identification of major crops in the sub-basins;

(ii) Estimation of the reference evapotranspiration ET_0: The ET_0 Calculator (Version 3.2) is used to estimate ET_0. This is a free online tool which can be downloaded from www.fao.org/nr/water.ET0.html.

(iii) Evapotranspiration of each crop (ET_c): ET_c is the amount of water demanded by the crop under standard conditions. It is calculated by multiplying the reference crop evapotranspiration (ET_0) in mm/day by the dimensionless crop coefficient (K_c) suggested by FAO and other secondary sources for the main crops in the sub-basins:

$$ET_c = ET_0 \times K_c;$$

(iv) Estimation of effective precipitation ($P_{effective}$) which is the rainfall available for crop production (based on the FAO/AGLW formula)

(v) FAO/AGLW developed an empirical formula based on different climate data to determine the dependable effective rainfall, i.e., the dependable rainfall at 80% probability corrected for the assumed losses due to runoff and percolation (Smith, 1988):

$$P_{effective} = 0.6 \times P_{total} - 10, \text{ if } P_{total} <= 70 \text{ mm}$$

$$P_{effective} = 0.8 \times P_{total} - 25, \text{ if } P_{total} > 70 \text{ mm}$$

(vi) Estimation of irrigation water requirement, which is ET_c - $P_{effective}$.

For future estimation, climate change scenarios of RCP 4.5 and RCP 8.5 for the periods from 2011 to 2050 based on the district-level changes in climate variables (precipitation and temperature) are considered for the existing dominant crops in the relevant sub-basins (see **Table 5**).

Table 5 Dominant crops in each sub-basin

Name of sub-basin	Dominant crops
Yamuna	Bajra, Cotton, Groundnut, Jowar, Maize, Rice, Sugarcane, Barley, Mustard, Potato, Wheat
Gandak	Maize, Rice, Sugarcane, Barley, Mustard, Potato, Wheat
Damodar	Maize, Bajra, Mustard, Potato, Wheat, Sugarcane, Rice
Chambal	Bajra, Cotton, Groundnut, Jowar, Maize, Rice, Barley, Mustard, Wheat, Potato, Sugarcane

To estimate the total irrigation water requirement at the district level, we used the national reference values from Amarasinghe et al. (2009). This reference factor of 1.45 is multiplied by the cereal irrigation water demand in 2010 to calculate the total irrigation water demand in the current period. For future periods, different multiplication factors are used to estimate the total irrigation water demand (1.003 for the 2020s, 1.007 for the 2030s, 1.168 for the 2040s and 1.329 for the 2050s).

3.1.3.3 Livestock water demand estimation

Livestock water demand was estimated at the district level and then aggregated to the sub-basin level by multiplying the livestock population by the water use rate per head for different types of livestock. Data on the district-level population of the livestock is collected from the census (2007 and 2012). There is a fluctuation in the number of different types of livestock and it is impossible to estimate the decadal growth for future livestock. Because of this, we assumed that there is an increase of 10% in the water demand at the decadal basis considering the increase in the livestock population and the impacts from climate change in terms of temperature increase.

3.1.3.4 Industrial water demand estimation

Due to the limitation of data availability and accessibility, it is difficult to estimate water use from industries. District-level data on the number of factories are available; however, it is not very useful for estimating industrial water use because the amount of water used by different sectors is often different. We use an alternative method for estimating industrial water demand as suggested by the Central Pollution Control Board (1989) and used by Van Rooijen et al. (2009) for the Krishna basin. This method considers urban and rural water demand for the calculation of industrial water use.

The annual industrial water use can be estimated as a percentage of urban and rural domestic water use, as suggested by the Central Pollution Control Board (1989).

$$I_{industry} = I_{rural} \times f_{rural} + I_{urban} \times f_{urban}$$

where $I_{industry}$ is industrial water use, I_{rural} and I_{urban} are rural and urban domestic water use, respectively, and f_{rural} and f_{urban} are urban and rural water use factors (dimensionless), respectively. In this study, f_{rural} and f_{urban} are considered as 25% and 5%, respectively.

3.1.3.5 Energy water demand estimation

As mentioned in Section 2, the project team conducted power plant surveys to collect the first-hand information on water use intensity for different power generation technologies and different cooling systems in the selected four sub-basins. During the power plant surveys, the team collected various information including fuels, power generation technologies, plant load factors (*PLF*), cooling technologies, source of water, volume of water use by the power plants, etc. The energy water demand (*EWD*) is calculated using the following equation:

EWD= Installed capacity x 24 hours x 365 days x *PLF* x water use per unit electricity generation

Future water demand from power generation is calculated based on the total planned capacity disclosed by the Central Energy Authority.

3.1.3.6 Environmental water requirements

Environmental water requirement is the amount of water that the ecosystems need to sustain their ecological processes and biodiversity. Due to limited data availability, it is difficult to estimate the environmental water requirement. In this study, the environmental water requirement is estimated by using a specific ratio of the total water demand, which is about 1.23% (Central Water Commission, 2015).

3.1.3.7 Water risk assessment for future power generation

Water supply and demand balance is assessed by subtracting the total water demand from the total water availability at the district level for each sub-basin, i.e., total water availability - total water demand. The supply-demand balance is estimated for the present and future time periods. A positive value of water supply-demand balance indicates water surplus and a negative value indicates water shortage. The results of the water supply-demand balance are further classified into three groups based on the water supply-demand gap ratio, which is the ratio of the water supply-demand balance to the total water supply (see **Table 6**).

Table 6 Classification of water risks for future power plants

No.	Water supply-demand gap ratio	Class	Explanation
1	<= 0	red area	Highly water-stressed area which is not appropriate for building new thermal power plants
2	(0 - 0.5]	orange area	Moderate water-stressed area with limited potential for building new thermal power plants
3	(0.5 - 1.0]	yellow area	High water surplus area which is appropriate for building new thermal power plants

Limitations of the water demand assessment include:

(i) Future domestic water demand estimation is based only on the population projection but does not take into account changes in the income levels and associated impacts. Similarly, the water demand from livestock is based on the future livestock population which is estimated to increase by 10% in each time period.

(ii) The water demand from agriculture is estimated using national-level data of the changes in the water requirement (Amarasinghe et al., 2009) which is not necessarily true for the specific districts due to different crops, water supply patterns and infrastructure.

3.1.4 Results and discussions

3.1.4.1 Water availability assessment at the sub-basin and district levels

Chambal sub-basin

In the Chambal sub-basin, the precipitation and its changes compared to the historical levels under the RCP 4.5 and RCP 8.5 scenarios are presented in **Table 7** and **Table 8**. The changes vary between 7% and 20% under RCP 4.5 and between 1% and 34% under RCP 8.5. It is observed that the increase in precipitation will be greater in the mid-future periods and then become lower in the second half of the century. This is a good sign for this sub-basin due to the increase in water supply. Under RCP 4.5, there will be a decrease in evapotranspiration in the near future but an increase in the mid- and far-future periods. Under RCP 8.5, evapotranspiration will increase in all three time periods.

Table 7 Water supply in the Chambal sub-basin for different time periods under two climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	PCP	ET	SURQ	WYLD	PCP	ET	SURQ	WYLD
Historical	854	443	373	425	854	443	373	425
2011-2020	962	423	438	540	1,054	506	462	549
2021-2030	918	425	419	490	1,004	479	449	522
2031-2040	939	420	434	522	1,014	497	451	522
2041-2050	1,021	549	420	482	1,148	519	516	627
2051-2060	988	516	426	482	1,097	486	508	606
2061-2070	1,010	533	433	494	1,113	507	513	610
2071-2080	952	479	412	478	990	508	448	527
2081-2090	916	448	412	469	995	478	442	511
2091-2100	933	476	414	469	861	459	428	497
Near Future	940	423	430	517	1,024	494	454	531
Mid Future	1,006	533	426	486	1,119	504	512	614
Far Future	934	468	413	472	949	482	439	512

Note: PCP – precipitation; ET – evapotranspiration; SURQ – surface runoff; WYLD – water yield; Near future – 2011-2040; Mid future – 2041-2070; Far future – 2071-2100.

Table 8 Percentage changes in the water supply compared with the historical level of the Chambal sub-basin for different time periods under two climate scenarios (%)

Period	RCP 4.5				RCP 8.5			
	PCP	ET	SURQ	WYLD	PCP	ET	SURQ	WYLD
2011-2020	13	-5	17	27	23	14	24	29
2021-2030	7	-4	12	15	18	8	20	23
2031-2040	10	-5	16	23	19	12	21	23
2041-2050	20	24	13	13	34	17	38	48
2051-2060	16	16	14	13	28	10	36	43
2061-2070	18	20	16	16	30	14	38	44
2071-2080	11	8	10	12	16	15	20	24
2081-2090	7	1	10	10	17	8	18	20
2091-2100	9	8	11	10	1	4	15	17
Near Future	10	-5	15	22	20	12	22	25
Mid Future	18	20	14	14	31	14	37	44
Far Future	9	6	11	11	11	9	18	20

Note: PCP – precipitation; ET – evapotranspiration; SURQ – surface runoff; WYLD – water yield; Near future – 2011-2040; Mid future – 2041-2070; Far future – 2071-2100.

Surface runoff in Chambal under the RCP 4.5 and RCP 8.5 scenarios is given in **Table 7**. There will be an increase in the runoff in all predicted time periods under both climate change scenarios, which varies from 10% to 17% under RCP 4.5 and from 15% to 38% under RCP 8.5. The changes are proportional to the increase in rainfall. For water yield, there is also an increase. Under RCP 4.5, the increase is between 10% and 27% and between 17% and 48% under RCP 8.5.

Monthly precipitation and its changes compared with the historical level for different future time periods is given in **Table 9** and **Table 10**, respectively. In Chambal, the average monthly precipitation will increase in the wet season (June to October) with the ranges between 68.2 mm and 166.5 mm under RCP 4.5 and between 142.6 mm and 293.3 mm under RCP 8.5. In the dry season, it shows slightly negative changes (-3.2 mm) to slightly positive changes (1.3 mm) under RCP 4.5 and varies between -3.1 mm and 2.8 mm under RCP 8.5.

Table 9 Average monthly precipitation in the Chambal sub-basin for different time periods under two climate scenarios (in mm)

Period	Hist.	RCP 4.5				RCP 8.5			
		2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	6.4	4.0	9.4	6.0	3.7	3.8	8.3	5.7	3.9
February	4.8	5.8	5.4	4.1	5.9	6.3	5.2	4.3	5.6
March	2.2	1.3	0.9	3.3	1.3	1.3	0.8	3.3	1.3
April	2.7	0.5	3.3	2.8	0.5	0.5	2.9	2.8	0.5
May	7.2	8.3	10.1	8.0	7.8	8.8	11.7	9.2	7.8
June	92.7	150.7	113.6	98.2	155.2	191.3	153.0	119.7	167.0
July	269.9	281.4	233.3	334.5	293.2	228.7	189.7	308.5	277.5
August	303.9	313.9	362.8	279.1	341.6	415.3	448.8	354.7	453.7
September	111.8	145.2	125.5	155.1	160.9	146.3	120.9	156.4	179.0
October	27.6	22.0	38.9	28.1	21.5	22.5	36.1	28.9	22.0
November	11.3	23.9	11.2	7.7	24.5	24.5	10.6	8.0	23.8
December	13.0	5.2	4.1	12.5	5.2	5.2	5.0	12.5	5.6
Wet Season	805.9	913.2	874.1	895	972.4	1004.1	948.5	968.2	1.099.2
Dry Season	47.6	49	44.4	44.4	48.9	50.4	44.5	45.8	48.5

Table 10 Average monthly precipitation changes compared with the historical level in the Chambal sub-basin for different time periods under two climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	-2.4	3	-0.4	-2.7	-2.6	1.9	-0.7	-2.5
February	1	0.6	-0.7	1.1	1.5	0.4	-0.5	0.8
March	-0.9	-1.3	1.1	-0.9	-0.9	-1.4	1.1	-0.9
April	-2.2	0.6	0.1	-2.2	-2.2	0.2	0.1	-2.2
May	1.1	2.9	0.8	0.6	1.6	4.5	2	0.6
June	58	20.9	5.5	62.5	98.6	60.3	27	74.3
July	11.5	-36.6	64.6	23.3	-41.2	-80.2	38.6	7.6
August	10	58.9	-24.8	37.7	111.4	144.9	50.8	149.8
September	33.4	13.7	43.3	49.1	34.5	9.1	44.6	67.2
October	-5.6	11.3	0.5	-6.1	-5.1	8.5	1.3	-5.6
November	12.6	-0.1	-3.6	13.2	13.2	-0.7	-3.3	12.5
December	-7.8	-8.9	-0.5	-7.8	-7.8	-8	-0.5	-7.4
Wet Season	107.3	68.2	89.1	166.5	198.2	142.6	162.3	293.3
Dry Season	1.4	-3.2	-3.2	1.3	2.8	-3.1	-1.8	0.9

Monthly variation in water yield and changes for different decades are given in **Table 11** and **Table 12**, respectively. In Chambal, average monthly water yields increase in the wet season with the ranges between 40.4 mm and 61.8 mm under RCP 4.5 and between 97.4 mm and 200.6 mm under RCP 8.5. In the dry season, there will be decreases between -5.3 mm and -0.8 mm under RCP 4.5 and changes between -1.8 mm and 6.2 mm under RCP 8.5.

Table 11 Average monthly water yields in the Chambal sub-basin for different periods and climate scenarios (in mm)

Period	Hist.	RCP 4.5				RCP 8.5			
		2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	2.8	0.7	0.9	1.8	1.3	0.8	0.9	1.8	1.0
February	0.8	0.5	0.9	0.5	0.7	0.6	0.9	0.6	0.6
March	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.4
April	0.3	0.2	0.3	0.2	0.2	0.3	0.3	0.3	0.3
May	0.3	0.2	0.2	0.3	0.2	0.3	0.3	0.3	0.3
June	7.5	17.7	9.5	8.7	16.9	28.0	18.1	13.0	19.9
July	95.3	117.2	80.5	127.4	115.4	100.5	68.7	115.0	116.8
August	177.1	167.5	210.0	171.3	169.7	215.2	252.9	212.3	242.6
September	84.5	123.0	94.7	109.7	126.1	139.3	106.1	119.8	168.0
October	31.8	32.1	41.7	32.7	29.8	40.6	47.8	38.5	49.4
November	11.5	15.1	14.6	9.9	16.2	19.1	17.4	12.3	22.9
December	9.2	3.8	2.7	7.7	5.7	4.6	3.1	8.1	5.9
Wet Season	396.1	457.4	436.5	449.7	457.9	523.6	493.5	498.6	596.7
Dry Season	25.2	20.8	19.9	20.7	24.4	26.0	23.4	23.8	31.4

Table 12 Average monthly water yield changes compared with the historical level in the Chambal sub-basin for different periods and climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	-2.2	-2.0	-1.1	-1.6	-2.0	-1.9	-1.0	-1.9
February	-0.3	0.1	-0.2	-0.1	-0.2	0.2	-0.2	-0.2
March	0.0	-0.1	0.0	-0.1	0.0	0.0	0.1	0.1
April	0.0	0.1	0.0	-0.1	0.0	0.1	0.0	0.1
May	0.0	0.0	0.0	-0.1	0.0	0.0	0.1	0.1
June	10.1	2.0	1.1	9.4	20.5	10.6	5.5	12.4
July	21.9	-14.8	32.1	20.1	5.2	-26.6	19.7	21.5
August	-9.5	33.0	-5.7	-7.3	38.2	75.8	35.3	65.5
September	38.6	10.2	25.2	41.7	54.8	21.6	35.4	83.5
October	0.3	9.9	0.9	-2.0	8.8	16.0	6.7	17.7
November	3.6	3.1	-1.7	4.6	7.5	5.9	0.8	11.3
December	-5.4	-6.5	-1.5	-3.6	-4.6	-6.1	-1.1	-3.3
Wet Season	61.3	40.4	53.6	61.8	127.4	97.4	102.5	200.6
Dry Season	-4.4	-5.3	-4.5	-0.8	0.8	-1.8	-1.4	6.2

Water availability at the district level in Chambal is provided in **Table 13**. The results show that water availability in most districts located in the Chambal sub-basin will increase in the future. However, the water availability in several districts will decrease in the future. Specifically, the water availability in Neemuch (Ch_13), Sawai Madhopur (Ch_16) and Tonk (Ch_21) will reduce substantially, particularly in 2030 compared with that in 2010.

Table 13 District-level water availability in the Chambal sub-basin for the periods in 2010, 2030 and 2050 under RCP 4.5 (MCM)

District Name	District Code	State Name	Area (km^2) in the Basin	Water 2010	Water_4.5 2030	Water_4.5 2050
Baran	Ch_01	Rajasthan	6,070	2,503	3,020	3,042
Bhilwara	Ch_02	Rajasthan	1,041	198	197	343
Bhopal	Ch_03	Madya Pradesh	612	250	327	313
Bundi	Ch_04	Rajasthan	5,414	1,074	1,003	1,827
Chittaurgarh	Ch_05	Rajasthan	3,070	1,048	1,108	1,412
Dewas	Ch_06	Madya Pradesh	3,086	1,230	1,805	1,696
Dhar	Ch_07	Madya Pradesh	1,579	521	662	487
Guna	Ch_08	Madya Pradesh	4,622	1,959	2,551	2,454
Indore	Ch_09	Madya Pradesh	2,875	929	1,266	1,404
Jhalawar	Ch_10	Rajasthan	6,248	2,494	3,132	3,186
Kota	Ch_11	Rajasthan	5,503	1,895	1,910	2,429
Mandsaur	Ch_12	Madya Pradesh	5,631	2,298	2,412	2,703
Neemuch	Ch_13	Madya Pradesh	3,531	1,666	1,265	1,588
Rajgarh	Ch_14	Madya Pradesh	6,120	2,631	3,506	2,943
Ratlam	Ch_15	Madya Pradesh	2,919	933	1,357	1,527
Sawai Madhopur	Ch_16	Rajasthan	730	193	43	91
Sehore	Ch_17	Madya Pradesh	3,151	1,341	1,790	1,641
Shajapur	Ch_18	Madya Pradesh	6,292	2,632	3,611	3,427
Sheopur	Ch_19	Madya Pradesh	1,422	557	691	709
Shivpuri	Ch_20	Madya Pradesh	60	24	32	30
Tonk	Ch_21	Rajasthan	423	92	66	141
Ujjain	Ch_22	Madya Pradesh	6,081	2,008	2,737	3,130
Vidisha	Ch_23	Madya Pradesh	391	159	209	200
		Total	**76,871**	**28,637**	**34,701**	**36,722**

Damodar sub-basin

The water supply in the Damodar sub-basin is shown in **Table 14**. The percent change in precipitation varies between 9% and 20% under RCP 4.5 and between 11% and 31% under RCP 8.5 (**Table 15**). Surface runoff changes between -4% and 19% under RCP 4.5 and between -3% and 32% under RCP 8.5. Water yield will increase between 13% and 39% under RCP 4.5 and between 14% and 55% under RCP 8.5. It can be expected that there will be increases in the precipitation in both dry and wet seasons. The Damodar sub-basin will get extra precipitation under the climate scenarios. For evapotranspiration, there will be an increase in all the time periods. The maximum change is up to 12% under RCP 4.5% and up to 21% under RCP 8.5.

Table 14 Water supply in the Damodar sub-basin for different time periods under two climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	PCP	ET	SURQ	WYLD	PCP	ET	SURQ	WYLD
Historical	1,464	712	520	724	1,464	712	520	724
2011-2020	1,644	790	524	818	1,627	827	526	822
2021-2030	1,631	793	522	825	1,620	835	506	824
2031-2040	1,681	795	547	871	1,736	825	600	950
2041-2050	1,758	797	588	961	1,794	832	611	981
2051-2060	1,751	783	567	968	1,785	832	592	988
2061-2070	1,718	709	620	1,009	1,908	833	685	1,112
2071-2080	1,612	786	530	827	1,815	845	609	992
2081-2090	1,603	785	500	818	1,810	860	581	987
2091-2100	1,722	768	602	955	1,925	842	684	1,123
Near Future	1,652	793	531	838	1,661	829	544	865
Mid Future	1,743	763	592	979	1,829	832	629	1,027
Far Future	1,646	780	544	867	1,850	849	625	1,034

Note: PCP – precipitation; ET – evapotranspiration; SURQ – surface runoff; WYLD – water yield; Near future – 2011-2040; Mid future – 2041-2070; Far future – 2071-2100.

Table 15 Percentage changes in the water supply compared with the historical level in the Damodar sub-basin for different time periods under two climate scenarios (%)

Period	RCP 4.5				RCP 8.5			
	PCP	ET	SURQ	WYLD	PCP	ET	SURQ	WYLD
2011-2020	12	11	1	13	11	16	1	14
2021-2030	11	11	0	14	11	17	-3	14
2031-2040	15	12	5	20	19	16	15	31
2041-2050	20	12	13	33	23	17	18	35
2051-2060	20	10	9	34	22	17	14	36
2061-2070	17	0	19	39	30	17	32	54
2071-2080	10	10	2	14	24	19	17	37
2081-2090	9	10	-4	13	24	21	12	36
2091-2100	18	8	16	32	31	18	32	55
Near Future	13	11	2	16	13	16	5	19
Mid Future	19	7	14	35	25	17	21	42
Far Future	12	9	5	20	26	19	20	43

Note: PCP – precipitation; ET – evapotranspiration; SURQ – surface runoff; WYLD – water yield; Near future – 2011-2040; Mid future – 2041-2070; Far future – 2071-2100.

In Damodar, the average monthly precipitation for different time periods under the two climate scenarios is shown in **Table 16** and **Table 17**. The average monthly precipitation in the wet season shows positive changes between 24.3 mm and 310.2 mm under RCP 4.5 and between 85.6 mm and 333.4 mm under RCP 8.5. In the dry season, it shows changes between -23.5 mm and 79 mm under RCP 4.5 and between -3.7 mm and 70.6 mm under RCP 8.5.

Table 16 Average monthly precipitation in the Damodar sub-basin for different time periods under two climate scenarios (in mm)

Period	Hist.	RCP 4.5				RCP 8.5			
		2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	13.4	13.2	10.0	18.9	12.7	13.1	9.7	18.5	13.1
February	20.7	22.9	27.3	21.0	22.6	22.9	27.3	21.2	22.2
March	27.9	26.1	32.1	21.5	22.5	25.5	32.1	20.0	25.2
April	36.0	38.6	54.4	60.3	33.3	34.2	42.8	43.9	32.5
May	84.1	106.8	132.6	127.4	75.0	118.3	140.6	133.2	94.8
June	257.6	273.7	302.3	297.1	270.2	280.9	324.5	332.9	420.6
July	333.3	381.8	345.9	341.3	457.6	406.4	396.7	405.9	379.7
August	307.6	314.7	301.8	340.7	409.0	304.8	284.9	316.6	371.6
September	252.2	280.5	239.7	311.6	312.9	286.7	241.2	309.9	297.2
October	103.4	114.6	88.7	86.9	114.7	117.3	92.6	94.7	118.4
November	16.9	10.4	15.0	24.7	12.9	10.3	14.9	24.7	11.6
December	10.8	6.7	13.1	15.0	7.4	6.8	13.0	14.8	6.7
Wet Season	1,254.2	1,365.2	1,278.6	1,377.5	1,564.4	1,396.1	1,339.8	1,460.0	1,587.6
Dry Season	209.8	224.8	284.4	288.8	186.3	231.0	280.4	276.3	206.1

Table 17 Average monthly precipitation changes compared with the historical level in the Damodar sub-basin for different time periods under two climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	-0.2	-3.4	5.5	-0.7	-0.3	-3.7	5.1	-0.3
February	2.2	6.6	0.4	2.0	2.3	6.7	0.5	1.5
March	-1.7	4.2	-6.4	-5.3	-2.4	4.2	-7.9	-2.6
April	2.6	18.4	24.2	-2.8	-1.8	6.8	7.8	-3.5
May	22.7	48.5	43.2	-9.2	34.2	56.4	49.0	10.7
June	16.0	44.7	39.5	12.6	23.3	66.8	75.2	162.9
July	48.5	12.7	8.0	124.3	73.1	63.4	72.6	46.5
August	7.1	-5.8	33.1	101.3	-2.9	-22.8	9.0	64.0
September	28.3	-12.5	59.4	60.7	34.5	-11.0	57.7	45.0
October	11.2	-14.7	-16.6	11.3	13.9	-10.8	-8.7	15.0
November	-6.4	-1.9	7.8	-4.0	-6.6	-2.0	7.8	-5.3
December	-4.1	2.3	4.2	-3.4	-4.0	2.2	4.0	-4.1
Wet Season	111.0	24.3	123.3	310.2	141.9	85.6	205.7	333.4
Dry Season	15.0	74.6	79.0	-23.5	21.3	70.6	66.5	-3.7

Table 18 and **Table 19** present the decadal water yield projections and relevant changes in twelve months in Damodar. The average monthly water yield will increase in the wet season, showing positive changes between 30.5 mm and 210.3 mm under RCP 4.5 and between 81.4 mm and 246.6 mm under RCP 8.5. In the dry season, it shows a decrease only in the 2020s under RCP 4.5. This shows that there will be an increase in the water yield in the dry season, which is a good indication that the sub-basin can provide extra water to various sectors in the future.

Table 18 Average monthly water yield in the Damodar sub-basin for different time periods under two climate scenarios (in mm)

Period	Hist.	RCP 4.5				RCP 8.5			
		2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	4.4	4.4	3.4	7.1	5.7	4.4	3.4	7.3	5.0
February	3.9	3.1	3.7	3.5	3.6	3.1	3.8	3.5	3.3
March	3.3	1.9	2.5	2.5	1.9	1.9	2.6	2.4	2.1
April	1.4	1.6	2.5	3.2	1.7	1.5	2.0	2.3	1.7
May	7.1	7.5	16.3	16.0	4.3	9.4	17.9	17.0	6.1
June	69.7	69.3	94.2	96.7	62.9	73.4	103.7	110.5	135.6
July	139.8	158.0	154.7	161.2	189.8	170.8	179.6	197.6	184.3
August	166.7	180.0	169.7	193.9	234.6	183.6	177.0	200.5	223.6
September	165.1	185.4	153.2	209.9	225.5	189.8	159.1	214.9	212.6
October	102.5	118.6	102.5	104.7	141.3	121.0	105.7	108.6	134.1
November	40.7	43.0	42.6	52.9	55.2	44.0	43.5	54.2	50.6
December	16.8	15.9	17.9	23.7	21.6	16.2	18.1	24.2	18.7
Wet Season	643.7	711.3	674.2	766.2	854.1	738.5	725.1	832.2	890.3
Dry Season	77.6	77.4	88.7	109.0	94.0	80.5	91.3	110.9	87.5

Table 19 Average monthly water yield changes compared with the historical level in the Damodar sub-basin for different time periods under two climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	0.0	-1.1	2.7	1.3	0.0	-1.0	2.8	0.6
February	-0.8	-0.2	-0.5	-0.4	-0.8	-0.1	-0.4	-0.6
March	-1.4	-0.8	-0.9	-1.4	-1.4	-0.7	-0.9	-1.2
April	0.2	1.1	1.8	0.4	0.1	0.6	0.9	0.3
May	0.4	9.2	8.9	-2.8	2.3	10.8	9.9	-1.0
June	-0.3	24.5	27.0	-6.8	3.7	34.1	40.9	66.0
July	18.2	14.9	21.4	50.0	31.0	39.8	57.9	44.5
August	13.3	2.9	27.2	67.9	16.9	10.3	33.8	56.9
September	20.3	-12.0	44.7	60.4	24.7	-6.1	49.7	47.5
October	16.1	0.1	2.2	38.9	18.5	3.3	6.1	31.7
November	2.4	1.9	12.3	14.6	3.3	2.8	13.5	9.9
December	-0.9	1.0	6.9	4.7	-0.6	1.3	7.4	1.9
Wet Season	67.6	30.5	122.5	210.3	94.8	81.4	188.4	246.6
Dry Season	-0.2	11.2	31.4	16.5	2.9	13.7	33.3	9.9

Water availability at the district level in Damodar is provided in **Table 20**. The results show that the water availability in most of the districts will increase in the future. However, the water availability in several districts will decrease in the future. Specifically, the water availability in Deograh (Da_05), Giridih (Da_08), Jamatara (Da_12), Latehar (Da_14) and Lohardaga (Da_15) will reduce particularly in 2030 compared with that in 2010.

Table 20 District-level water availability in the Damodar sub-basin for the periods in 2010, 2030 and 2050 (MCM) under RCP 4.5

District Name	District Code	State Name	Area (km^2) in the Basin	Water 2010	Water_4.5 2030	Water_4.5 2050
Bankura	Da_01	West Bengal	6,965	5,186	6,084	6,065
Barddhaman	Da_02	West Bengal	2,095	1,551	1,797	1,878
Bokaro	Da_03	Jharkhand	2,848	1,579	1,831	2,184
Chatra	Da_04	Jharkhand	646	356	409	516
Deograh	Da_05	Jharkhand	7	5	5	5
Dhanbad	Da_06	Jharkhand	2,084	1,385	1,448	1,659
East Midnapore	Da_07	West Bengal	2,674	2,316	2,337	2,720
Giridih	Da_08	Jharkhand	3,494	2,482	2,343	2,803
Haora	Da_09	West Bengal	276	218	266	269
Hazaribag	Da_10	Jharkhand	5,367	3,181	3,344	4,341
Hugli	Da_11	West Bengal	1,062	759	934	927
Jamatara	Da_12	Jharkhand	539	441	367	422
Koderma	Da_13	Jharkhand	546	288	313	424
Latehar	Da_14	Jharkhand	692	454	387	497
Lohardaga	Da_15	Jharkhand	59	39	32	42
Purba Singhbhum	Da_16	Jharkhand	313	194	234	293
Puruliya	Da_17	West Bengal	5,238	3,430	4,122	4,308
Ranchi	Da_18	Jharkhand	809	503	512	655
Saraikela Kharsawan	Da_19	Jharkhand	9	5	6	8
West Midnapore	Da_20	West Bengal	6,830	5,799	5,949	6,403
		Total	**42,549**	**30,171**	**32,720**	**36,418**

Gandak sub-basin

Table 21 and **Table 22** show the water supply and its changes in the Gandak sub-basin for different decades under two climate scenarios. There will be increases in the precipitation, which varies between -5% and 26% under RCP 4.5 and between -1% and 34% under RCP 8.5. For evapotranspiration, the percentage changes vary between -3% and 10% under RCP 4.5 and between 1% and 12% under RCP 8.5. The surface runoff shows changes between -9% and 39% under RCP 4.5 and between -7% and 50% under RCP 8.5. An increase in the water yield of the Gandak sub-basin is predicted under both scenarios. The changes vary between -9% and 43% under RCP 4.5 and between -5% and 58% under RCP 8.5.

Table 21 Water supply in the Gandak sub-basin for different time periods under two climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	PCP	ET	SURQ	WYLD	PCP	ET	SURQ	WYLD
Historical	1,075	608	425	496	1,075	608	425	496
2011-2020	1,268	671	515	617	1,186	666	466	544
2021-2030	1,356	667	583	708	1,278	664	535	634
2031-2040	1,134	620	438	537	1,061	615	396	472
2041-2050	1,246	666	500	600	1,338	683	552	674
2051-2060	1,334	662	568	691	1,420	676	619	762
2061-2070	1,120	620	427	523	1,197	635	470	584
2071-2080	1,137	639	451	523	1,353	680	569	692
2081-2090	1,228	640	517	610	1,441	676	638	783
2091-2100	1,016	591	383	453	1,211	627	491	607
Near Future	1,253	653	512	621	1,175	649	466	550
Mid Future	1,233	649	498	605	1,318	665	547	673
Far Future	1,127	624	450	529	1,335	661	566	694

Note: PCP – precipitation; ET – evapotranspiration; SURQ – surface runoff; WYLD – water yield; Near future – 2011-2040; Mid future – 2041-2070; Far future – 2071-2100.

Table 22 Percentage changes in the water supply compared with the historical level in the Gandak sub-basin for different time periods under two climate scenarios (%)

Period	RCP 4.5				RCP 8.5			
	PCP	ET	SURQ	WYLD	PCP	ET	SURQ	WYLD
2011-2020	18	10	21	24	10	10	10	10
2021-2030	26	10	37	43	19	9	26	28
2031-2040	5	2	3	8	-1	1	-7	-5
2041-2050	16	10	18	21	24	12	30	36
2051-2060	24	9	34	39	32	11	46	54
2061-2070	4	2	0	5	11	4	11	18
2071-2080	6	5	6	5	26	12	34	40
2081-2090	14	5	22	23	34	11	50	58
2091-2100	-5	-3	-10	-9	13	3	16	22
Near Future	17	7	20	25	9	7	10	11
Mid Future	15	7	17	22	23	9	29	36
Far Future	5	3	6	7	24	9	33	40

Note: PCP – precipitation; ET – evapotranspiration; SURQ – surface runoff; WYLD – water yield; Near future – 2011-2040; Mid future – 2041-2070; Far future – 2071-2100.

In Gandak, the average monthly precipitation in the wet season shows positive changes between 60.8 mm and 257.4 mm under RCP 4.5 and from negative to positive changes from -15 to 258.1 mm under RCP 8.5 (**Table 23** and **Table 24**). In the dry season, the variation is between -2.1 mm and 23.4 mm under RCP 4.5 and between 1.2 mm and 29.4 mm under RCP 8.5.

Table 23 Average monthly precipitation in the Gandak sub-basin for different time periods under two climate scenarios (in mm)

Period	Hist.	RCP 4.5				RCP 8.5			
		2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	11.2	13.6	12.7	10.8	13.3	13.5	12.7	10.7	13.3
February	11.6	15.5	13.0	9.9	14.5	14.9	12.4	9.5	14.2
March	7.7	6.2	11.2	6.0	6.1	6.0	11.0	5.9	6.1
April	12.9	18.0	17.6	10.0	17.9	18.1	18.7	11.6	17.8
May	37.8	41.6	49.9	36.6	40.8	48.7	55.6	38.8	38.8
June	153.2	178.1	212.8	195.9	152.9	152.7	186.9	169.0	211.6
July	313.7	412.0	474.8	324.8	379.7	356.4	422.4	282.2	415.1
August	261.2	267.4	262.6	272.2	302.4	257.4	254.3	263.8	314.9
September	190.5	220.2	218.4	203.9	220.4	221.9	220.2	205.6	208.6
October	61.9	87.2	69.3	44.5	88.5	87.9	69.9	45.0	88.5
November	6.9	6.0	5.0	10.9	6.1	6.1	5.0	11.1	6.1
December	6.6	3.1	8.7	8.3	3.1	3.1	8.7	8.3	3.0
Wet Season	980.6	1,,164.9	1237.9	1,041.3	1,143.9	1,076.3	1153.6	965.6	1,238.6
Dry Season	94.6	103.9	118.0	92.5	101.7	110.4	124.0	95.8	99.3

Table 24 Average monthly precipitation changes compared with the historical level in the Gandak sub-basin for different time periods under two climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	2.4	1.5	-0.4	2.1	2.3	1.5	-0.5	2.1
February	3.9	1.4	-1.7	2.9	3.3	0.9	-2.1	2.6
March	-1.6	3.5	-1.7	-1.6	-1.8	3.2	-1.8	-1.6
April	5.2	4.8	-2.8	5.0	5.3	5.8	-1.3	5.0
May	3.9	12.1	-1.2	3.0	11.0	17.9	1.0	1.0
June	25.0	59.7	42.7	-0.3	-0.4	33.7	15.8	58.4
July	98.3	161.1	11.1	66.0	42.7	108.7	-31.5	101.4
August	6.1	1.4	11.0	41.1	-3.9	-7.0	2.5	53.7
September	29.6	27.9	13.4	29.8	31.3	29.6	15.1	18.0
October	25.3	7.4	-17.4	26.5	26.0	7.9	-16.9	26.5
November	-0.9	-1.9	4.0	-0.8	-0.8	-1.9	4.2	-0.8
December	-3.5	2.1	1.7	-3.5	-3.5	2.1	1.7	-3.6
Wet Season	184.3	257.4	60.8	163.3	95.7	173.0	-15.0	258.1
Dry Season	9.3	23.4	-2.1	7.1	15.8	29.4	1.2	4.6

In Gandak, the average monthly water yield in the wet season shows positive changes between 41 mm and 190.5 mm under RCP 4.5 and changes from -17.3 mm to 161.2 mm under RCP 8.5 (see **Table 25** and **Table 26**). Under RCP 8.5 in both the dry and wet seasons, it shows positive changes except for the period in the 2040s which has negative changes, i.e. from -17.3 mm to -0.8 mm.

Table 25 Average monthly water yield in the Gandak sub-basin for different time periods under two climate scenarios (in mm)

Period	Hist.	RCP 4.5				RCP 8.5			
		2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	3.0	2.5	3.5	2.3	2.6	2.3	3.3	2.1	2.6
February	2.1	2.1	1.8	1.4	2.0	1.9	1.7	1.3	2.0
March	1.1	0.6	1.0	0.5	0.6	0.6	0.9	0.4	0.7
April	0.5	3.8	1.0	0.3	3.7	3.6	0.9	0.3	3.6
May	1.3	2.6	2.1	1.7	2.3	2.7	2.3	1.7	2.2
June	27.4	27.5	48.5	33.9	22.0	22.6	42.1	27.3	36.6
July	120.7	160.2	212.6	137.3	138.1	127.8	178.2	110.6	167.8
August	128.0	147.0	159.0	132.9	154.8	131.2	145.2	119.6	172.4
September	107.7	130.7	134.9	125.4	130.8	122.7	127.4	118.5	134.8
October	52.1	80.2	71.5	47.4	82.0	75.1	66.5	42.6	85.4
November	15.3	18.3	21.3	19.1	19.2	15.8	18.9	16.8	20.3
December	6.1	6.2	7.7	6.8	6.8	5.4	6.9	6.1	6.8
Wet Season	435.8	545.6	626.4	476.8	527.7	479.3	559.4	418.5	597.0
Dry Season	29.5	36.0	38.5	32.1	37.2	32.2	34.9	28.7	38.0

Table 26 Average monthly water yield changes compared with the historical level in the Gandak sub-basin for different time periods under two climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	-0.5	0.5	-0.7	-0.5	-0.8	0.2	-0.9	-0.5
February	0.0	-0.3	-0.7	-0.1	-0.2	-0.4	-0.8	-0.1
March	-0.5	-0.1	-0.6	-0.5	-0.5	-0.2	-0.7	-0.4
April	3.3	0.5	-0.2	3.2	3.1	0.4	-0.2	3.0
May	1.2	0.8	0.3	1.0	1.3	1.0	0.4	0.8
June	0.1	21.1	6.5	-5.4	-4.8	14.7	-0.1	9.2
July	39.6	91.9	16.6	17.5	7.1	57.5	-10.1	47.2
August	19.0	31.0	4.9	26.8	3.2	17.2	-8.4	44.4
September	23.0	27.2	17.7	23.1	15.0	19.7	10.9	27.2
October	28.1	19.4	-4.7	29.9	23.0	14.4	-9.5	33.3
November	3.0	6.0	3.9	3.9	0.6	3.6	1.6	5.0
December	0.0	1.6	0.6	0.7	-0.8	0.8	-0.1	0.6
Wet Season	109.8	190.5	41.0	91.8	43.5	123.5	-17.3	161.2
Dry Season	6.5	9.0	2.6	7.7	2.7	5.4	-0.8	8.5

Water availability at the district level in Gandak is provided in **Table 27**. The results show that the water availability in all districts located in the Gandak sub-basin will increase in 2030. The water availability in most of the districts will increase in 2050 except for a few districts, namely Deoghar (Gd_06), Dumka (Gd_07) and Munger (Gd_20), where it will decrease in 2050 compared with that in 2010.

Table 27 District-level water availability in the Gandak sub-basin for the periods in 2010, 2030 and 2050 (MCM) under RCP 4.5

District Name	District Code	State Name	Area (km^2) in the Basin	Water 2010	Water_4.5 2030	Water_4.5 2050
Aurangabad	Gd_01	Bihar	2,819	1,136	1,513	1,493
Banka	Gd_02	Bihar	3,090	1,629	2,164	1,702
Begusarai	Gd_03	Bihar	502	333	388	357
Bhagalpur	Gd_04	Bihar	1,606	846	1,153	969
Chatra	Gd_05	Jharkhand	2,569	1,067	1,451	1,523
Deoghar	Gd_06	Jharkhand	192	119	119	107
Dumka	Gd_07	Jharkhand	112	64	70	63
Gaya	Gd_08	Bihar	4,965	2,140	3,032	2,700
Giridih	Gd_09	Jharkhand	1,189	712	1,025	830
Godda	Gd_10	Jharkhand	1,806	766	1,130	1,016
Gopalganj	Gd_11	Bihar	698	403	611	480
Hazaribag	Gd_12	Jharkhand	637	301	426	380
Jamui	Gd_13	Bihar	2,695	1,416	2,203	1,511
Jehanabad	Gd_14	Bihar	1,431	617	871	807
Khagaria	Gd_15	Bihar	164	114	140	120
Khushinagar	Gd_16	Uttar Pradesh	771	458	646	546
Koderma	Gd_17	Jharkhand	399	258	383	285
Lakhisarai	Gd_18	Bihar	1,336	684	1,001	803
Maharajganj	Gd_19	Uttar Pradesh	37	24	36	27
Munger	Gd_20	Bihar	1,355	734	1,086	706
Muzaffarpur	Gd_21	Bihar	1,844	900	1,317	1,113
Nalanda	Gd_22	Bihar	2,337	1,079	1,608	1,357
Nawada	Gd_23	Bihar	2,485	1,272	1,858	1,529
Palamu	Gd_24	Jharkhand	728	291	379	391
Pashchim Champaran	Gd_25	Bihar	2,366	1,527	2,266	1,688
Patna	Gd_26	Bihar	2,501	1,197	1,661	1,555
Purba Champaran	Gd_27	Bihar	1,449	824	1,216	956
Sahibganj	Gd_28	Jharkhand	148	63	93	83
Samastipur	Gd_29	Bihar	688	312	443	410
Saran	Gd_30	Bihar	1,703	885	1,322	1,196
Sheikhpura	Gd_31	Bihar	604	264	394	385
Siwan	Gd_32	Bihar	125	65	101	83
Vaishali	Gd_33	Bihar	2,009	958	1,329	1,236
		Total	**47,360**	**23,456**	**33,433**	**28,407**

Yamuna sub-basin

In the Yamuna sub-basin, overall there will be an increase in precipitation in the future periods under both scenarios (**Table 28** and **Table 29**). There will be increases in precipitation in the near-future compared to the mid-future periods and then decreases in the far-future period. The changes in precipitation range from -2% to 21% under RCP 4.5 and vary from 1% to 29% under RCP 8.5 scenario. Overall, there will be positive changes in the sub-basin.

For the surface runoff (see **Table 29**), the changes vary from -1% to 33% under RCP 4.5 and between -6% and 51% under the RCP 8.5 scenario. This pattern is similar to that for precipitation. An increase in the water yield is shown in **Table 29**. The changes vary between -1% and 36% under RCP 4.5 and between -3% and 60% under RCP.

Table 28 Water supply in the Yamuna sub-basin for different time periods under two climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	PCP	ET	SURQ	WYLD	PCP	ET	SURQ	WYLD
Historical	744	452	210	271	744	452	210	271
2011-2020	902	506	275	369	782	471	225	299
2021-2030	864	516	239	320	755	478	197	264
2031-2040	898	513	280	358	787	480	232	293
2041-2050	861	490	264	346	962	512	318	434
2051-2060	823	497	229	301	913	520	276	377
2061-2070	857	499	266	332	948	520	314	412
2071-2080	743	459	207	267	872	509	258	350
2081-2090	726	467	183	240	836	517	224	304
2091-2100	751	470	216	263	879	518	269	345
Near Future	888	512	265	349	775	476	218	286
Mid Future	847	495	253	326	941	517	303	408
Far Future	740	465	202	257	862	515	250	333

Note: PCP – precipitation; ET – evapotranspiration; SURQ – surface runoff; WYLD – water yield; Near future – 2011-2040; Mid future – 2041-2070; Far future – 2071-2100.

Table 29 Percentage changes in the water supply compared with the historical level in the Yamuna sub-basin for different time periods under two climate scenarios (%)

Period	RCP 4.5				RCP 8.5			
	PCP	ET	SURQ	WYLD	PCP	ET	SURQ	WYLD
2011-2020	21	12	31	36	5	4	7	10
2021-2030	16	14	14	18	1	6	-6	-3
2031-2040	21	13	33	32	6	6	10	8
2041-2050	16	8	26	28	29	13	51	60
2051-2060	11	10	9	11	23	15	31	39
2061-2070	15	10	27	23	27	15	50	52
2071-2080	0	2	-1	-1	17	13	23	29
2081-2090	-2	3	-13	-11	12	14	7	12
2091-2100	1	4	3	-3	18	15	28	27
Near Future	19	13	26	29	4	5	4	6
Mid Future	14	10	20	20	26	14	44	51
Far Future	-1	3	-4	-5	16	14	19	23

Note: PCP – precipitation; ET – evapotranspiration; SURQ – surface runoff; WYLD – water yield; Near future – 2011-2040; Mid future – 2041-2070; Far future – 2071-2100.

An increase in evapotranspiration has been projected under both RCP 4.5 and RCP 8.5 scenarios in Yamuna, as shown in **Table 29**, which means that there will be more water loss through evapotranspiration. Overall, evapotranspiration increases from 2% to 15% under both climate scenarios.

Monthly precipitation and its changes for different time periods are given in **Table 30** and **Table 31**, respectively. In Yamuna, the average monthly precipitation in the wet season will increase from 79.6 mm to 174 mm under RCP 4.5 and change from -25.9 mm to 233.3 mm under RCP 8.5. There will be decreases in most of the time periods in the dry season in the 2030s, which could further degrade the present water scarcity situation in the sub-basin.

Table 30 Average monthly precipitation in the Yamuna sub-basin for different time periods under two climate scenarios (in mm)

Period	Hist.	RCP 4.5				RCP 8.5			
		2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	21.3	23.5	19.2	24.0	22.6	22.5	18.3	22.8	22.8
February	27.6	27.0	34.6	31.7	26.0	24.6	32.3	29.6	28.2
March	22.2	18.2	31.9	18.0	17.0	17.4	30.7	17.2	17.6
April	15.4	9.8	21.5	13.1	9.3	9.5	21.3	12.9	9.7
May	26.7	22.7	38.1	19.2	23.2	23.8	39.5	20.2	22.3
June	69.2	101.4	67.7	92.4	88.6	97.8	60.6	81.9	94.5
July	206.0	285.4	233.9	245.4	317.0	207.8	168.2	182.0	399.9
August	214.8	271.0	261.5	289.4	207.3	243.9	236.2	264.5	211.7
September	103.2	112.0	109.7	132.4	117.4	103.4	101.9	122.9	122.6
October	20.0	17.5	20.1	20.6	18.2	17.9	20.5	20.9	17.9
November	4.6	6.0	7.0	4.1	6.0	6.0	7.0	4.0	6.0
December	12.3	8.4	18.9	8.9	8.4	8.4	18.8	8.8	8.4
Wet Season	613.2	787.2	692.9	780.1	748.6	670.8	587.4	672.2	846.6
Dry Season	130.1	115.5	171.3	118.9	112.5	112.2	167.7	115.5	114.9

Table 31 Average monthly precipitation changes compared with the historical level in the Yamuna sub-basin for different time periods under two climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	2.2	-2.0	2.7	1.3	1.2	-3.0	1.5	1.6
February	-0.7	7.0	4.1	-1.6	-3.0	4.6	2.0	0.6
March	-4.0	9.7	-4.2	-5.2	-4.8	8.5	-5.0	-4.7
April	-5.6	6.1	-2.3	-6.1	-5.9	5.9	-2.5	-5.7
May	-4.0	11.4	-7.5	-3.4	-2.9	12.8	-6.4	-4.4
June	32.2	-1.6	23.2	19.4	28.6	-8.7	12.7	25.2
July	79.4	27.9	39.4	111.0	1.8	-37.8	-24.0	193.9
August	56.2	46.7	74.6	-7.4	29.1	21.4	49.7	-3.1
September	8.8	6.5	29.1	14.1	0.2	-1.3	19.6	19.4
October	-2.5	0.1	0.6	-1.8	-2.1	0.5	1.0	-2.1
November	1.4	2.4	-0.5	1.4	1.4	2.4	-0.6	1.4
December	-3.9	6.6	-3.4	-3.9	-3.9	6.4	-3.5	-3.9
Wet Season	174.0	79.6	166.9	135.3	57.6	-25.9	59.0	233.3
Dry Season	-14.6	41.2	-11.2	-17.6	-17.9	37.6	-14.5	-15.1

Average monthly water yield and its changes compared with the historical period in Yamuna are given in **Table 32** and **Table 33**. Average monthly water yield in the wet season shows increases from 42.4 mm to 104.3 mm under RCP 4.5 and changes from -16.6 mm to 155.7

mm under RCP 8.5. In the dry season, there will be decreases in the water yield except for the 2030s. A similar precipitation pattern can be observed in the sub-basin.

Table 32 Average monthly water yield in the Yamuna sub-basin for different time periods under two climate scenarios (in mm)

Period	Hist.	RCP 4.5				RCP 8.5			
		2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	5.6	5.7	4.1	5.0	5.4	5.2	3.6	4.6	5.5
February	7.9	5.9	7.4	7.4	5.4	5.1	6.5	6.4	5.9
March	7.9	4.1	8.4	4.3	4.0	3.6	7.6	3.9	4.2
April	3.7	1.2	4.4	1.9	1.2	1.1	3.9	1.7	1.2
May	4.0	3.4	6.7	1.6	3.5	3.3	6.6	1.6	3.3
June	8.6	16.9	7.9	15.2	14.6	16.3	7.4	13.7	15.3
July	58.5	90.6	63.0	70.0	102.1	62.5	43.7	47.8	145.0
August	91.1	134.4	115.7	134.4	112.1	108.7	93.6	110.8	127.2
September	58.6	75.3	67.4	83.2	71.1	62.2	55.6	69.0	79.9
October	17.1	21.0	22.2	25.0	18.3	14.9	17.0	18.6	22.1
November	4.5	7.6	7.0	7.5	6.3	5.4	4.8	4.9	7.4
December	3.5	2.6	5.7	3.1	2.3	2.0	5.1	2.6	2.6
Wet Season	233.9	338.2	276.2	327.8	318.3	264.6	217.3	259.9	389.6
Dry Season	37.1	30.5	43.6	30.8	28.0	25.7	38.1	25.6	30.1

Table 33 Average monthly water yield changes compared with the historical level in the Yamuna sub-basin for different time periods under two climate scenarios (in mm)

Period	RCP 4.5				RCP 8.5			
	2020s	2030s	2040s	2050s	2020s	2030s	2040s	2050s
January	0.0	-1.6	-0.6	-0.2	-0.4	-2.0	-1.1	-0.1
February	-2.1	-0.5	-0.5	-2.5	-2.9	-1.5	-1.5	-2.1
March	-3.8	0.5	-3.6	-3.9	-4.3	-0.3	-4.0	-3.7
April	-2.5	0.7	-1.8	-2.6	-2.6	0.2	-2.0	-2.5
May	-0.5	2.7	-2.4	-0.5	-0.6	2.7	-2.4	-0.7
June	8.3	-0.7	6.6	6.0	7.7	-1.3	5.1	6.7
July	32.1	4.5	11.4	43.6	4.0	-14.9	-10.7	86.5
August	43.3	24.6	43.3	21.0	17.6	2.5	19.7	36.1
September	16.7	8.9	24.7	12.6	3.6	-2.9	10.4	21.4
October	3.9	5.1	7.9	1.2	-2.2	0.0	1.6	5.0
November	3.1	2.5	3.0	1.8	0.9	0.3	0.4	2.9
December	-1.0	2.2	-0.4	-1.2	-1.5	1.6	-0.9	-1.0
Wet Season	104.3	42.4	93.9	84.4	30.8	-16.6	26.0	155.7
Dry Season	-6.6	6.5	-6.3	-9.1	-11.5	1.0	-11.5	-7.0

Water availability at the district level of Yamuna is provided in **Table 34**. The results show that water availability in most of the districts located in Yamuna will increase in the future except for a small number of districts. Specifically, the water availability in Aligarh (Ya_02), Auraiya (Ya_04), Bulandshahr (Ya_07), Etawah (Ya_12), Gautam Buddha Nagar (Ya_15), Ghaziabad (Ya_16), Haridwar (Ya_18), Mathura (Ya_27) and Meerut (Ya_28) will decrease in the future compared with that in 2010.

Table 34 District-level water availability in the Yamuna sub-basin for the periods in 2010, 2030 and 2050 (MCM) under RCP 4.5

District Name	District Code	State Name	Area (km^2) in the Basin	Water 2010	Water_4.5 2030	Water_4.5 2050
Agra	Ya_01	Uttar Pradesh	2,986	520	661	600
Aligarh	Ya_02	Uttar Pradesh	1,495	248	307	239
Alwar	Ya_03	Rajasthan	4,899	763	964	1,137
Auraiya	Ya_04	Uttar Pradesh	88	22	27	21
Baghpat	Ya_05	Uttar Pradesh	1,332	440	442	587
Bharatpur	Ya_06	Rajasthan	5,051	714	900	1,036
Bulandshahr	Ya_07	Uttar Pradesh	216	33	40	30
Dausa	Ya_08	Rajasthan	2,374	425	484	605
Dehra Dun	Ya_09	Uttaranchal	2,079	1,168	1,390	1,562
Delhi	Ya_10	Delhi	1,502	379	440	505
Dhaulpur	Ya_11	Rajasthan	2,246	361	436	580
Etawah	Ya_12	Uttar Pradesh	479	117	146	115
Faridabad	Ya_13	Haryana	2,162	341	416	420
Firozabad	Ya_14	Uttar Pradesh	1,092	228	312	249
Gautam Buddha Nagar	Ya_15	Uttar Pradesh	1,302	177	194	163
Ghaziabad	Ya_16	Uttar Pradesh	580	173	172	244
Gurgaon	Ya_17	Haryana	2,007	387	469	523
Haridwar	Ya_18	Uttaranchal	288	84	94	79
Jaipur	Ya_19	Rajasthan	474	95	101	133
Jhajjar	Ya_20	Haryana	631	159	184	207
Jind	Ya_21	Haryana	1	0	0	0
Karauli	Ya_22	Rajasthan	2,998	470	578	687
Karnal	Ya_23	Haryana	859	341	352	414
Kinnaur	Ya_24	Himachal Pradesh	17	9	11	12
Kurukshetra	Ya_25	Haryana	145	57	59	70
Mahamaya Nagar (Hathras)	Ya_26	Uttar Pradesh	747	138	174	142
Mathura	Ya_27	Uttar Pradesh	3,374	433	495	383
Meerut	Ya_28	Uttar Pradesh	241	66	65	94
Muzaffarnagar	Ya_29	Uttar Pradesh	2,634	835	880	973
Panipat	Ya_30	Haryana	978	325	349	404
Rohtak	Ya_31	Haryana	801	202	234	262
Saharanpur	Ya_32	Uttar Pradesh	3,555	1,245	1,319	1,403
Sawai Madhopur	Ya_33	Rajasthan	122	19	24	27
Shimla	Ya_34	Himachal Pradesh	3,171	1,402	1,793	1,730
Sirmaur	Ya_35	Himachal Pradesh	2,325	935	1,181	1,034
Solan	Ya_36	Himachal Pradesh	190	75	98	79
Sonepat	Ya_37	Haryana	2,076	607	675	769
Tehri Garhwal	Ya_38	Uttaranchal	436	385	464	569
Uttarkashi	Ya_39	Uttaranchal	3,083	2,067	2,524	2,943
Yamuna Nagar	Ya_40	Haryana	808	321	331	390
		Total	**61,844**	**16,764**	**19,784**	**21,419**

3.1.4.2 Water demand estimation

Chambal sub-basin

Table 35 shows the water demand for six sectors in the Chambal sub-basin for the base period (2010) and two future periods (2030 and 2050, respectively). Among all the sectors, the demand from irrigation is the highest, followed by the domestic sector. The pattern of water demand is similar to the other sub-basins studied and will continue until 2050. Dominant crops which are considered to calculate the irrigation water requirement for the base period are given in **Table 5**. The water demand from irrigation will increase from 8,895 MCM in 2010 to 11,822 MCM in 2050, an approx. 30% increase. It is observed that there will be a decrease in the energy water demand due to the low number of new power plants planned in this sub-basin as well as retirement of many existing power plants in 2050, assuming lifetimes of 40 years.

Table 35 Sectoral water demand and future estimations in the Chambal sub-basin (in MCM)

Water demand	Base period (2010)	Future (2030)	Future (2050)
Domestic	725	1,082	1,359
Industry	113	181	246
Livestock	189	228	276
Irrigation	8,895	8,958	11,822
Energy	66	45	39
Environmental water requirement	125	131	172
Total	**10,112**	**10,625**	**13,914**

Damodar sub-basin

Table 36 shows the water demand from six sectors in the Damodar sub-basin for the base period and two future periods (2030 and 2050). Among all the sectors, irrigation demand is highest, followed by domestic water demand, both of which account for almost 85% of total water demand. This trend will continue until 2050. Dominant crops considered in calculating the irrigation water requirement for the base period are given in **Table 5**. The water demand from irrigation will increase from 20,281 MCM in 2010 to 26,953 MCM in 2050, which is an approx. 33% increase compared to the base period. There will be an increase in the water requirement for energy until the period of 2030 due mainly to new installations, and then a decrease from 2030 to 2050 due to the retirement of many existing power plants in the near future.

Table 36 Sectoral water demand and future estimations in the Damodar sub-basin (in MCM)

Water demand	Base period (2010)	Future (2030)	Future (2050)
Domestic	925	1,238	1,550
Industry	123	176	229
Livestock	200	242	293
Irrigation	20,281	20,423	26,953
Energy	298	408	156
Environmental water requirement	273	281	365
Total	**22,099**	**22,767**	**29,546**

Gandak sub-basin

Table 37 shows the water demand from six sectors in the Gandak sub-basin for the based period and two future periods (2030 and 2050). Among all the sectors, irrigation demand is the highest which will increase by 25% by 2050. Dominant crops considered to estimate the irrigation water requirement for the base period is listed in **Table 5**. In 2050, the water demand from irrigation will reach to 30,152 MCM. Except for irrigation, there will be a high demand from the domestic sector which will increase by almost 2 times in 2050. There will be a high increase in the water demand from the energy sector from 71 MCM in 2010 to 182 MCM in 2050, which is about 2.5 times of the level in the base period. It indicates that there will be more planned power plants to be built in this sub-basin.

Table 37 Sectoral water demand and future estimations in the Gandak sub-basin (in MCM)

Water demand	Base period (2010)	Future (2030)	Future (2050)
Domestic	1,375	2,095	2,816
Industry	139	221	302
Livestock	218	263	318
Irrigation	22,688	22,847	30,152
Energy	71	253	182
Environmental water requirement	306	321	422
Total	**24,796**	**26,000**	**34,193**

Yamuna sub-basin

Table 38 shows the water demand for six sectors in the Yamuna sub-basin for the base period and two future periods (2030 and 2050). Among all the sectoral water demand, irrigation demand is the highest, which will continue until 2050. Dominant crops considered to estimate the irrigation water requirement for the base period are listed in **Table 5**. In 2050, the water demand from irrigation will reach 31,148 MCM, about 1.35 times the level in the base period. Except for the irrigation demand, there will be high demand from domestic and industrial sectors, which will increase in the future. The water demand from these two sectors will increase by about two times compared with levels in the base period. There will be no apparent changes in the water demand from the energy sector in Yamuna – in other words, the present situation will remain unchanged, which indicates that new installations mainly comprise replacements of retired power plants in this sub-basin.

Table 38 Sectoral water demand and future estimations in the Yamuna sub-basin (in MCM)

Water demand	Base period (2010)	Future (2030)	Future (2050)
Domestic	**2,291**	**3,655**	**5,018**
Industry	446	756	1,067
Livestock	333	403	487
Irrigation	23,437	23,601	31,148
Energy	102	102	102
Environmental water requirement	333	356	473
Total	**26,940**	**28,872**	**38,294**

3.1.4.3 Power plant water demand

We conducted field surveys in the selected power plants to collect the primary data on water use intensity. Power plants were selected based on the fuel types, power generation technologies and type of cooling systems, i.e., open-loop cooling system, close-loop cooling system and dry cooling system. The survey results indicated that selection of cooling technologies has a great impact on the water demand of power generation. The water use intensity of power plants equipped with the open-loop cooling system is about 70 m^3/MWh (Coal 4), while that of power plants installed with the close-loop cooling system ranges from 3.4 m^3/MWh to 5.0 m^3/MWh (Coal 1-3). We also observed that coal-based power plants require more water than gas-based power plants (see **Figure 13**).

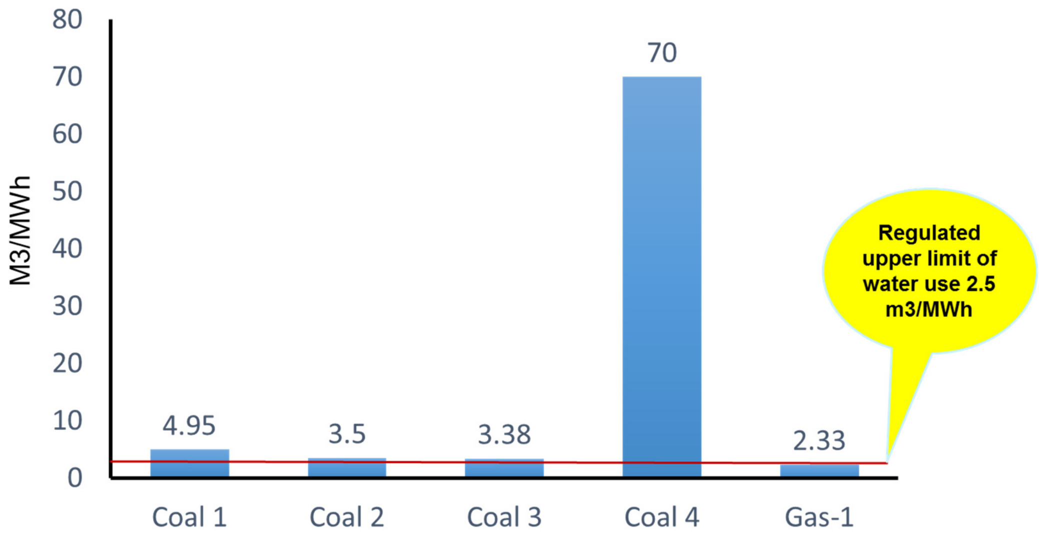


Figure 13 Water use intensity in the existing power plants

We also found that coal-based power plants account for the majority of existing installed thermal power capacity in four sub-basins. In Damodar and Gandak, all the installed capacity is based on coal (**Figure 14**).

Among the four sub-basins, Damodar has the largest thermal power capacity (17,956 MW). As a result, the water demand from power generation is the highest among the four sub-basins. This situation will continue until 2030. In 2030, the water demand from thermal power generation will reach 408 MCM in Damodar (see **Figure 15**). Gandak has the second highest water demand from thermal power generation and in 2030 thermal power generation will require 253 MCM of water. In contrast, estimates show thermal power generation will reduce in Chambal and Yamuna in 2030.

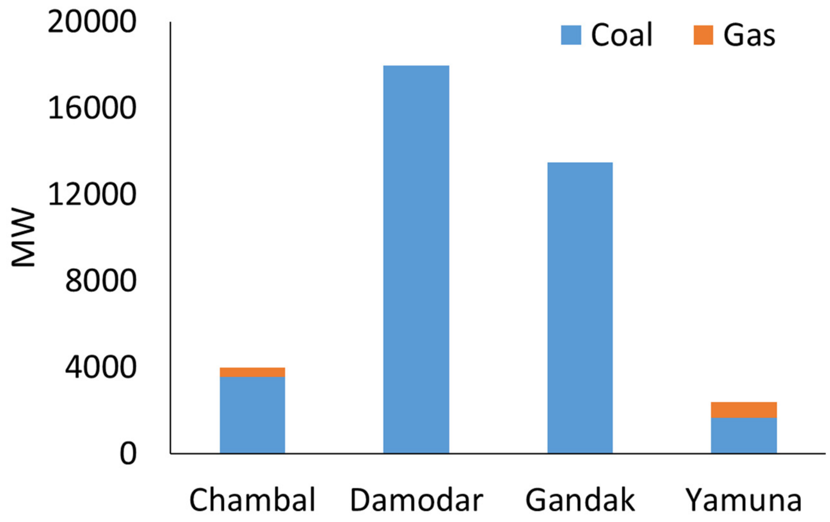


Figure 14 Installed thermal power capacity in four sub-basins

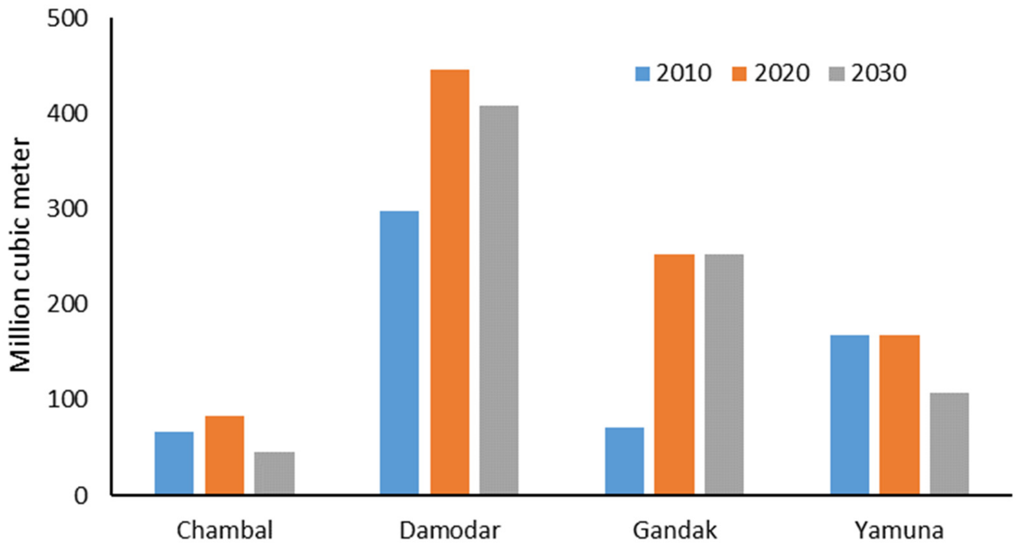


Figure 15 Water demand from energy generation in four sub-basins

3.1.4.4 Water supply-demand balance at the sub-basin level

Results of the assessment of water supply-demand balance are shown in **Table 39**. The results show that Chambal and Damodar will have surplus water over all time periods. Chambal will have the largest water surplus among the four studied sub-basins. The amount of water surplus in Damodar will reduce from 8,072 MCM in 2010 to 6,872 MCM in 2050. The situation of water deficit will become more serious in both Yamuna and Gandak. In particular, the water deficit in Yamuna will increase by 86%.

Table 39 Water supply-demand balance assessment under RCP 4.5 (in MCM)

	2010			2030			2050		
Sub-basin	Supply	Demand	**Balance**	Supply	Demand	**Balance**	Supply	Demand	**Balance**
Chambal	28,637	10,112	**18,525**	34,701	10,625	**24,076**	36,722	13,914	**22,809**
Damodar	30,171	22,099	**8,072**	32,720	22,767	**9,953**	36,418	29,546	**6,872**
Gandak	23,456	24,796	**-1,340**	33,433	26,000	**7,433**	28,407	34,193	**-5,786**
Yamuna	16,764	25,791	**-9,026**	19,784	28,872	**-9,088**	21,419	38,294	**-16,875**

3.1.4.5 Assessment of the water risks for future power generation

The maps of water supply-demand gap ratios, or the ratio of water supply-demand balance to total water supply (see classification in **Table 6**), were created for 2010, 2030 and 2050 using ArcGIS, which provides a spatial distribution of water supply-demand balance at the district level for four sub-basins.

Chambal sub-basin

Based on the three maps (2010, 2030 and 2050) of the water supply-demand gap ratios (**Figure 16**), it can be seen that only a small part of the Chambal sub-basin located in the upper part of the area will face high water stress (in red) and some parts will have moderate water stress (in orange). The sub-basin will mainly have water surplus (in yellow), meaning that there will be more room for installation of new thermal power capacity in this sub-basin, particularly in the middle and lower part of the sub-basin. However, it can also be observed that existing power plants are located in the water-stressed region and depend on water resources from the upstream area.

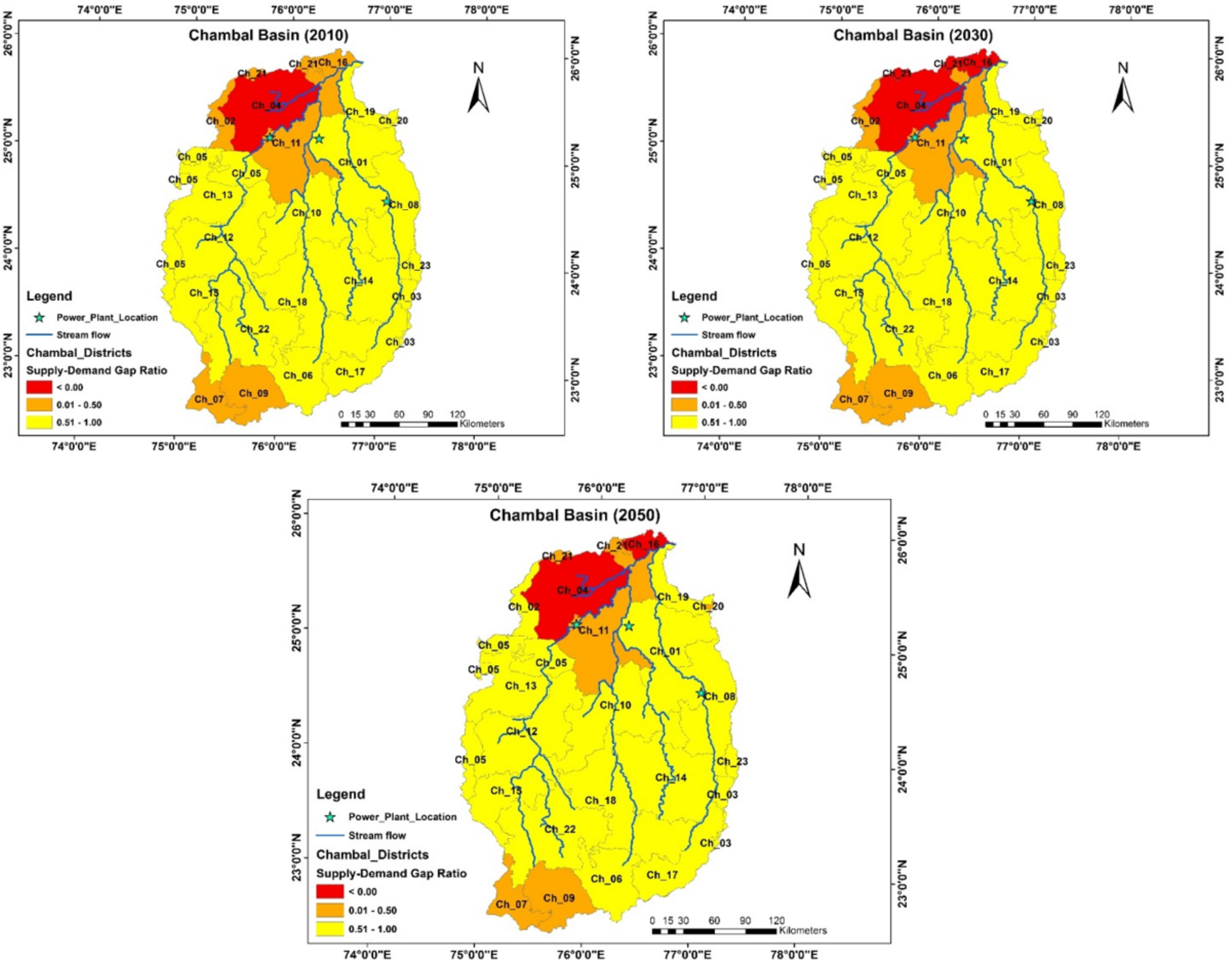


Figure 16 Water risk assessment for power plants in the Chambal sub-basin

Damodar sub-basin

Based on the three maps created for the water supply-demand gap ratios, it can be seen that only a small part of the Damodar sub-basin located in the lower part of the sub-basin will face water stress (in red). In addition, the area of the yellow part and the orange parts are about the same size. There is little change in 2030 compared with 2010. In the period of 2050, some areas will change from yellow to red (see **Figure 17**), which means that existing power plants located in these areas will face water stress in the future. In the upper part of the sub-basin, there will be sufficient water for existing power plants and new thermal power plants.

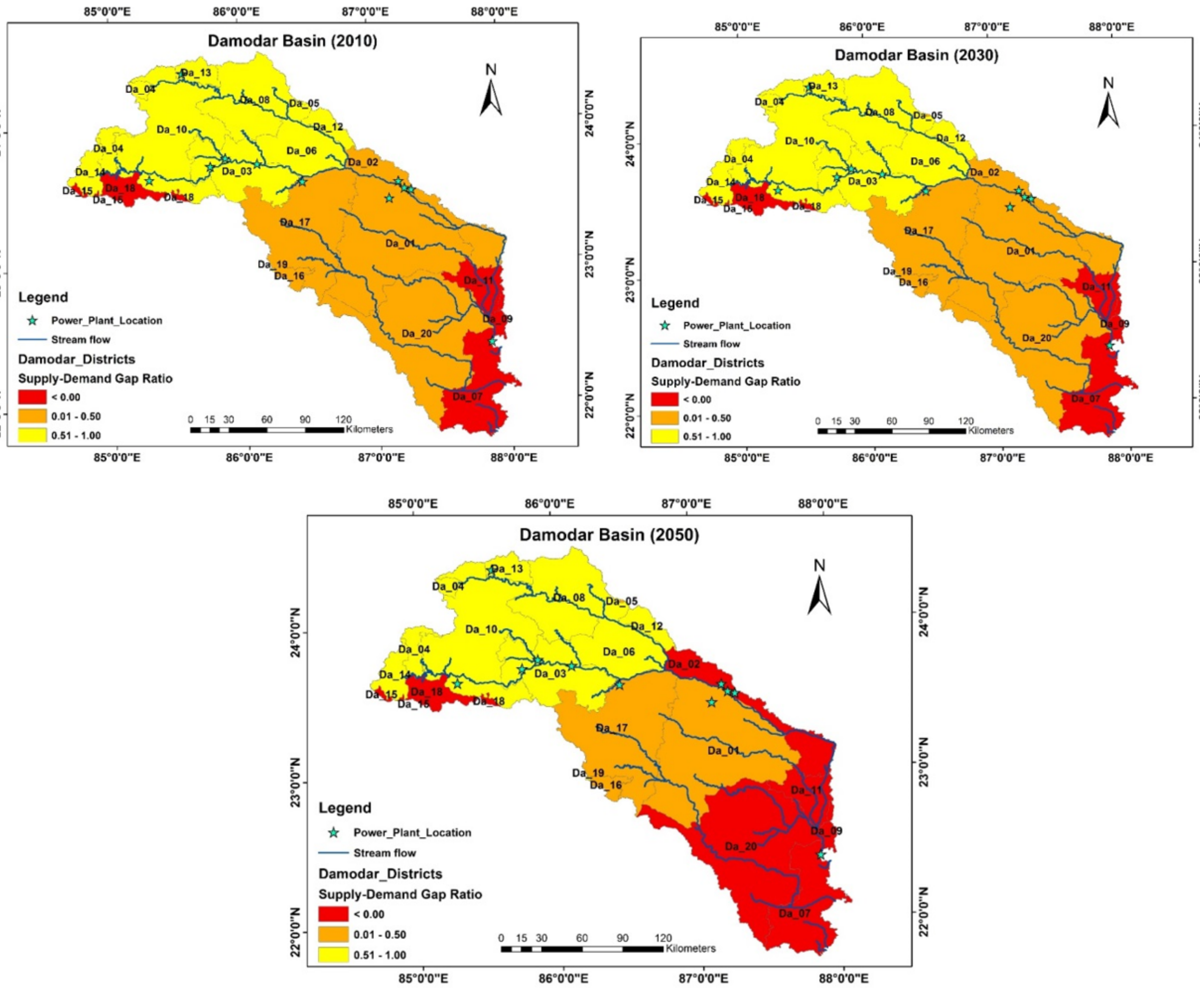


Figure 17 Water risk assessment for power plants in the Damodar sub-basin

Gandak sub-basin

All three maps for the Gandak sub-basin show different patterns of distribution of water supply-demand balance (**Figure 18**). It can be seen that from 2010 to 2030, some areas will change from red to orange and some areas will change from orange to yellow, indicating water stress will be reduced to some extent in this sub-basin up to 2030. However, from 2030 onwards, many areas will change from orange or yellow to red, indicating that existing power plants located in these areas will face water stress in the future. Except for Chatra District (Gd_5), all other districts in Gandak will face severe water stress or moderate water stress in 2050, which means that both existing and planned power plants will face high water risks in Gandak in the future.

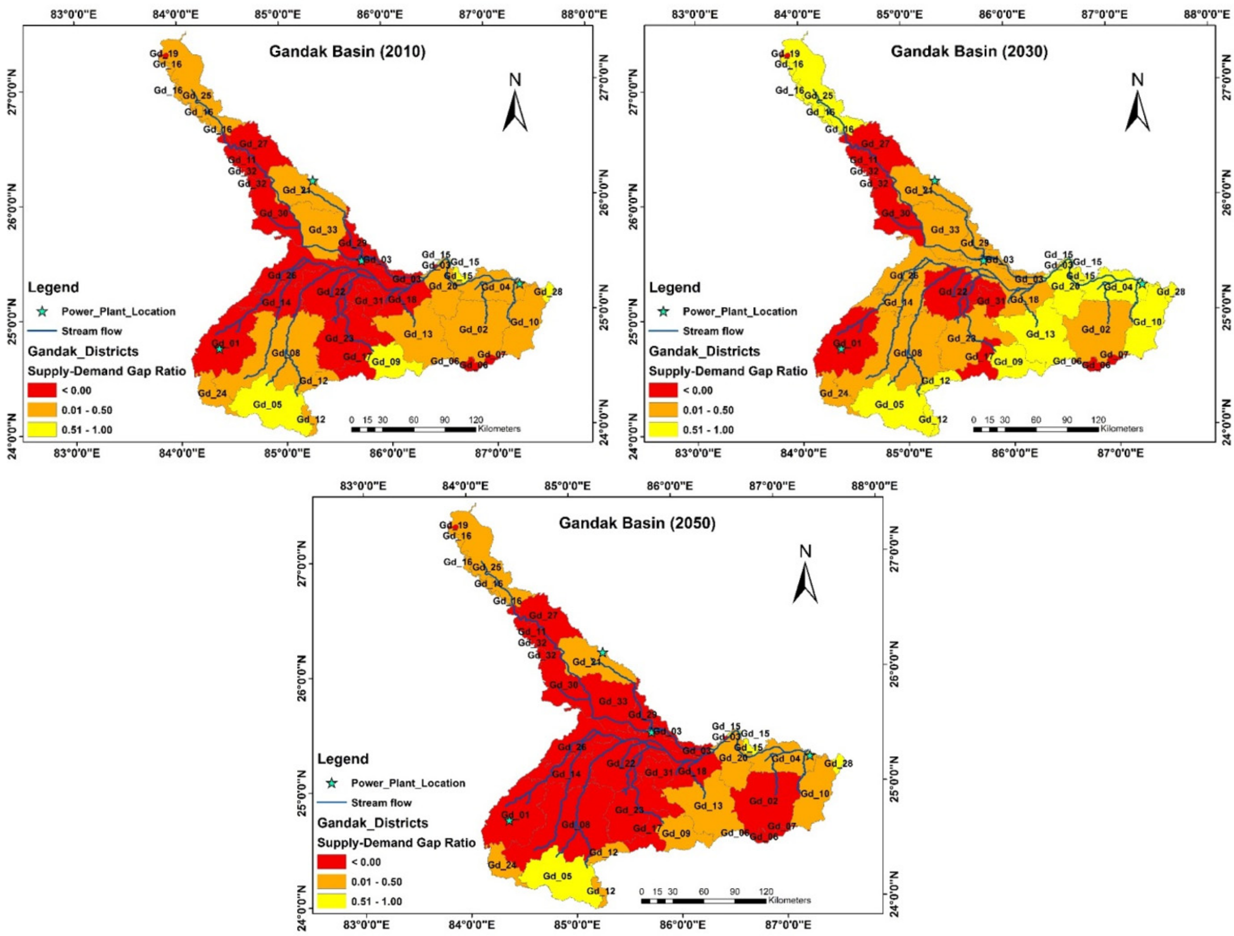


Figure 18 Water risk assessment for power plants in the Gandak sub-basin

Yamuna sub-basin

All three maps of the Yamuna sub-basin show similar patterns of water supply-demand balance, with about 75% of the area facing serious water stress (**Figure 19**). Many existing power plants are located in the water-stressed area. It is clearly indicated that there is insufficient water in this sub-basin to support new thermal power plants, particularly in the red areas. The upper part of this basin may have enough water to support existing thermal power plants.

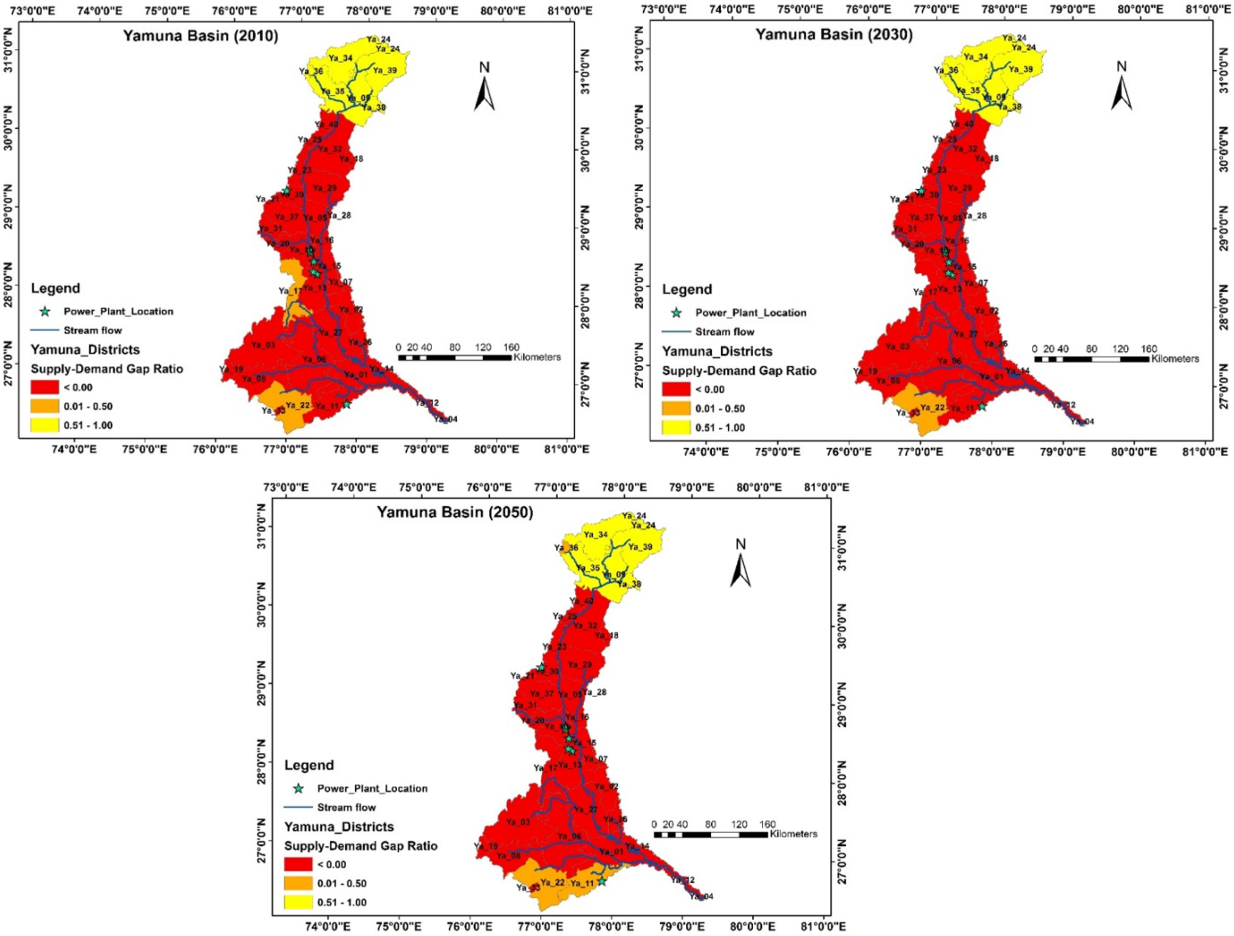


Figure 19 Water risk assessment for power plants in the Yamuna sub-basin

3.1.5 Web tool for water-energy nexus assessment and energy planning

To support the spatial analysis of water-energy nexus and energy planning in India, we developed a free on-line tool on Water-Energy Nexus Assessment to visualise the data used in the hydrological modelling and the spatial distribution of the results at present and in the future in maps, including water supply, water demand, water supply-demand balance and water stress for existing and planned thermal power installations.

The structure of the web tool interface includes the following:

- Project
- Methodology
- Maps/Data
- Simulation
- Publications

The Project tab introduces the background to the project, importance of understanding the water-energy nexus and the project objective. Information about the project members and collaborating institutions is also provided.

The Methodology tab presents the overall analytical framework for the integrated assessment of the water-energy nexus in the Ganges sub-basins. The Water Supply Module, Water Demand Module, Water Supply-Demand Balance Assessment, Water-Energy Nexus Assessment, the methodologies used for conducting different modules and the links between the modules are introduced.

The Maps/Data tab provides the spatial data and modelling results on water supply and water demand projections, which can be visualised in maps at the district level for the four selected sub-basins, i.e., Chambal, Damodar, Gandak and Yamuna. From the supply side, key data used for hydrological modelling, including land cover, precipitation and evapotranspiration, can be visualised (see **Figure 20**). The spatial distribution of water availability resulting from hydrological modelling can be shown using maps (see **Figure 21**). From the demand side, water demand for irrigation, livestock, domestic use and industry are provided.

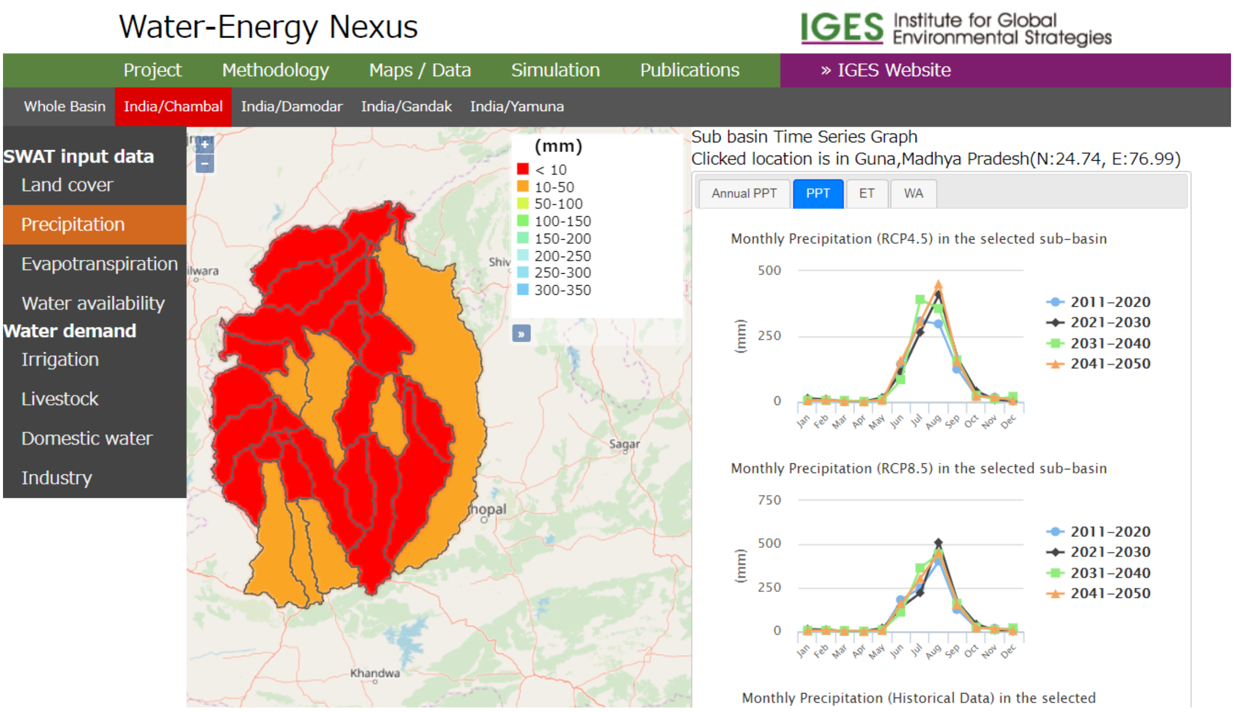


Figure 20 Screenshot of the visualisation of the spatial distribution of precipitation

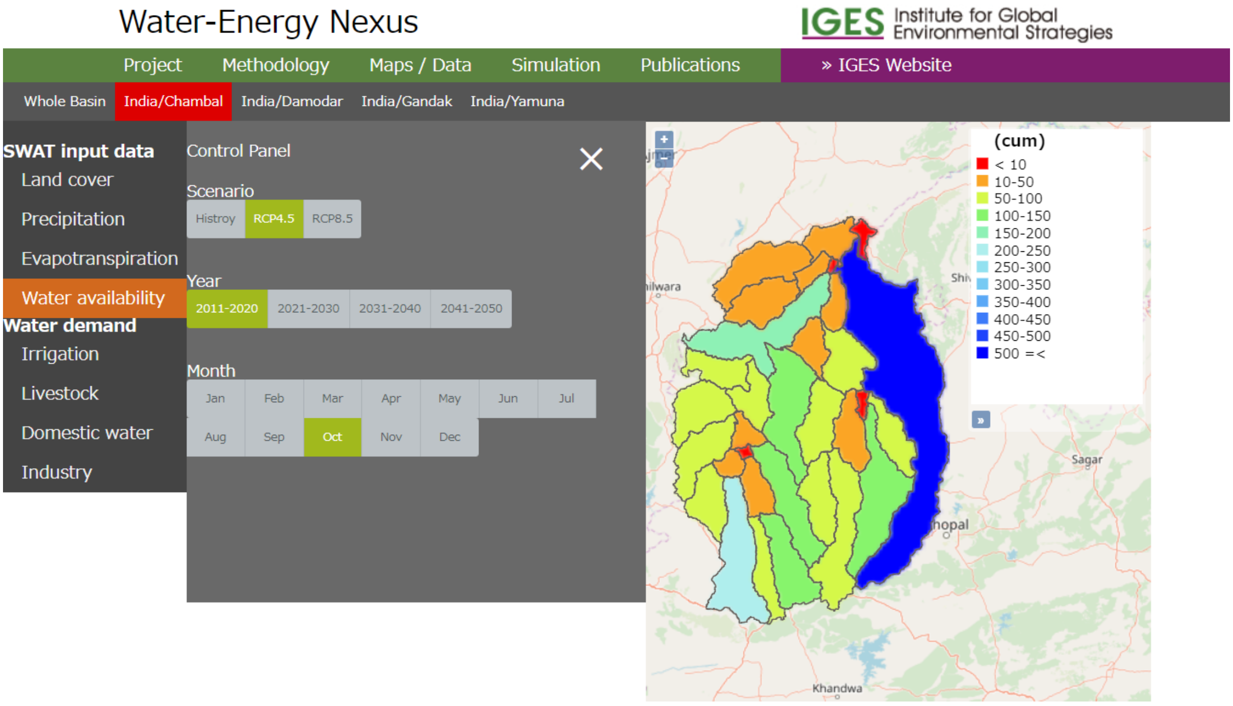


Figure 21 Screenshot of the visualisation of the spatial distribution of water availability in Chambal

The Simulation tab provides the simulation results for water supply-demand balance and water risks of existing and newly planned thermal power plants. Through these maps, users can easily visualise where water surpluses can satisfy water demands from thermal powper generation and where water stress may occur, indicating a challenge for installation of new capacity (see **Figure 22**), etc. These maps can help decision makers in effective energy planning and inform investors about water risks when investing in new thermal power plants in locations where water is scarce.

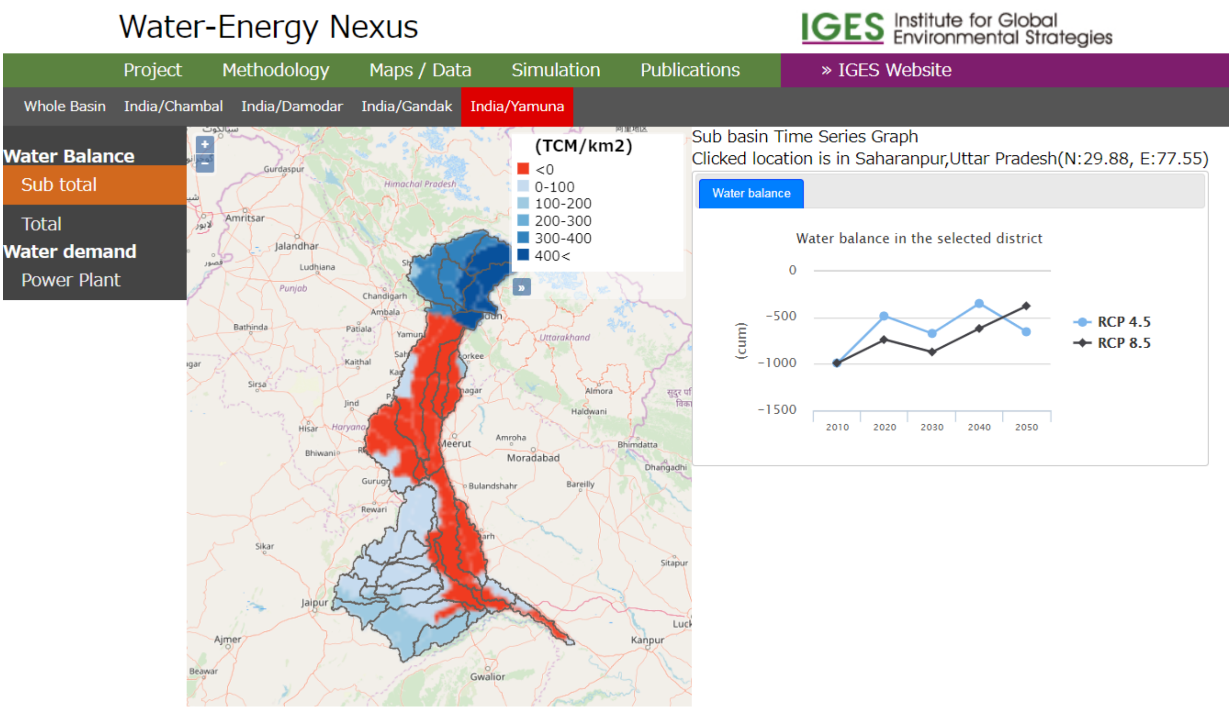


Figure 22 Screenshot of the visualisation of the spatial distribution of water supply-demand balance in Yamuna

3.1.6 Conclusions

As the most populous river basin in India, the Ganges basin provides water for drinking, irrigation, industrial use and power plant cooling. Changes in the water availability in the basin will impact economic development and people's lives. From the supply side, results from the hydrological model, SWAT, show that the overall annual water availability in the four selected sub-basins will increase in the future, particularly in Chambal, Damodar and Gandak. However, the annual water availability in Yamuna will decrease, particularly in the far future (2071-2100) under RCP 4.5.

However, water availability will not be evenly distributed throughout the year and will vary from month to month depending on the physical conditions such as precipitation, evapotranspiration and surface runoff, etc. The water availability in Damodar and Gandak will increase in both the dry and wet season; however, it will decrease in Chambal and Yamuna in the dry season. In addition, at the district level, water availability in most districts in the four sub-basins will increase; however, some districts will see their water availability decrease in either 2030 or 2050.

From the demand side, future water demand will increase due to population growth, industrial development, and increase in power generation and irrigation. Out of the four sub-basins, Chambal will have the smallest water demand and Yamuna will have the largest. In all four sub-basins, irrigation water demand will dominate, followed by domestic water demand, and this trend will continue until 2050. In particular, Yamuna will have the largest irrigation water demand and the largest domestic water demand among the four sub-basins, followed by Gandak which has the second largest water demand from both irrigation and the domestic sector. Damodar has the largest energy water demand, followed by Gandak. The energy water demand will decrease in Chambal and Damodar and will remain at the same level in Yamuna; however, it will greatly increase in Gandak.

For water supply-demand balance at the sub-basin level, Chambal and Damodar will have water surplus in the future. Chambal will have the largest water surplus among the four selected sub-basins. Yamuna and Gandak will face serious water deficit in the future, particularly the Yamuna sub-basin.

At the district level, in general there will be more districts that will face water stress in the future, particularly in 2050. The water stress situation varies among the sub-basins. In Chambal and Damodar, particularly in Chambal, most districts will have water surplus, which will not only satisfy the water demand from operating existing and planned thermal power plants, but can also support additional thermal power installations in the future. However, in Gandak and Yamuna, most districts will face water deficit in the future and existing and planned thermal power plants will face high water risks. Particularly in Gandak, the many newly planned thermal power installations will face severe water shortage.

Spatial distribution of the water supply-demand balance at the district level can be used as an important indicator to assess the location and technologies for future power plants. District-level analysis indicates that many existing power plants are located in water-stressed areas, and many newly planned thermal power plants will be installed in areas with high or moderate water stress. This implies that these power plants will face high risks of water shortage in the future, which may force some power plants to shut down, particularly in the dry season. The results showed that most existing power plants as well as the newly planned power plants in Yamuna and Gandak, a few plants in the upper part of Chambal and a few plants in the middle and right part and the lower part of Damodar will face high risks of water shortage. Related governmental organisations such as the development and planning organisation and the energy planning organisation as well as investors need to be cognisant of this situation and make relevant decisions to prevent new installations being locked in in water-stressed locations. If new capacity has not yet been installed, alternative locations with water surplus should be considered. Among the four sub-basins, most of the districts in the middle and lower part of Chambal and the districts located in the upper part of Damodar (the yellow area) can be considered as appropriate alternative locations, from a water availability perspective.

The results of the project and the Water-Energy Nexus Assessment web tool can inform relevant governmental decision makers, energy planners and investors about where the risks of water shortage lie for existing and planned power plants, and thus help them identify suitable locations for new thermal power installations to ensure sufficient water is available for cooling operations.

3.2 Case study in Bangladesh

3.2.1 Introduction

Bangladesh has set up a goal to become a middle-income country by 2021. According to the World Bank's latest estimates, the economic performance of Bangladesh has been continuously improving and the country has become a lower-middle income country. From the experiences of other countries, demands for satisfying basic needs such as food, water and energy will likely increase sharply in Bangladesh. Bangladesh identified its top priorities in Vision 2021, including ensuring food security, sustainable agriculture, water security and energy security (Planning Comission, 2012).

Agricultural development is critical to ensure food security for 160 million people in Bangladesh. Agriculture also plays an important role in the country's economy and changes in agriculture development will have economy-wide impacts. In fiscal year 2013-2014, agriculture contributed to 16.33% of the national GDP. Recognising the importance of agriculture, the Government of Bangladesh prioritised agriculture development to help achieve zero poverty and become a middle income country.

Agriculture in Bangladesh is dominated by water-intensive rice cultivation, which accounts for 81% of the total cropped area. To ensure food security for all the population, low-yield rain-fed rice cultivation has been substantially shifted to dry-season irrigated rice cultivation with considerable environmental costs such as groundwater degradation due to overexploitation. Such a shift towards high-yield irrigated rice cultivation has resulted in high cost of production, high water consumption, high fertiliser requirement and high electricity and diesel used for pumping the irrigation water.

Agriculture needs to grow further from its present rate of around 3.5% annually to feed an increasing population, yet faces several challenges to achieving this continuous growth, including water shortage, particularly in the dry season, as well as land area constraints, soil degradation due to salinity intrusion and possible impacts from climate change.

Governmental supportive policies such as providing subsidies to irrigation water pumping resulted in an increase in irrigation area from 26% in 1990 to 45% in 2010. In Bangladesh, 90% of the irrigation water comes from groundwater. To ensure food security, it is expected that the irrigation area will increase in the future, which however will threaten the sustainable use of groundwater resources. Similarly, water demand from other users will increase in the future, which will intensify competition among users, the total demand of which will be about 147 BCM against a total supply of 90 BCM (NWMP, 2004).

Unsustainable expansion of groundwater-based irrigation for rice cultivation will also impact energy security. During the dry season, 1.5 million pumps are operated to irrigate rice fields, which consumes 800 million litres of diesel and 760 MW of electricity. Increasing the irrigated area and associated energy use will impact on the energy use of other users thus requires more electricity generation capacity to be installed in the future.

As industrialisation has been recognised as one of the important drivers of economic growth, some prospective plans for achieving Vision 2021 have prioritised industrial growth in order for the country to be a middle income country by 2021. Although industrial growth shows a declining trend in recent years, its share in the GDP increased from 26.5% in FY2009-2010 to 29.6% in FY2013-2014. It is projected that the industrial sector will account for 37% of national GDP in the future. Rapid industrialisation will not only increase water demand but also increase electricity demand.

To support irrigation-based agriculture production and industrial development, the country needs to close the gaps between electricity supply and demand. At present, 60 million people do not have direct access to grid electricity and 90 million people lack reliable power supply. Shortage of electricity supply has severe consequences for economic growth. Realising these challenges, the Government of Bangladesh has set electricity generation as a priority sector. It is projected that electricity generation capacity will grow to about 39,000 MW by 2040, which is about three times more than the current capacity. It is likely that thermal power generation will continue to dominate the fuel mix, and coal-based thermal power plants (TPP) will take the lead over gas-based TPP in the future. As coal-based TPP is a water-intensive technology for electricity generation, great pressure will be placed on freshwater resources unless appropriate advanced cooling technologies are adopted by the power plants.

Impacts of climate change will further intensify the pressure on water resources. Global climate change will cause major changes in the seasonal and spatial patterns of water availability, as well as degradation of water quality due to saline water intrusion. As a result, the economic development of Bangladesh will be affected adversely.

Nationwide water availability may become a major constraint for future economic development in Bangladesh and the country may not be able to meet increasing demands for water to achieve its economic growth anticipated based on Vision 2021.

Lutz and Immerzeel (2013) studied water availability for the Upper Indus, Ganges, Brahmaputra, Salween and Mekong River Basins. They found that in the upper Ganges the stream flow is dominated by the rainfall runoff (66%), with 20% of the stream flow contributed from melt glacier. It is likely that the total runoff will increase by 1% to 27% by 2050. They also found that the share of melt glacier will decrease and the share of rainfall runoff in the total runoff will increase.

Whitehead et al. (2015) assessed future changes in water flow and water quality in the Ganges, Brahmaputra and Meghna river systems under different climate conditions by using the INCA-N model. This study selected three model realisations from 17 perturbed model runs of the global and regional climate models of the Met Office Hadley Centre to evaluate the range of potential climate change effects. The simulation results indicated a significant increase in flow in the monsoon during the 2050s and 2090s, which will increase flooding risk. The simulation also showed that low flows would further fall with longer drought seasons, which may lead to negative impacts on water supply, irrigated agriculture and intensity of saline water intrusion.

Ahmed et al. (2015) studied the impacts of climate change on water availability in the Ganges basin using SWAT. Temperature and precipitation data from 9 GCMs and the two Special Report on Emissions Scenarios (SRES) are used together with various input data. They found that the annual flow generated from the Ganges basin is 361,593 Mm^3, and point out that water availability will decrease during the dry period and increase during the monsoon period. They conclude that the average annual flow volume would increase 22% by 2030, 26% by 2050 and 19% by 2080 for A1B scenarios.

Siderius et al. (2015) found that the actual snowmelt contribution to the discharge in the Ganges basin remains conjectural under both present and future climate conditions. As snowmelt is likely to be perturbed by the global warming, four hydrological models appropriate for the coupling with the regional climate models were used to provide the baseline estimate of the snowmelt contribution to the flow at the seasonal and annual timescales. They estimated the contribution of snowmelt to overall runoff of the basin at between 1% and 5%, and also found that snowmelt was significant in spring, a period when other sources of runoff are scarce.

The objective of this case study is to inform relevant decision makers and other stakeholders of the state of future water availability and potential water risks for existing and future thermal power generation by assessing the current and future water availability of the Ganges basin in Bangladesh's territory under two climate scenarios, RCP 4.5 and RCP 8.5, and assessing the water-energy nexus for future power development plans of Bangladesh.

3.2.2 Methodology

The part of the Ganges basin within Bangladesh covers an area of 40,450 km^2, about 27% of the total area of Bangladesh. This vast area is inhabited by 130 million people, or a quarter of the country's total population. More than 60% of the area is under cultivation. The part of the Ganges basin in Bangladesh comprises 35 districts (see **Figure 23**). **Table 40** gives the name, area and population of these districts.

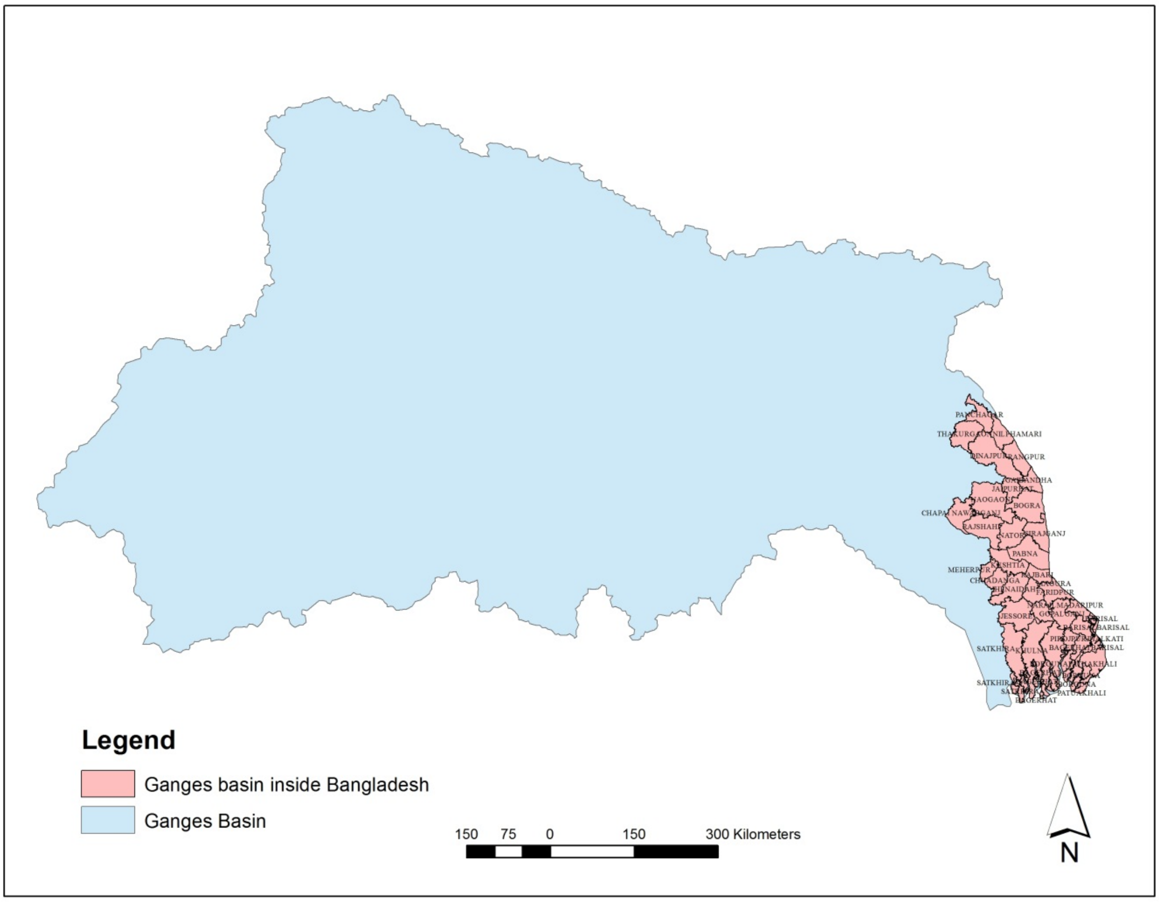


Figure 23 The Ganges basin and its part inside Bangladesh

Table 40 List of the districts of Bangladesh in the Ganges basin (BBS, 2012)

No.	Name of the district	Area (km^2)	Population
1	Panchagar	1,387	987,644
2	Nilphamari	1,219	1,834,231
3	Thakurgaon	1,815	1,390,042
4	Dinajpur	3,463	2,990,128
5	Rangpur	1,367	2,881,086
6	Gaibandha	938	2,379,255
7	Jaipurhat	965	913,768
8	Naogaon	3,447	2,600,157
9	Bogra	2,583	3,400,874
10	Chapainawabganj	1,729	1,647,521
11	Sirajganj	1,484	3,097,489
12	Rajshahi	2,375	2,595,197
13	Nator	1,912	1,706,673
14	Pabna	2,351	2,523,179
15	Kushtia	1,685	1,946,838
16	Meherpur	709	655,392
17	Rajbari	9,430	1,049,778
18	Chuadanga	1,225	1,129,015
19	Jhenaidah	1,942	1,771,304
20	Faridpur	1,352	1912969
21	Magura	1,044	918,419
22	Madaripur	795	1,165,952
23	Shariyatpur	51	1,155,824
24	Jessore	2,528	2,764,547
25	Gopalganj	1,544	1,172,415
26	Narail	964	721,668
27	Barisal	1,768	2,324,310
28	Khulna	3,526	2,318,527
29	Bagerhat	3,587	1,476,090
30	Satkhira	3,305	1,985,959
31	Pirojpur	1,196	113,257
32	Jhalkati	747	682,669
33	Bhola	6	1,776,795
34	Patuakhali	1,866	1,535,854
35	Borguna	1,266	892,781

There have been significant changes in land use in the Ganges basin inside Bangladesh. Islam et al. (2015) studied temporal variations in agriculture land use changes and its implications for ecosystem services in the Ganges basin inside Bangladesh. It was found that agricultural land has been decreasing over time and wetlands have been increasing rapidly due mainly to the growing popularity of saltwater shrimp farming. In the past 28 years, agricultural land has been reduced by about 50%, while wetlands have increased by more than five times. Settlements and other land use types have also increased to nearly 5%. There is an increasing trend of shrimp and fish production in the study area. These findings suggest that there are significant linkages between agricultural land use and ecosystem services in the Ganges basin inside Bangladesh.

3.2.2.1 Water availability assessment

The SWAT model is used in this study to predict the impacts of land use changes on water, sediment and chemicals in large and complex watersheds with different soil types, land use and management conditions over long periods of time. The model has been developed by following five sequential steps: (i) watershed delineation; (ii) analysis of the hydrologic response units (HRUs); (iii) definition of the weather data; (iv) editing the inputs to the SWAT model, and (v) model simulation. **Figure 24** shows a schematic diagram of the SWAT model.

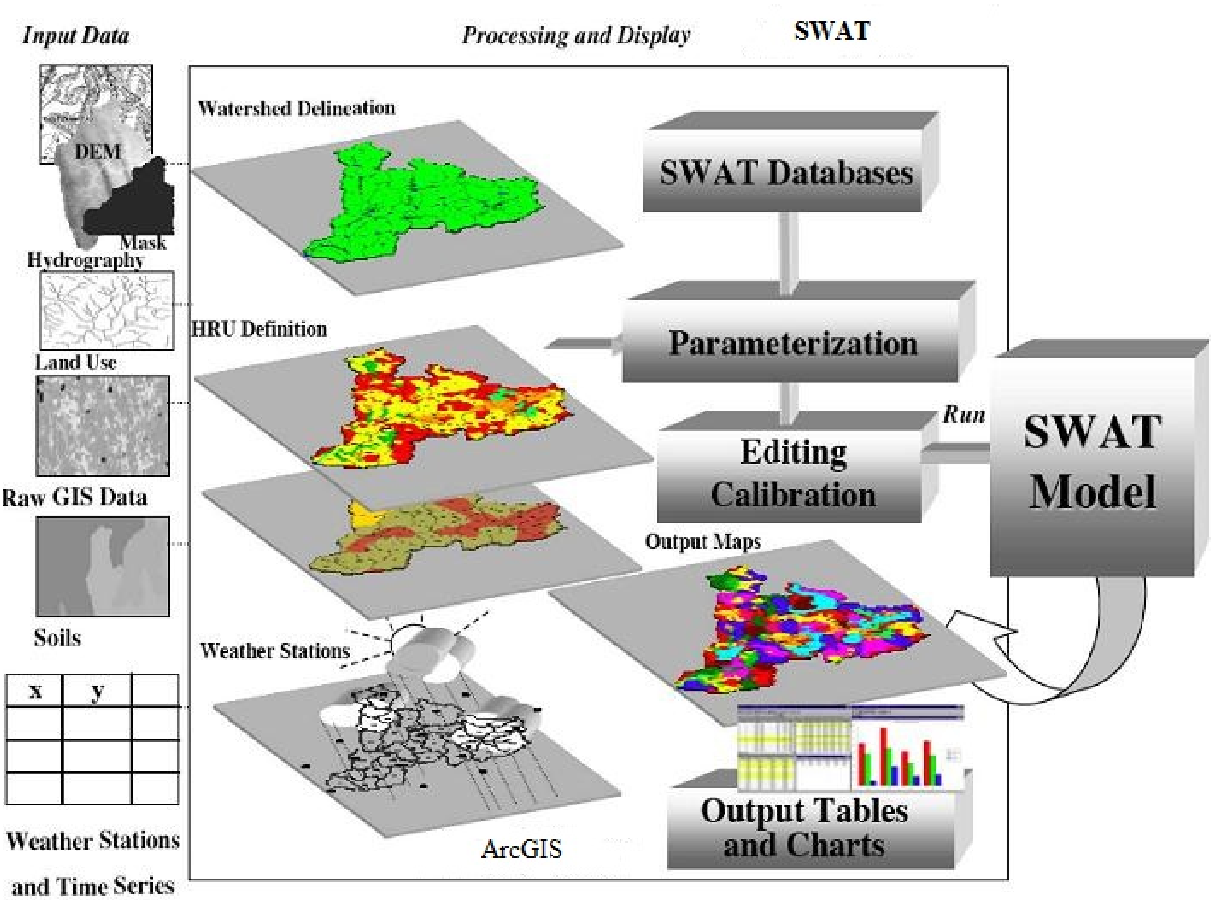


Figure 24 Schematic diagram of the SWAT model

Watershed delineation is accomplished using the automatic watershed delineation tool of SWAT 2012 by using the 90 m Digital Elevation Model (DEM) of the Shuttle Radar Topography Mission (SRTM). After watershed delineation, the Ganges basin was divided into 124 watersheds (**Figure 25**).

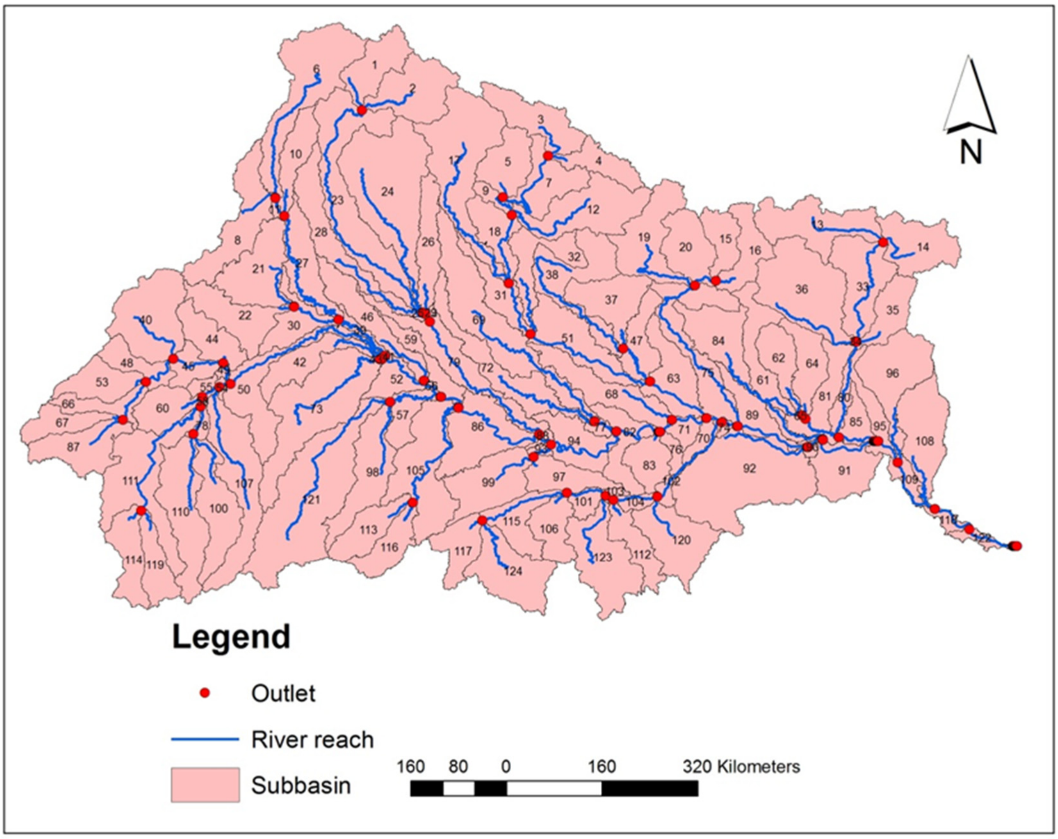


Figure 25 Delineated watersheds of the Ganges basin

The next step of the model setup is to define the HRUs. One HRU is a unique combination of land use, soil and slope. The overlay of 22 land use classes, 69 soil types and 3 slope classes for the Ganges basin resulted in 1,404 HRUs. Daily precipitation and maximum and minimum air temperatures have been taken for the period from 1998 to 2013. Available information from 44 reservoirs has been considered for the development of the model (**Figure 26**).

Efforts have been made to assess water availability using newly introduced climate scenarios RCP 4.5 and RCP 8.5. Four different types of GCMs data have been selected for the entire Ganges basin to assess the water availability under scenarios RCP 4.5 and RCP 8.5.

To describe the distribution of precipitation, SWAT provides two options: a skewed normal distribution and a mixed exponential distribution. In this study, the skewed normal probability distribution function was selected. The SWAT tool uses Manning's equation to calculate the rate and velocity of flows (Winai et al., 2013). Flows are routed through the channel network using the variable storage routing method. For estimating the runoff, the curve number method of the Soil Conservation Service has been used and the variable Curve Number for the moisture condition is selected. The Hargreaves method has been used to calculate the potential evapotranspiration, which requires less weather parameters (Neitsch et al. 2011).

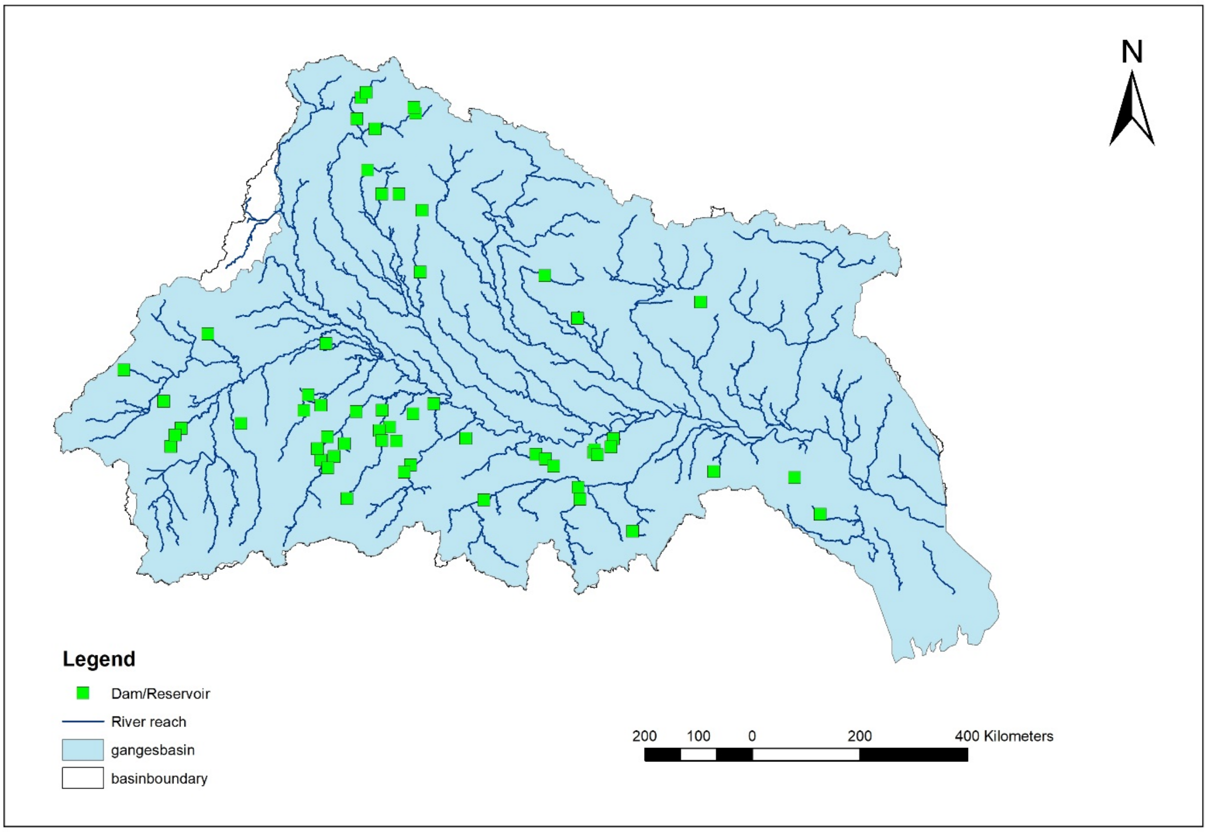


Figure 26 Location of major reservoirs in the Ganges basin

Input data to the hydrological model

Like other hydrological models, the SWAT model needs various data as the inputs to the model setting-up, calibration and validation, etc. DEM, land cover/land use, soil types, different hydro-meteorological data are the major inputs to the SWAT Model.

<u>Digital Elevation Model</u>

DEM is used to delineate sub-watersheds which are used as the inputs to the hydrological model. SRTM DEM with a geometric resolution of 90 m is used for this study. Fourteen 5 degree by 5 degree tiles were downloaded from http://srtm.csi.cgiar.org/ and merged to prepare the DEM of the whole Ganges basin. Sinks were first identified and then filled up to produce seamless DEM. **Figure 27** shows the derived DEM of the Ganges basin. The middle part of the basin mostly comprises floodplain, compared to the upper part of the basin, where the Himalayan ranges are located.

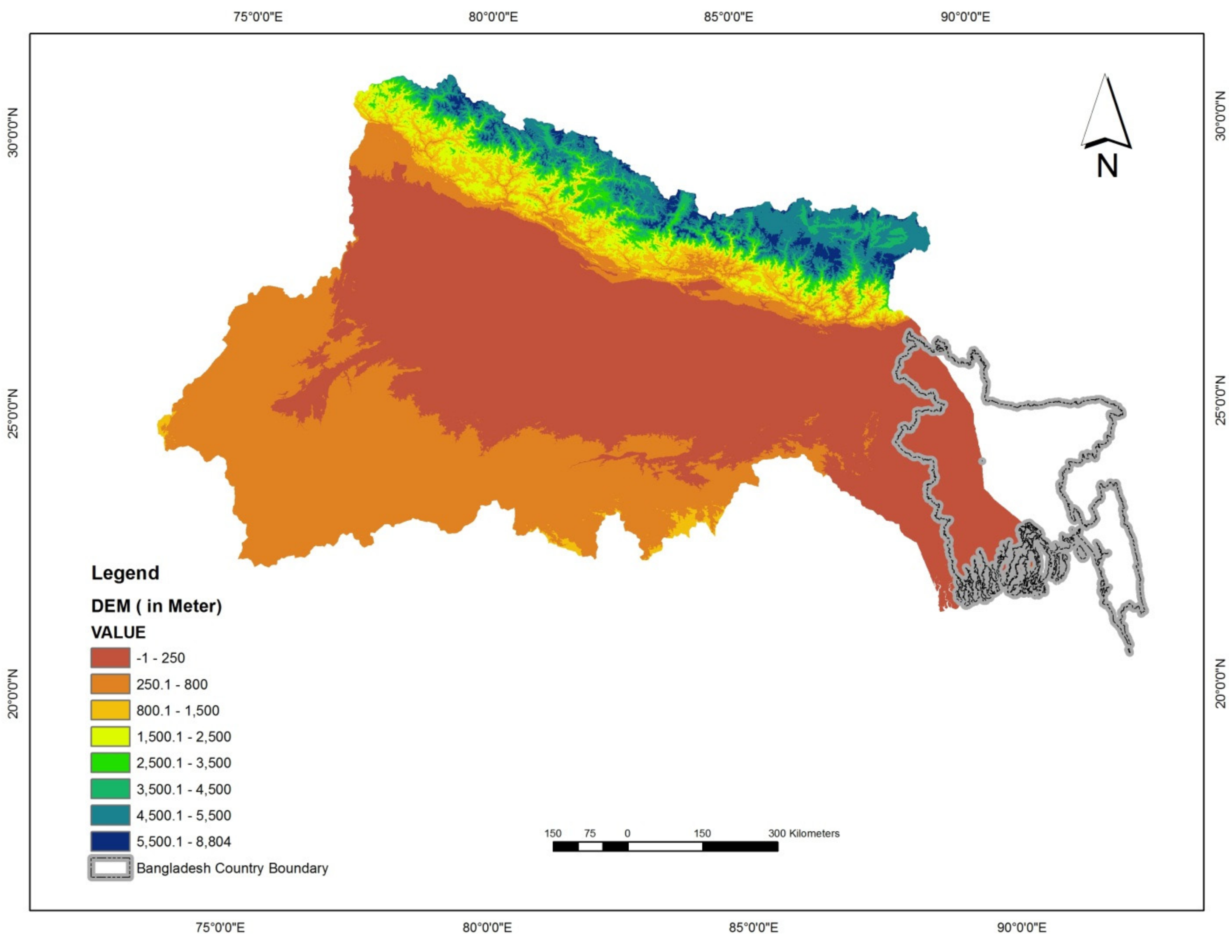


Figure 27 DEM of the Ganges basin

<u>Soil data</u>

Soil data is an important input to the SWAT model. The FAO-UNESCO (1977) Soil Map of the World was used which is available at http://www.fao.org/soils-portal/. This is a digitised soil map of the world at 1:5,000,000 scale. The map is in a 'shape file' which contains several fields, including a sequential code number (ranges from 1 to 6,999) for each soil mapping unit. A description of one FAO soil type (e.g., soil type Bk23-2/3ab) is presented in **Table 41**, as an example. There are 29 types of soil in the Ganges basin (**Figure 28**).

Table 41 The FAO soil types description

Unit	Classification
Bk	Calcic cambisols
Bk23	Refers to the soil components described on the back of the map
	Associated soils: K and E each covering 20% of the mapping unit
2/3	Texture classes of the dominant soil
ab	Slope classes of the dominant soil

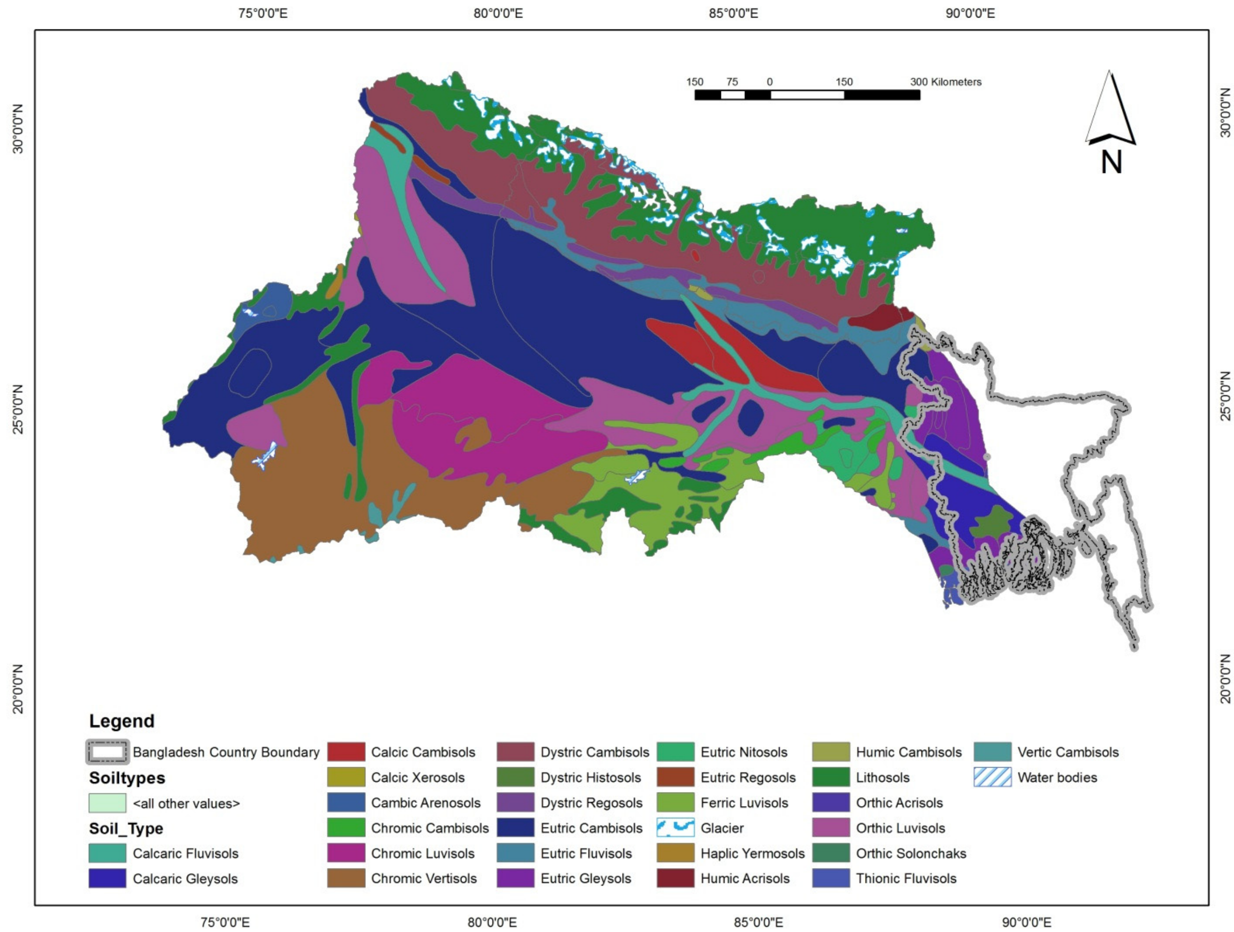


Figure 28 FAO soil types in the Ganges basin

Land cover data

Land cover data for the Ganges basin was taken from the GlobCover Project of European Space Agency, which has a resolution of 300 m and is available at http://due.esrin.esa.int/page_globcover.php. GlobCover 2009 has 23 classifications (Bontemps et al., 2011).

Table 42 shows the land cover classes that were used for the Ganges basin in the SWAT model while the land use map of the Ganges basin is shown in **Figure 29**. Agricultural land use is dominant in the Ganges basin.

Precipitation data

It is very difficult to obtain upstream hydro-meteorological information. Satellite-based observation is the major source of information for hydrological modelling particularly when monitoring data is not available. Multi-satellite Precipitation Analysis (TMPA) of the Tropical Rainfall Measuring Mission (TRMM), developed by the Goddard Space Flight Center (GSFC) of the National Aeronautics and Space Administration (NASA), provides a calibration-based sequential scheme for combining the precipitation estimates from multiple satellites and the monthly gauge analyses where feasible at the spatial and temporal scales (0.25 × 0.25 degree and every 3 hours) over 50 N – 50 S (Huffman et al., 2007). For the present study, TMPA 3B42 V7, hereafter referred to as 3B42V7, is used. TRMM rainfall data from January, 1998 to

December, 2013 has been used. **Figure 30** shows the grid of TRMM rainfall data set in the Ganges basin.

Table 42 GlobCover land cover classes

Sl. No.	Value	Label
1	11	Post-flooding or irrigated croplands (or aquatic)
2	14	Rain-fed croplands
3	20	Mosaic cropland (50-70%) / vegetation (grassland/shrub land/forest) (20-50%)
4	30	Mosaic vegetation (grassland/shrub land/forest) (50-70%) / cropland (20-50%)
5	40	Close to open (>15%) broadleaved evergreen or semi-deciduous forest (>5m)
6	50	Close (>40%) broadleaved deciduous forest (>5m)
7	60	Open (15-40%) broadleaved deciduous forest/woodland (>5m)
8	70	Close (>40%) needle leaved evergreen forest (>5m)
9	90	Open (15-40%) needle leaved deciduous or evergreen forest (>5m)
10	100	Close to open (>15%) mixed broadleaved and needle leaved forest (>5m)
11	110	Mosaic forest or shrub land (50-70%) / grassland (20-50%)
12	120	Mosaic grassland (50-70%) / forest or shrub land (20-50%)
13	130	Close to open (>15%) (broadleaved or needle leaved, evergreen or deciduous) shrub land (<5m)
14	140	Close to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)
15	150	Sparse (<15%) vegetation
16	160	Close to open (>15%) broadleaved forest regularly flooded (semi-permanently or temporarily) - Fresh or brackish water
17	170	Close (>40%) broadleaved forest or shrub land permanently flooded - Saline or brackish water
18	180	Close to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil - Fresh, brackish or saline water
19	190	Artificial surfaces and associated areas (Urban areas >50%)
20	200	Bare areas
21	210	Water bodies
22	220	Permanent snow and ice
23	230	No data (burnt areas, clouds)

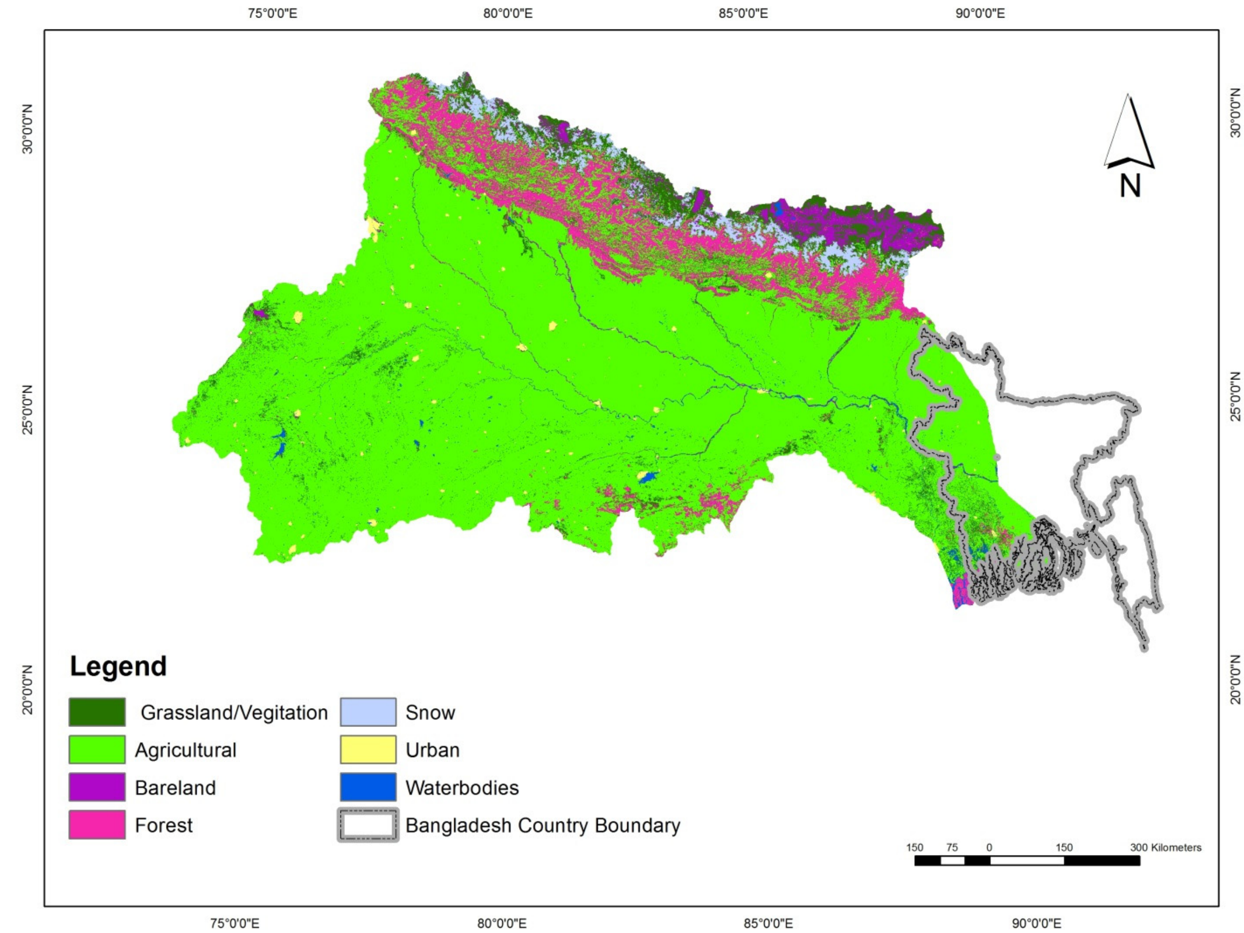


Figure 29 Major land use in the Ganges basin

Source: GlobCover, 2009.

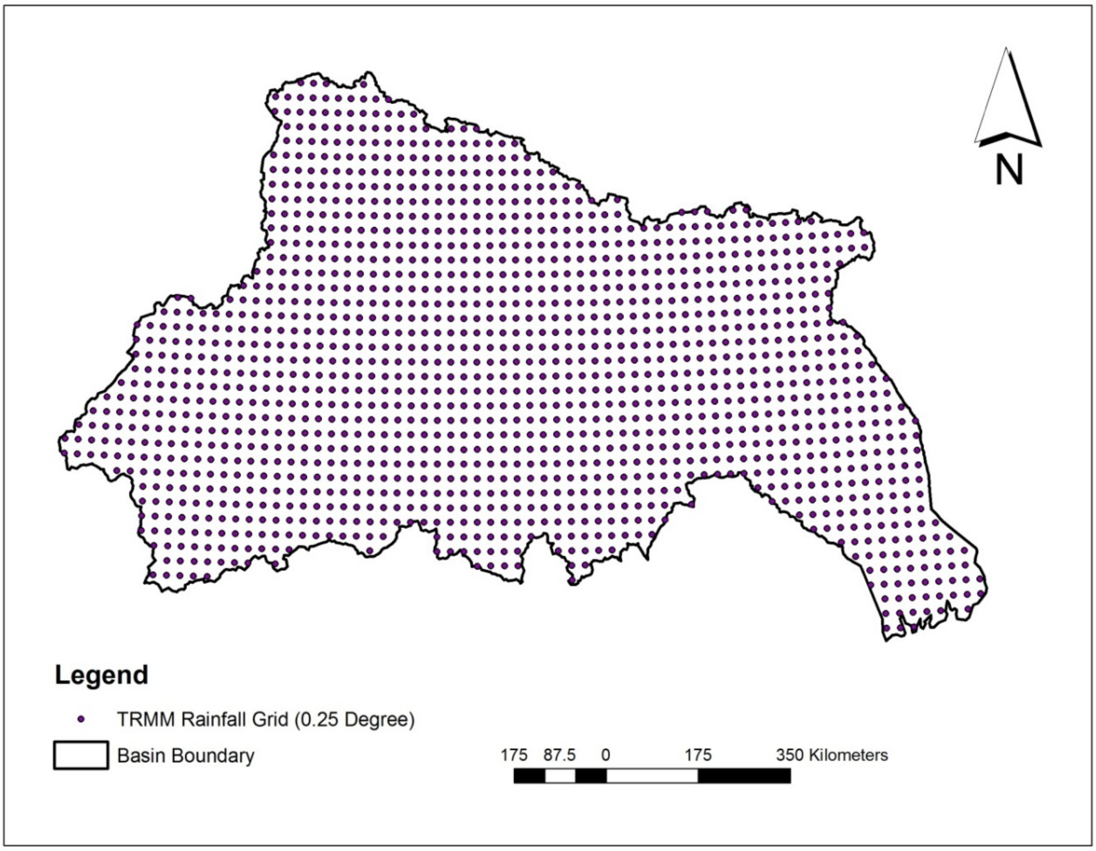


Figure 30 TRMM (0.25 × 0.25 degree) grid in the Ganges basin

Temperature

Temperature is another important weather parameter used for simulation in the SWAT model. The maximum and minimum temperatures are required as inputs. ERA-Interim is the latest global atmospheric analysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA-Interim Project was conducted in part to prepare for a new atmospheric re-analysis to replace ERA-40, which is extended back to the early twentieth century (Dee et al., 2011). ERA-Interim data is available from 1979 and is continuously updated on a real time basis, and can be retrieved from http://apps.ecmwf.int/datasets/. ERA-Interim 0.25 degree-gridded temperature data has been used for the present study (**Figure 31**).

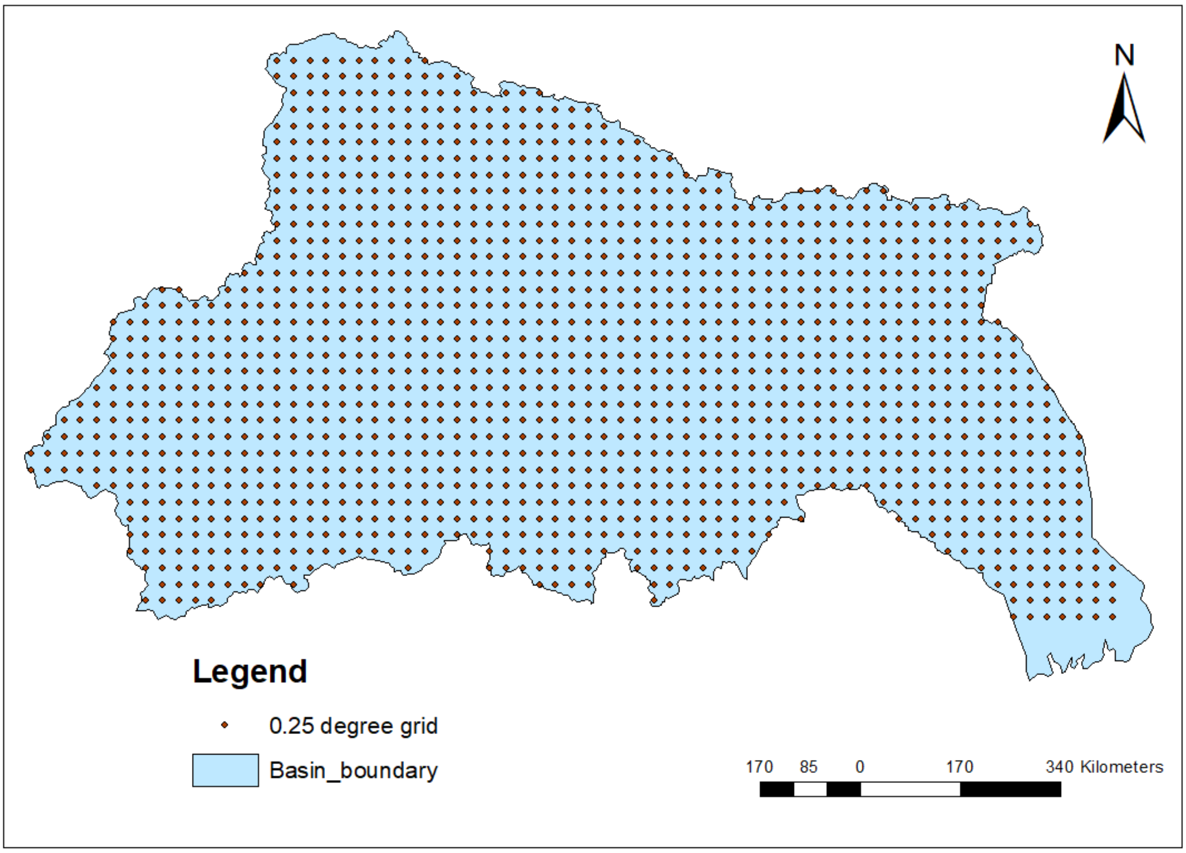


Figure 31 ERA Interim 0.25 x 0.25 degree grid in the Ganges basin

Hydrological data

The hydrological data, particularly the water level and discharge at the Hardinge Bridge gage station, was collected from BWDB. The discharge data from 1998 to 2013 was used for the calibration and validation of the SWAT model.

Reservoir information

The reservoir characteristics such as storage capacity and diversion of water from channels are important inputs to the SWAT model because upstream storage and withdrawal have significant impacts on the water flow at the outlet of a channel. Reservoir locations and relevant characteristics are obtained from the National Register of Large Dams of India (available at www.cwc.nic.in) and FAO Aqua State (http://www.fao.org/nr/water/aquasta).

Figure 32 presents the major hydroelectric projects in the Ganges basin inside India. Based on the available information, 44 reservoirs have been included for the setup of the Ganges basin model.

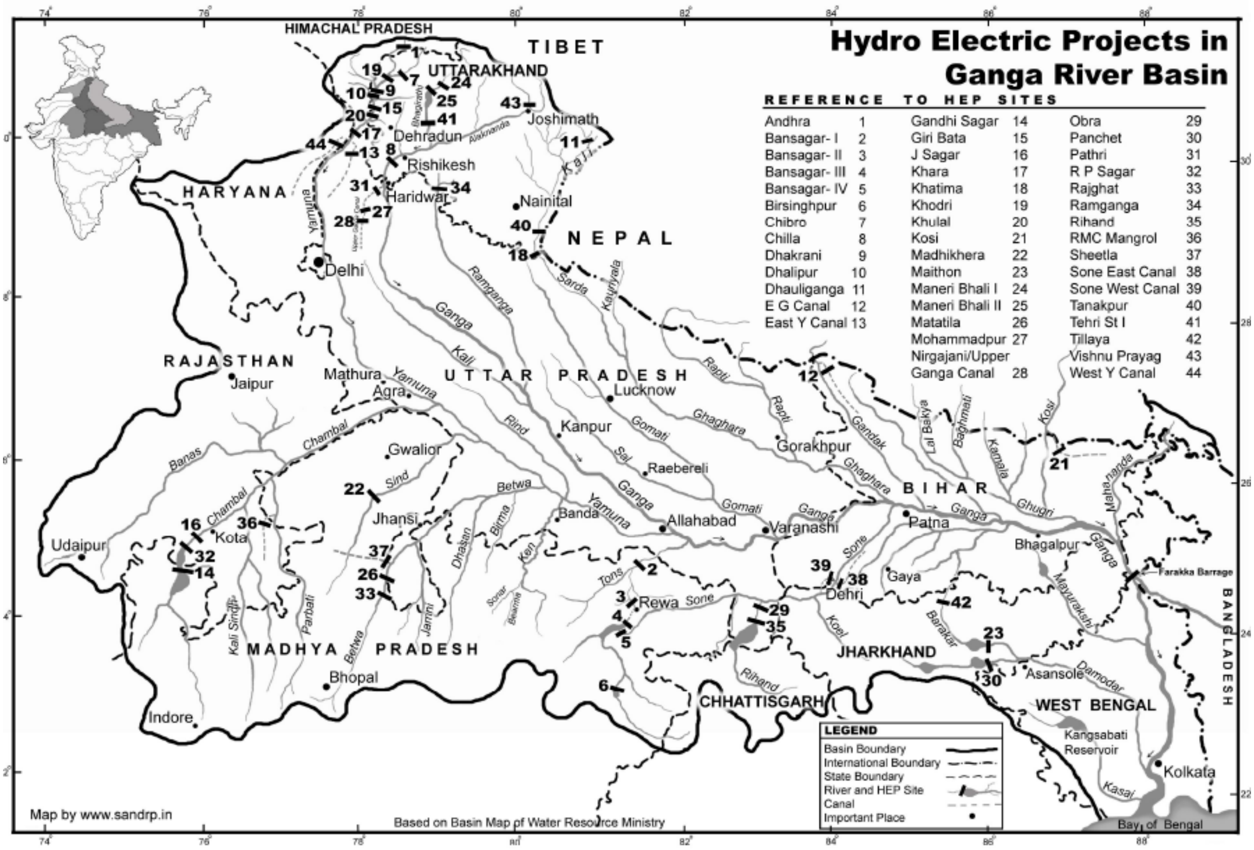


Figure 32 Location of hydroelectric projects in the Ganges basin inside India

Source: http://sandrp.in/basinmaps/

Setting-up the SWAT Model

(i) Watershed delineation: This is the first step in the SWAT modelling, and includes DEM processing such as filling of the DEM, creation of the flow direction and flow accumulation. For watershed delineation, stream networks are created and watersheds are divided into different sub-basins with the outlets.

(ii) HRU analysis: For the HRU analysis, maps of land use/vegetation cover, soil attributes and slope definition are overlaid. In the HRU definition, sub-dividing watersheds into areas with unique land use and soil combinations enables the model to reflect differences in evapotranspiration and other hydrologic conditions for different land covers/crops and soils.

(iii) Defining the weather data: This step allows users to load weather station locations into the current project and assign weather data such as precipitation, maximum and minimum air temperature, wind speed, solar radiation and relative humidity to the sub-watersheds. In this step a database of files containing relevant information is required to generate default inputs to the SWAT model.

(iv) Editing the SWAT input: The Edit SWAT Input tool allows to edit the SWAT model databases and the watershed database containing the inputs such as point discharge, sub-basin parameters and reservoir information to the SWAT model.

(iv) SWAT simulation: The final step in setting up the SWAT model is to simulate or run the model and conduct sensitivity analysis for different parameters and calibrate the parameters. This also includes the validation of the model.

Selection of the emissions scenarios and GCMs

Emissions scenarios are determined by the driving forces such as demographic development, socio-economic development and technological change. They are required for climate change analysis, including climate modelling and assessment of the impacts of adaptation and mitigation. Scenarios RCP 4.5 and RCP 8.5 have been selected for the present study. Downscaled results of four GCMs are available under CORDEX experiments for scenarios RCP 4.5 and RCP 8.5. **Table 43** shows a list of GCM models that have been used for existing studies. The precipitation and temperature data from the four GCMs for the two selected scenarios are used to identify potential climate change impacts on the long-term water availability for the Ganges basin. The downscaled dynamic data of the GCMs (**Table 43**) was taken from CORDEX South Asia, and is available at ftp://cccr.tropmet.res.in (McGregor and Dix, 2001).

Table 43 List of the GCMs for climate change studies

Sl. No.	Model	Description	Institution	Data availability	Remarks
1	NorESM-M	Norwegian Earth System Model	Bjerknes Centre for Climate Research University of Bergen	Scenarios 4.5 and 8.5 Period of 2006 to 2099	
2	CCSM4	Community Climate System Model	National Center for Atmospheric Research (NCAR)	Scenarios 4.5 and 8.5 Period of 2006 to 2099	Used for the present study
3	ACCESS1.0	Australian Community Climate and Earth-System Simulator (ACCESS)	CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), and BOM (Bureau of Meteorology, Australia)	Scenarios RCP 4.5 and 8.5 Period of 2006 to 2099	Used for the present study
4	CNRM-CM5	Centre National de Recherches Météorologiques climate model version 5	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avanceesen Calcul Scientifique	Scenarios RCP 4.5 and 8.5 Period of 2006 to 2099	Used for the present study
5	MPI-ESM-LR	Max Planck Institute Earth System Mode at base resolution	Max Planck Institute for Meteorology (MPI-M)	Scenarios RCP 4.5 and 8.5 Period of 2006 to 2099	Used for the present study

Sl. No.	Model	Description	Institution	Data availability	Remarks
6	GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory coupled model version CM 2.1	Geophysical Fluid Dynamics Laboratory	Scenarios RCP 4.5 and 8.5 Period of 2006 to 2070	

Calibration and validation

Model calibration is the process of estimating relevant model parameters by comparing the model predictions (the outputs of a given set of assumed conditions) with the observed data under the same conditions. Generally speaking, model evaluation guidelines consider the recommended model evaluation statistics with corresponding performance ratings and appropriate graphical analyses (Moriasi et al., 2007).

The most widely used model evaluation statistics are the Coefficient of Determination (R^2), Percent Bias (PBIAS), Nash-Sutcliffe Efficiency (NSE) and RMSE-Observations Standard Deviation Ratio (RSR). The model evaluation statistics are described below.

<u>Coefficient of Determination</u>

The Coefficient of Determination (R^2) is defined as the squared value of the coefficients of correlation, which is calculated as follows:

$$\boldsymbol{R^2} = \frac{[\sum_i (Q_{obs} - \bar{Q}_{sim})(Q_{obs} - \bar{Q}_{sim})]^2}{\sum_i (Q_{obs} - \bar{Q}_{sim})^2 \sum_i (Q_{obs} - \bar{Q}_{sim})^2}$$

where

Q_{obs} = *Observed value*
Q_{sim} = *Simulated value*
$\bar{Q}_{obs}$ = *Mean of the observed values*
$\bar{Q}_{sim}$ = *Mean of the simulated values*

The range of R^2 lies between 0 and 1 which describes how much of the observed variance is explained by the simulated values. The value of zero means no correlation while the value of 1 means that the variance of the prediction or the simulated data is equal to that of the observation (Krause et al., 2005).

<u>Nash-Sutcliffe Efficiency</u>

The efficiency proposed by Nash and Sutcliffe (1970) is defined as one minus the sum of the absolute squared difference between the predicted and observed values normalised by the variance of the observed values during the period of investigation (Krause et al., 2005). It is calculated as follows:

$$\boldsymbol{NSE = 1 - \frac{\sum_i (Q_{obs} - Q_{sim})^2}{\sum_i (Q_{sim} - \bar{Q}_{obs})^2}}$$

The range of *NSE* lies between - ∞ and 1. An *NSE* equal to 1 is considered a perfect fit or optimal value, and values between 0 and 1 are generally viewed as acceptable levels of performance, whereas values less than 0 indicate that the mean observed value is a better predictor than the simulated values, indicating unacceptable performance (Moriasi et al. 2007).

Percent Bias

The PBIAS measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). The optimal value of *PBIAS* is 0. A lower magnitude value indicates better model simulation. Positive values indicate underestimation bias and negative values indicate overestimation bias (Gupta et al., 1999).

PBIAS is calculated as follows:

$$\boldsymbol{PBIAS} = 100\,\frac{\sum_i^n (Q_{obs} - Q_{sim})}{\sum_i^n Q_{obs}}$$

RMSE-Observations Standard Deviation Ratio (RSR)

RSR is calculated as the ratio of the RMSE and the standard deviation of the observed data:

$$\boldsymbol{RSR}\ \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_i^n (Q_{obs} - Q_{sim})^2}}{\sqrt{\sum_i^n (Q_{obs} - \bar{Q}_{sim})^2}}$$

The RSR varies from the optimal value 0 indicating zero RMSE or no residual variation and therefore perfect model simulation, to a large positive value.

In this study, SWAT-CUP, a computer program which assists in sensitivity analysis, calibration, validation and uncertainty analysis, is used for the calibration (Abbaspour et al., 2007). The SUFI-2 algorithm of SWAT-CUP has been used for the calibration and validation. Calibration and validation periods were selected from 1998 to 2008 and from 2009 to 2013, respectively. After setting-up the model, it was simulated for the period from 1998 to 2008 for the calibration, of which the first three years from 1998 to 2000 were skipped due to the model initialisation. Hydrological data of the upstream watersheds of the Ganges basin was not available for detailed calibration. Therefore, the model was calibrated and validated based on the available data from the Hardinge Bridge gage station inside Bangladesh (**Table 44**).

Table 44 Location of the calibration point

Station	River	Location	Latitude (°)	Longitude (°)
Hardinge Bridge	Ganges	Bangladesh	24.06400	89.02550

A list of parameters and final parameter values obtained after auto-calibration of the model is shown in **Table 45**.

Table 45 List of major parameters and final calibrated values

Parameter	Name	Calibrated value
CN2.mgt	Initial SCS runoff curve number for moisture condition II	74.8
ALPHA_BF.gw	Base flow alpha factor(days)	0.975
SOL_AWC(1).sol	Available water capacity of the first soil layer (mm/mm)	0.1035
SOL_K(1).sol	Saturated hydraulic conductivity of first soil layer (mm/hr)	0.187
ESCO.hru	Soil evaporation compensation factor	0.706
GW_DELAY.gw	Groundwater delay (days)	418 (days)
GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow to occur (mm H_2O)	3875 (mm)
REVAPMN.gw	Threshold depth of water in the shallow aquifer for revap to occur (mm H_2O)	0.975 (mm)
CH_N2.rte	Manning's n value for the main channel	0.068
CH_K2.rte	Effective hydraulic conductivity in main channel alluvium (mm/hr)	64.375(mm/hr)
CANMX.hru	Maximum Canopy Storage (mm H_2O)	1.25
RCHRG_DP.gw	Deep aquifer percolation fraction	0.525

3.2.2.2 Water demand estimation

Estimation of the water demand for four sectors (irrigation, domestic, industrial and power generation) under current and future conditions is mainly dependent on the secondary information. As most of the relevant information is available at the national level, water demand is estimated at the national level in this study.

Domestic water demand estimation

Domestic water use was estimated at the national level by multiplying the population by per capita water use for urban and rural settlements. Population data from the World Population Prospects 2017 (DESA, 2017) was used to make future population projections using the arithmetic increase method. In urban areas, per capita water use is often higher than in rural areas due to better water infrastructure in cities and resource intensive lifestyles of urban households. For the base year (2015), per capita water use for urban and rural areas were considered as 100 litres per capita per day (lpcd) and 70 lpcd, respectively. Future water demand for urban and rural areas were considered as 126 lpcd and 100 lpcd, respectively.

Irrigation water demand estimation

Base year (2015) irrigation water demand was estimated at the national level by multiplying the area covered by major cultivated crops (including rice, wheat and sugarcane) and water requirement for growing particular crops in a season. Crop area data from the year book of agricultural statistics of Bangladesh 2015 (BBS, 2016) and the water requirement data for specific crops from Fishman et al. (2015) were used to estimate irrigation water demand in 2010. Due to the lack of available data on future crop areas, future irrigation demand was estimated based on the assumption that food demand will increase proportionally with population growth, which is 25% in 2040. Achieving food self-sufficiency is one of the priorities of the development plan of Bangladesh. In this estimation, it was assumed that these targets will be archived by increasing the areas of crop cultivation or increasing the cultivation intensity.

Industrial water demand estimation

Due to limited data availability and accessibility, it is difficult to estimate the amount of water used for the industrial sector. The estimation only considered water demand in two major industries; the textile and garments sector and the leather sector, which accounted for 85% of the GDP of export-oriented sectors. The base year's (2015) industrial water demand was estimated at the national level by multiplying the annual production of the industrial sectors by the sectoral water requirement per unit of production. Water requirement, which is 300 m^3/ton for the textile and garments sector and 40 m^3/ton for the leather sector in 2030 based on the Water Resource Group (2015), was used for the estimation.

Energy water demand (EWD) estimation

The project team conducted power plant surveys to collect first-hand information on water use intensity for different power generation technologies and different cooling methods in a few selected power plants in Bangladesh. During the power plant surveys, the team collected various information including fuel types, power generation technologies, plant load factor (*PLF*), cooling technologies, source of water, volume of water used by the power plants, etc. Water demand from power generation is calculated as follows:

EWD= Installed capacity x 24 hours x 365 days x *PLF* x water use per unit power generation (m^3/MWh)

Future water demand for energy generation was calculated based on the energy generation scenarios provided in the 2016 Power System Master Plan of the Government of Bangladesh. The water demand from power generation is calculated for both the open-loop cooling system and the close-loop cooling system scenarios.

3.2.3 Results and discussions

3.2.3.1 Results of water availability assessment in the Ganges sub-basin

The calibration and validation results for the Ganges sub-basin at the Hardinge Bridge gage station in Bangladesh is shown in **Figure 33**. The results show that the simulated flow does not match well with the peak flow in the first few years and the base flow is overestimated to some extent.

The values and performance of different statistical parameters are presented in **Table 46**. During the calibration periods, the parameters including *NSE* (0.93) and R^2 (0.96) are very satisfactory. Similarly, *PBIAS* and *RSR* are within satisfactory limits. However, in the validation periods, the results show overestimations particularly during the dry period.

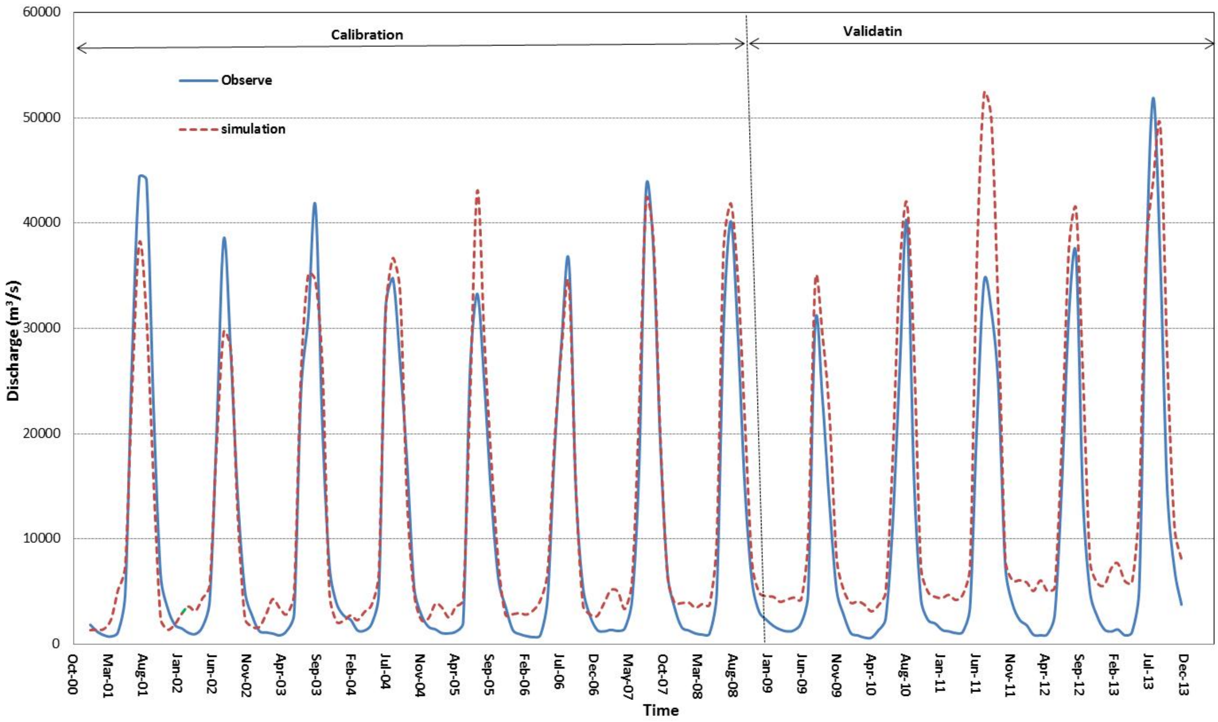


Figure 33 Calibration and validation results of the SWAT model at Hardinge Bridge gage station in Bangladesh

Table 46 Model performance for the calibration and validation periods of the Ganges sub-basin at Hardinge Bridge

	Calibration period (1998-2008)				**Validation period (2009-2013)**			
	NSE	*PBIAS*	*RSR*	R^2	*NSE*	*PBIAS*	*RSR*	R^2
Parameters	0.93	-7.4	0.26	0.96	0.75	-48	0.47	0.96
Evaluation results	Accept-able	Largely under-estimated	Accept-able	Accept-able	Accept-able	Largely under-estimated	Accept-able	Accept-able

The calibrated and validated SWAT model was used to assess the future flow under two climate scenarios of RCP 4.5 and RCP 8.5 based on the Regional Climate Model (RCM) outputs from four GCMs, i.e., CNRM-CM5, CCSM4, ACCESS1.0 and MPI-ESM-LR (see also **Table 43**). Simulations were conducted for different time scales including the historical period (1998-2013), 2010-2020, 2021-2030, 2031-2040, 2041-2050, 2051-2060, 2061-2070, 2071-2080, 2081-2090 and 2091-2099, respectively. The estimated average available monthly flow of the Ganges sub-basin in Bangladesh in a ten-year period based on each of the four GCM models under RCP 4.5 and RCP 8.5 is shown in **Figure 34** - **Figure 41**. The estimated average available monthly flow from the ensemble of the four GCM models under RCP 4.5 and RCP 8.5, respectively, is shown in **Figure 42** and **Figure 43**. Monthly variations of available flow in the Ganges sub-basin under RCP 4.5 and RCP 8.5, respectively, are shown in **Figure 44** and **Figure 45**. The simulation results show some overestimations for the months of April, May, June, and July under both scenarios. On the other hand, the simulation results show that the flow may decease in the months of August, September and October, especially in the second half of the century.

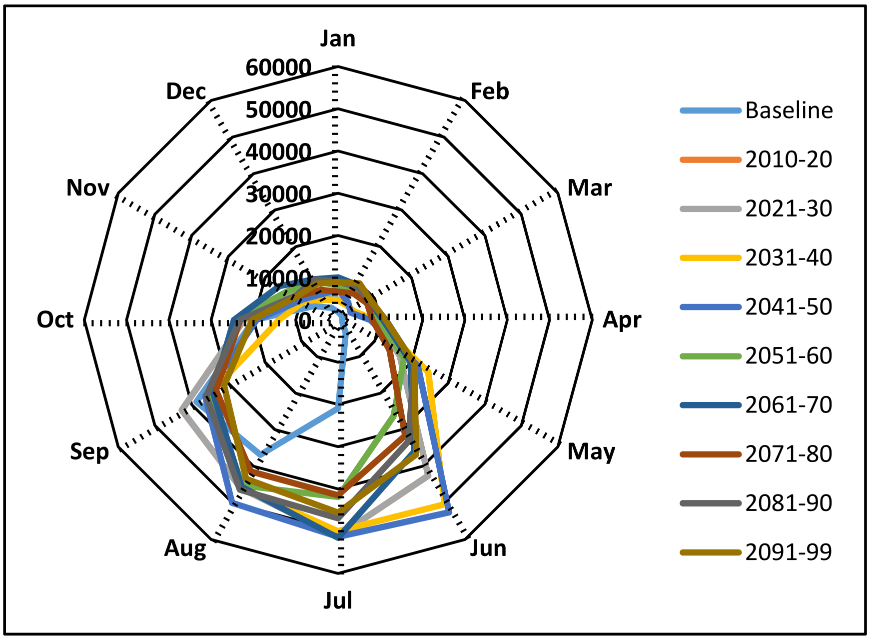


Figure 34 Average available monthly flow (m³/s) in the Ganges sub-basin in Bangladesh from the CNRM-CM5 model under RCP 4.5

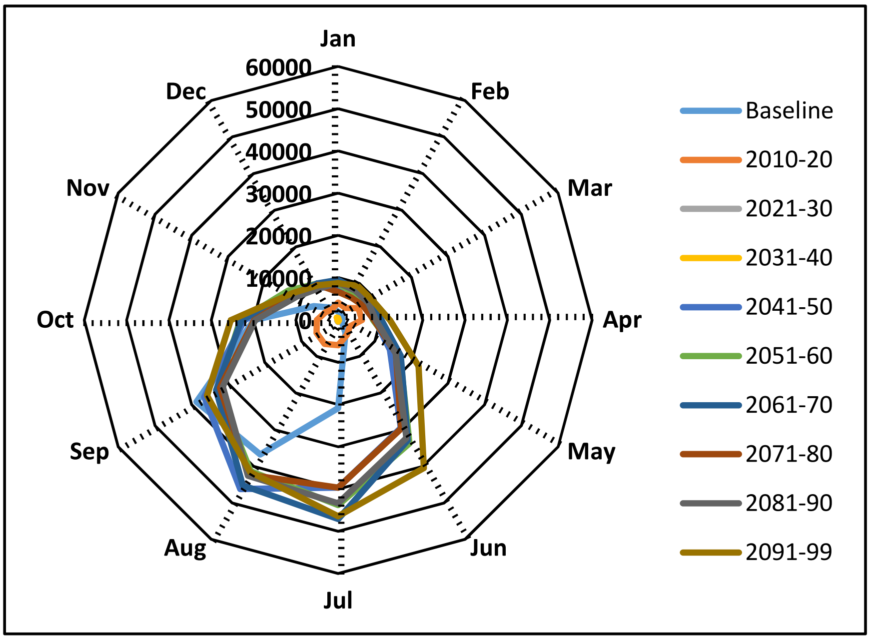


Figure 35 Average available monthly flow (m³/s) in the Ganges sub-basin in Bangladesh from the CCSM4 model under RCP 4.5

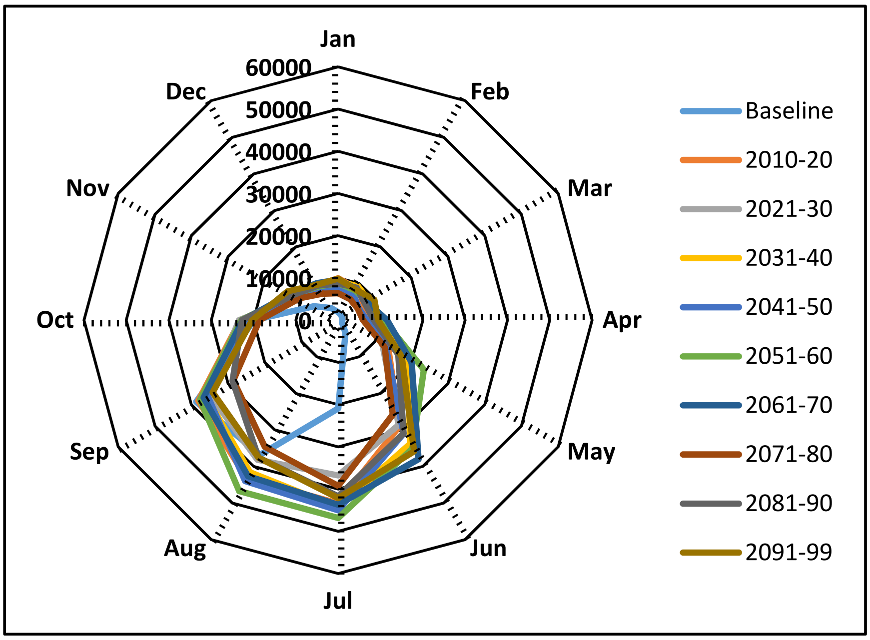


Figure 36 Average available monthly flow (m^3/s) in the Ganges sub-basin in Bangladesh from the ACCESS1.0 model under RCP 4.5

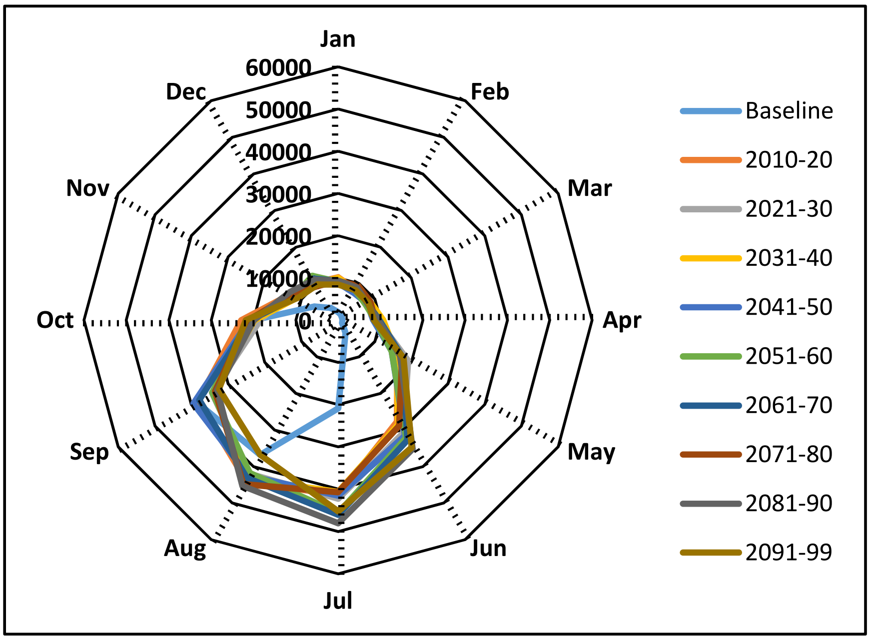


Figure 37 Average available monthly flow (m^3/s) in the Ganges sub-basin in Bangladesh from the MPI-ESM-LR model under RCP 4.5

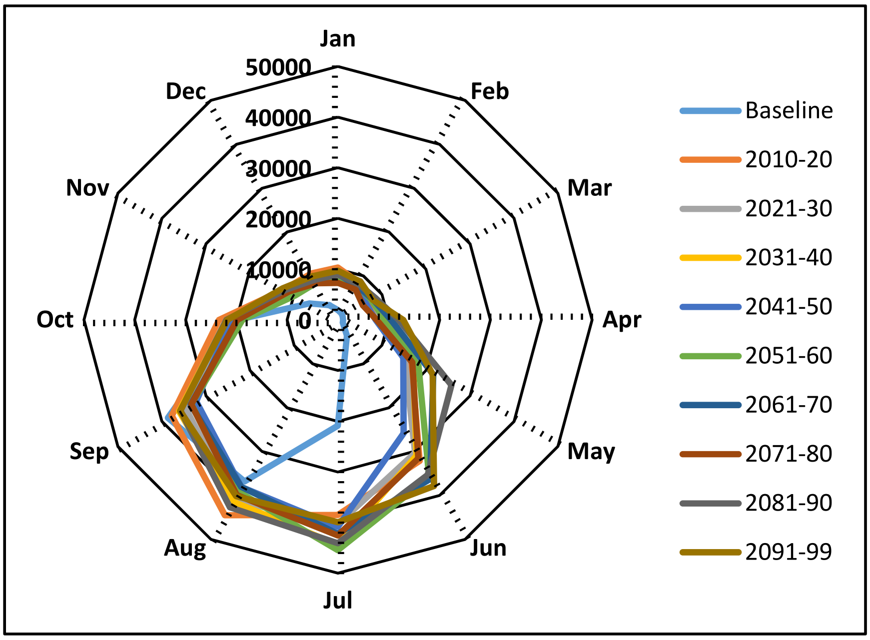


Figure 38 Average available monthly flow (m^3/s) in the Ganges sub-basin in Bangladesh from the CNRM-CM5 model under RCP 8.5

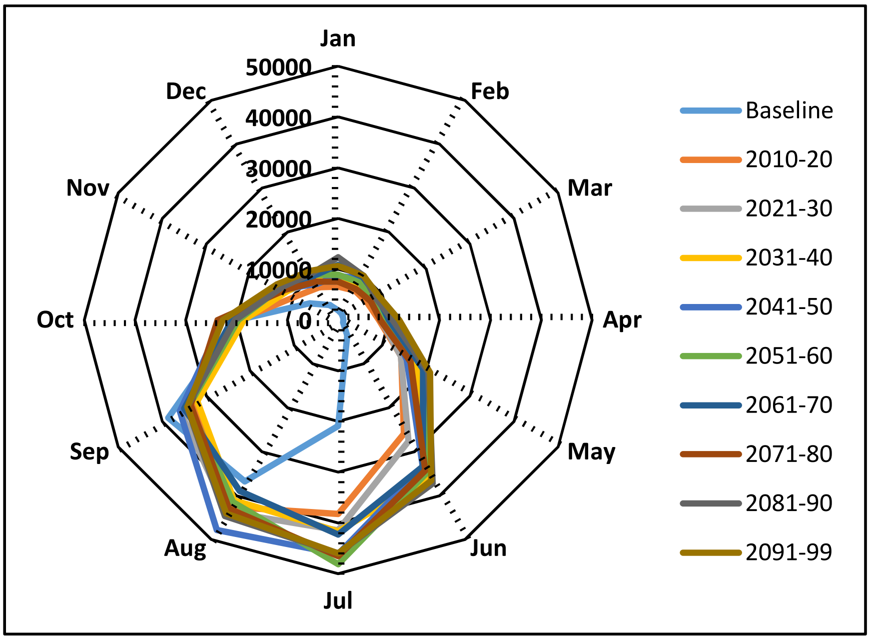


Figure 39 Average available monthly flow (m^3/s) in the Ganges sub-basin in Bangladesh from the CCSM4 model under RCP 8.5

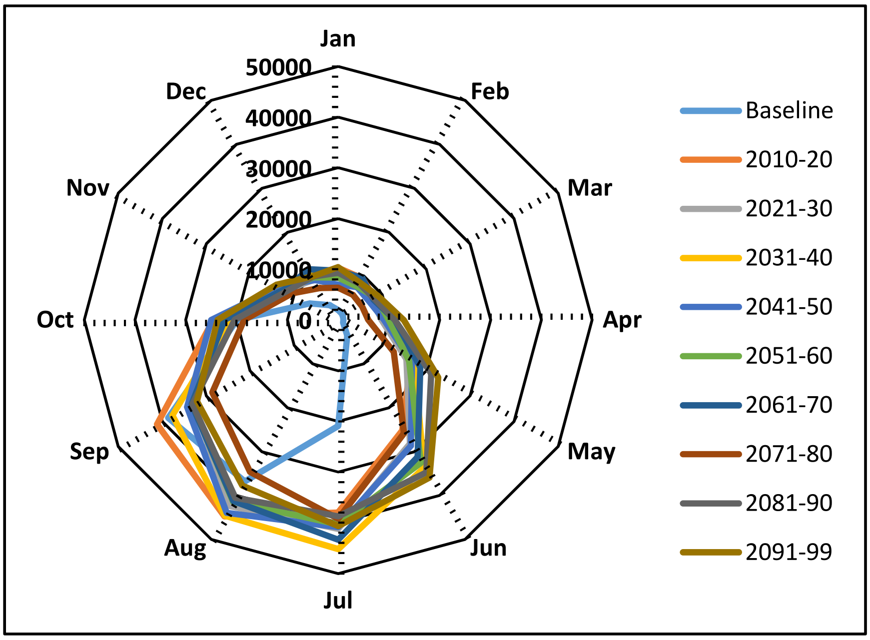


Figure 40 Average available monthly flow (m³/s) in the Ganges sub-basin in Bangladesh from the ACCESS1.0 model under RCP 8.5

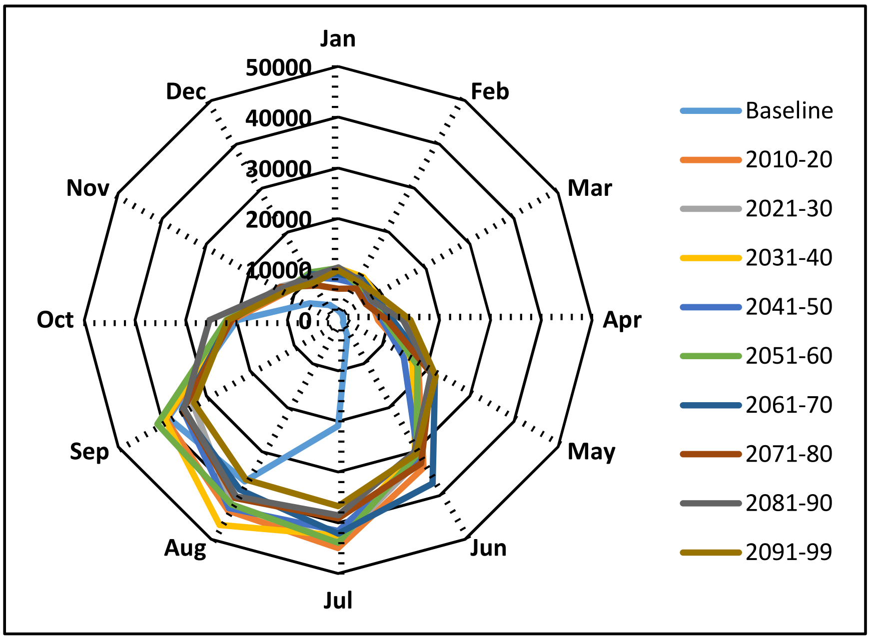


Figure 41 Average available monthly flow (m³/s) in the Ganges sub-basin in Bangladesh from the MPI-ESM-LR model under RCP 8.5

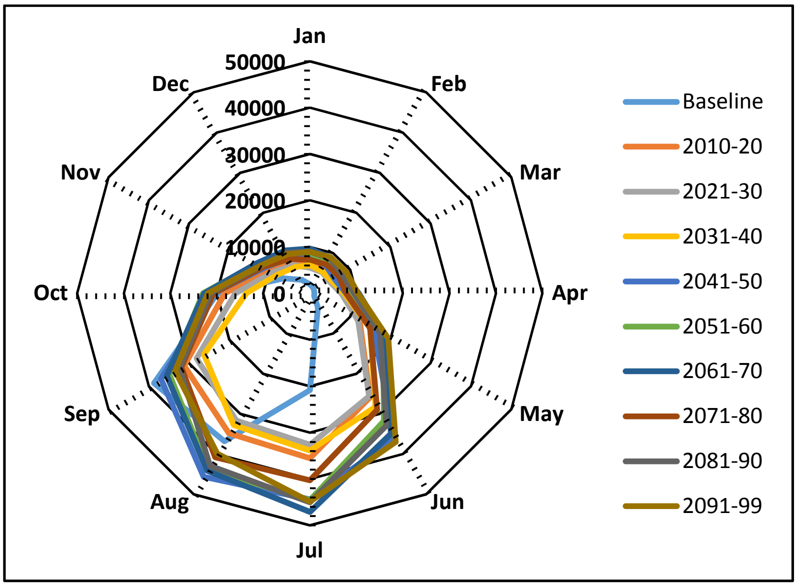


Figure 42 Average available monthly flow (m^3/s) in the Ganges sub-basin in Bangladesh under RCP 4.5 (an ensemble of four GCMs)

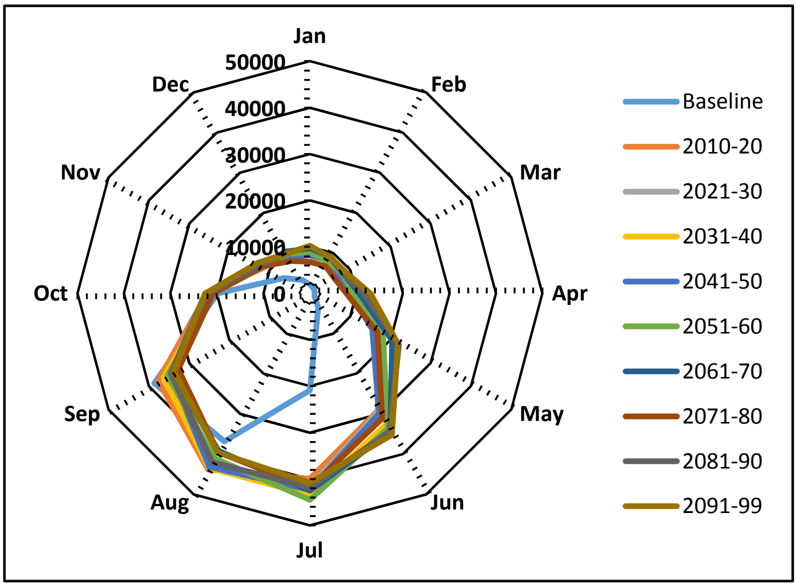


Figure 43 Average available monthly flow (m^3/s) in the Ganges sub-basin in Bangladesh under RCP 8.5 (an ensemble of four GCMs)

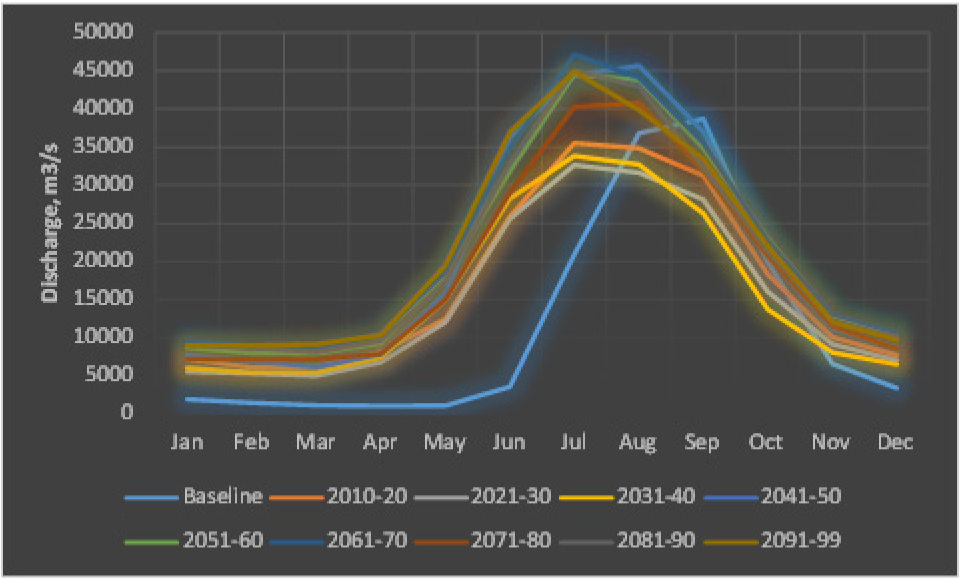


Figure 44 Monthly variation of available flow in the Ganges sub-basin in Bangladesh under RCP 4.5

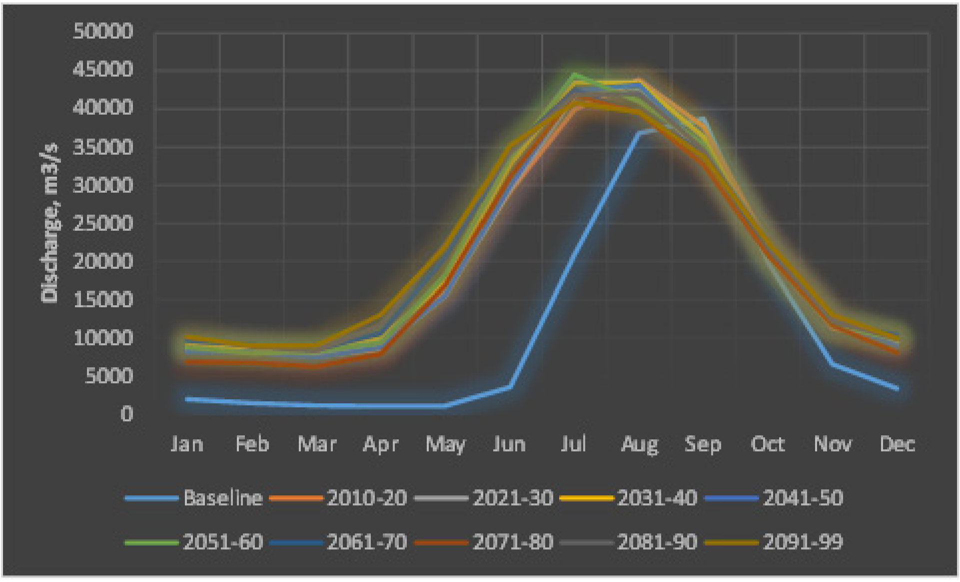


Figure 45 Monthly variation of available flow in the Ganges sub-basin in Bangladesh under RCP 8.5.

Except for the availability of water in terms of discharge or flow per unit time which is presented in the above, it is also important to estimate the amount of water availability volume in different time periods. This will be useful to assess whether water is sufficient to meet the water demand from various sectors. **Table 47** and **Table 48** show the average monthly water quantity (MCM) in the Ganges basin under RCP 4.5 and RCP 8.5, respectively. **Table 47** shows that more water will be available for the months of January, February, March, April, May, June, July, November and December under RCP 4.5 compared to the baseline condition. On the other hand, less water will be available for September compared to the baseline condition under RCP 4.5. The quantity of water for the months of August and October will be less until the

2040s compared with the baseline condition. **Table 48** shows that more water will be available for all months except for September under RCP 8.5 compared to the baseline condition. **Table 49** and **Table 50** show the average seasonal water quantity (MCM) in the Ganges basin under RCP 4.5 and RCP 8.5, respectively. It is shown that more water will be available for all seasons.

Table 47 Average monthly water quantity in the Ganges basin under RCP 4.5 (MCM)

Period	Baseline	2010-2020	2021-2030	2031-2040	2041-2050
Jan	5,145	19,319	14,788	16,220	20,758
Feb	3,447	14,763	12,751	13,114	16,729
Mar	2,925	16,464	13,342	14,476	16,514
Apr	2,613	21,001	17,449	19,100	20,300
May	2,898	33,343	32,141	40,079	42,459
Jun	9,176	67,033	66,268	73,212	93,754
Jul	55,936	95,149	87,433	90,627	118,918
Aug	98,541	93,317	84,662	87,655	122,307
Sep	100,233	80,954	72,842	68,079	95,801
Oct	53,249	49,055	42,937	36,653	55,536
Nov	16,936	26,110	23,668	20,865	28,868
Dec	8,970	20,663	18,820	17,415	23,317

Table 48 Average monthly water quantity in the Ganges basin under RCP 8.5 (MCM)

Period	Baseline	2010-2020	2021-2030	2031-2040	2041-2050
Jan	5,145	24,205	22,645	23,657	21,926
Feb	3,447	19,899	20,636	21,022	19,665
Mar	2,925	20,088	21,042	22,347	19,867
Apr	2,613	22,083	22,652	25,760	22,548
May	2,898	43,944	41,459	46,307	41,612
Jun	9,176	75,710	76,470	84,750	77,388
Jul	55,936	106,918	111,632	116,314	113,531
Aug	98,541	117,382	113,304	116,327	115,705
Sep	100,233	97,567	88,565	94,077	89,377
Oct	53,249	59,237	57,411	55,782	60,258
Nov	16,936	29,301	31,560	30,135	31,107
Dec	8,970	25,379	25,016	27,184	23,973

Table 49 Average seasonal water quantity in the Ganges basin under RCP 4.5 (MCM)

Period	Baseline	2010-2020	2021-2030	2031-2040	2041-2050
Pre-monsoon	8,431	70,739	62,830	73,493	79,091
Monsoon	263,217	335,880	310,747	319,053	430,048
Post-monsoon	69,609	74,809	66,307	57,274	83,989
Dry season	17,353	54,509	46,186	46,600	60,577

Table 50 Average seasonal water quantity in the Ganges basin under RCP 8.5 (MCM)

Period	Baseline	2010-2020	2021-2030	2031-2040	2041-2050
Pre-monsoon	8,431	85,917	84,984	94,249	83,867
Monsoon	263,217	396,849	389,094	410,695	395,083
Post-monsoon	69,609	88,071	88,571	85,519	90,911
Dry season	17,353	69,305	68,234	71,724	65,488

3.2.3.2 Water demand estimation

Water demand estimation shows that the cumulative water demand from domestic, industrial and agriculture uses will increase by 20% in year 2040 compared with that in 2015. Agriculture is the largest water consumer (78 BCM) in 2015. Agriculture will continue to be the dominant water user in the future. The industrial sector accounted for 2.5% of the water use in 2015. However, industrial water use will increase to account for 9% of the water use by 2040. Domestic water use will increase from 1 BCM in 2015 to 1.5 BCM in 2040 (**Figure 46**). The increase in water demand from domestic use is attributable to population growth and lifestyle changes.

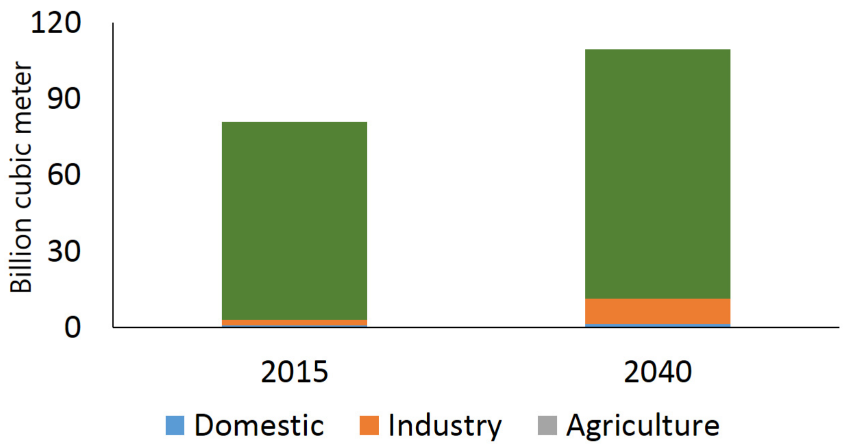


Figure 46 Water demand for domestic, industrial and agriculture sectors

Based on our best knowledge, there are no available estimations on the amount of water used by the energy sector for Bangladesh. This present study can be considered as the first attempt to estimate water demand from the energy sector for Bangladesh. We conducted power plant surveys in Bangladesh to estimate water use intensity in the power plants. Based on the survey results we estimated the water demand from power generation in 2040. The 2016 Power System Development Plan provided five fuel mix scenarios for future power generation in Bangladesh as shown in **Figure 47**. The five scenarios vary mainly due to the different shares of gas and coal in the fuel mix. Renewable energy will account for 15% of total electricity generation in all five scenarios.

Since thermal power generation will dominate future power generation, water demand for the cooling systems of thermal power plants could significantly increase, depending on the types of cooling technologies used. We estimated the future water demand from electricity generation for two cooling technology scenarios. **Figure 48** shows that if all power plants are installed with the open loop cooling system, water demand for power generation will range from 175 BCM under fuel mix Scenario 5 to 220 BCM under fuel mix Scenario 1. The differences in water demand among various fuel mix scenarios is due to the fact that coal-based thermal power generation requires more water than gas-based thermal power generation. **Figure 49** shows the water demand from power generation using the close-loop cooling system. Thermal power plants using the close-loop cooling system will reduce water use substantially to less than 10 BCM.

The estimated total water demand showed that the selection of the cooling system by the thermal power plants will play a critical role in influencing the total water demand. **Figure 50** shows that if all the thermal power plants are installed with the open loop cooling system, the energy sector will be the largest water consumer in the country followed by the agriculture sector. Under this case, the total water demand will be 305 BCM. If the power plants are installed with the close-loop cooling system, the total water demand will be 119 BCM, which is nearly one third of the open loop cooling system scenario. Under this case, water demand for power generation will be less than 10 BCM. However, the energy sector will still be the second largest water consumer in the country.

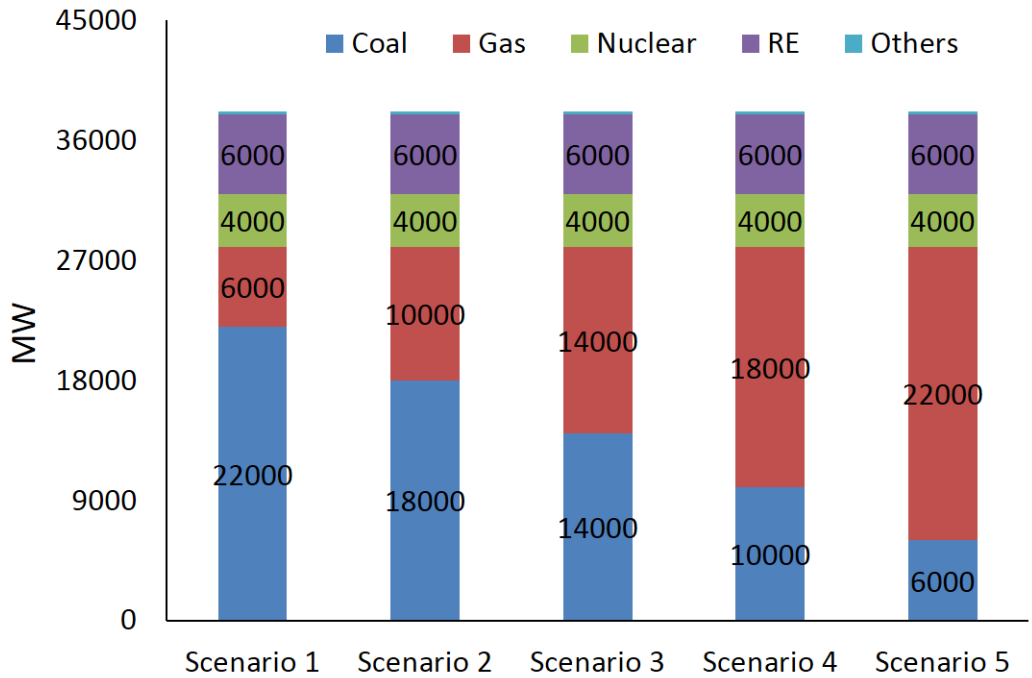


Figure 47 Five fuel mix scenarios for future power generation in Bangladesh

Source: Ministry of Power, Energy and Mineral Resources (2016)

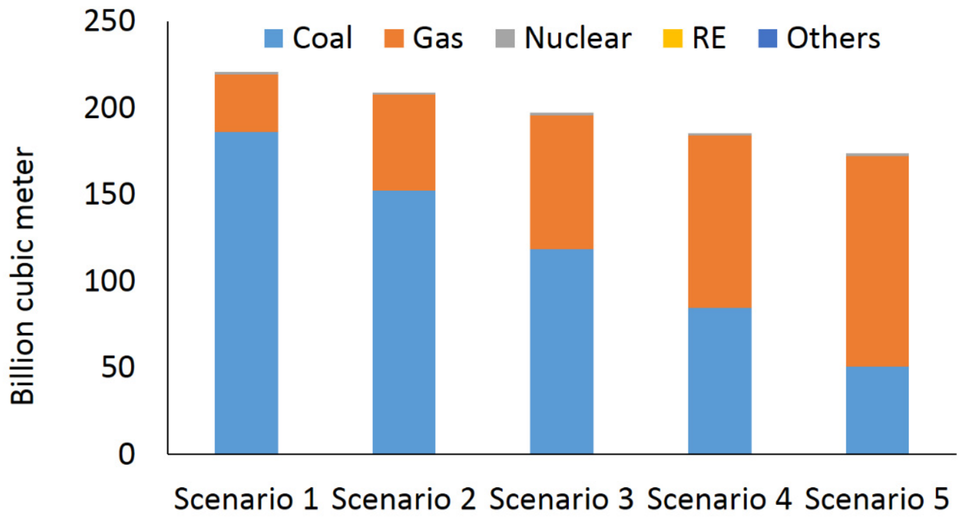


Figure 48 Water demand from power generation under the open loop cooling system scenario

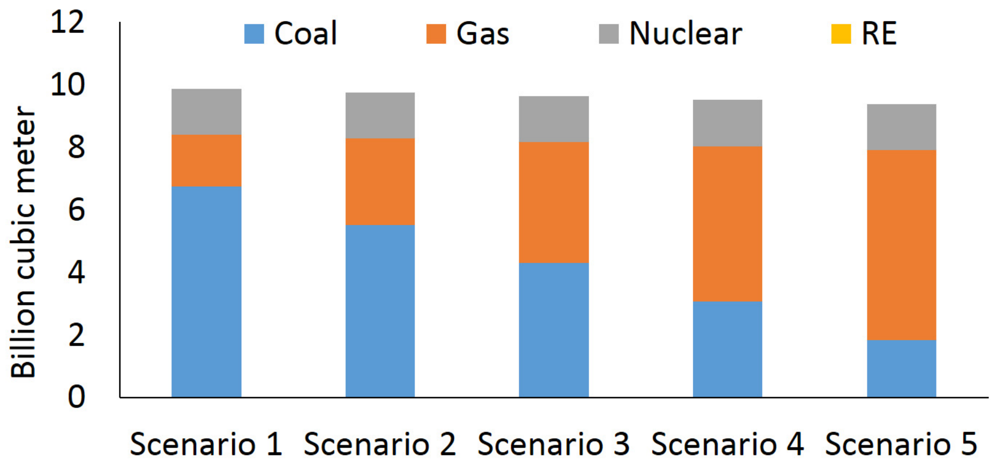


Figure 49 Water demand from power generation under the close-loop cooling system scenario

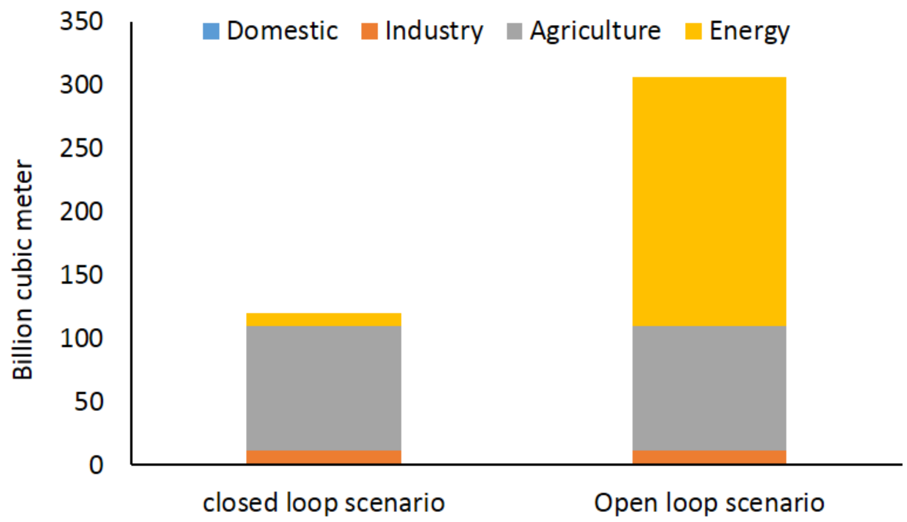


Figure 50 Water demand under different cooling system scenarios for thermal power generation

3.2.4 Conclusions

The case study for Bangladesh assessed the water availability in the Ganges sub-basin within Bangladesh using the SWAT modelling tool. The calibration and validation of the SWAT model were conducted based on the observation data from the Ganges sub-basin at Hardinge Bridge gage station. The calibrated and validated model was run based on the Regional Climate Model outputs of four GCMs, i.e., CNRM-CM5, CCSM4, ACCESS1.0 and MPI-ESM-LR, under RCP 4.5 and RCP 8.5 climate scenarios for ten different time scales, i.e., the base period (1998-2013), 2010-2020, 2021-2030, 2031-2040, 2041-2050, 2051-2060, 2061-2070, 2071-2080, 2081-2090 and 2091-2099 to assess the long-term water availability for the Ganges sub-basin in Bangladesh.

The four GCM models show similar results on future water supply except for the CCSM4 model under RCP 4.5. The results show that the Ganges flow will increase significantly in the future compared to the present situation, particularly during the pre-monsoon (April to May) and the monsoon months (June to September) under both RCP 4.5 and RCP 8.5. There will be a decrease in the inflow during the post-monsoon period (October-November). The results also show that the winter flow may likely increase in the future due to the increase in winter precipitation (December- February) under the climate change scenarios.

Water demand estimation shows that the water demand will increase significantly in the future due to population growth, rapid industrial development, expansion of irrigation areas for maintaining food security and increase in power generation to support rapid economic growth. Our estimates show that the power generation sector will become the largest water consumer if power plants are equipped with the open-loop cooling system. However, if the close-loop cooling system is used, a significant amount of water can be saved though the sector will still remain as the second largest water consumer followed by irrigation in Bangladesh. Therefore, the choice of power generation technologies and cooling systems will be critical in influencing total water demand in the country.

Though the hydrological modelling results show that the annual flow of the Ganges will increase in the coming decades, it also shows that in the dry season (December-May) the flow accounts for less than 25% of the total flow in the Ganges sub-basin in Bangladesh. Therefore, competition among the major water users will be more severe in the dry season. In addition, the spatial diversity of water availability will greatly affect many development projects, particularly energy projects, from the perspective of future water risk. This can also be understood from the case study in India, which provides results on the assessment of the water supply-demand balance at the district-level.

Considering the potential impacts of climate change and the increasing competition for water in the future, Bangladesh's power development sector should consider developing a guideline and start to regulate water use for thermal power generation. Bangladesh can learn from the experiences in India. As discussed in the case study for India, India heavily relies on thermal power generation to maintain its energy security. The power generation sector has already encountered water conflicts with other major users. To minimise water use by thermal power plants, India's Government set a maximum limit of 2.5 m^3/MWh for the water use by thermal power plants, which was adopted in January 2017 (MOEFCC, 2015).

3.2.5 Limitation of the study

The Ganges basin is a large river basin. Calibration and validation of the hydrological model is critical to building an accurate model for the expected assessment. In this study, the calibration and validation were conducted using the observation flow data of the Ganges sub-basin, but such data was limited to one mornitoring station – the Hardinge Bridge gage station in Bangladesh. Hydrological data from upstream locations in India was not obtained, which represents a major limitation to the hydrological simulation of the Ganges in Bangladesh. In addition, a large amount of water use infrastructure such as dams, reservoirs and irrigation facilities exist inside the Ganges basin. To improve simulation results it is important to include the characteristics of such major water use infrastructure in modelling exercises. However, it was not achievable in the present study due to the lack of hydro-meteorological data in the upper reaches of the Ganges in India. Four downscaled climate projection models have been used for the present study. The hydrological model outputs based on the climate projection models can thus only be considered as indicative results of future water availability in the Ganges sub-basin.

4. Conclusions

As the most populous river basin in South Asia, the Ganges basin provides water for domestic use, irrigation, industrial use and power plants. Changes in the water availability in the basin will impact on the economic development as well as human life in the region. This is true for the nexus between water and energy due to the fact that the energy sector, particularly thermal power generation, consumes a large amount of water and will expand rapidly to satisfy increasing energy demand. Ensuring sufficient water for maintaining stable operation of existing and future planned thermal power plants is therefore crucial. To achieve rapid economic development in this region will require more water and energy. Filling the gaps between supply and demand of both water and energy requires in-depth knowledge on the linkages between energy and water, in particular using quantitative methods. However, such knowledge is lacking in the existing literature.

This project, entitled "*Assessment of Climate-Induced Long-Term Water Availability in the Ganges Basin and the Impacts on Energy Security in South Asia*", is funded by the Asia Pacific Network for Global Change Research (APN). The objective of the project is to inform the decision makers, relevant stakeholders and investors about water supply and demand balance under the long-term impacts from climate change up to 2050, as well as the level of water risks for future energy security. It is expected to support effective energy planning and integrated water management in the Ganges basin and help reduce the risks of power plant investment which may be locked in in water-stressed areas.

To achieve these objectives, we developed an integrated assessment approach which combines various modelling techniques including a hydrological model (the SWAT model) and water demand projections for major water use sectors including domestic, agriculture and industrial sectors, together with power plant field surveys, to assess the water-energy nexus from the perspective of energy security under water constraints.

To inform the decision makers, relevant stakeholders and investors on the spatial distribution of water stress particularly from the perspective of long-term energy security, we conducted a series of stakeholder consultation workshops in three countries to communicate with relevant stakeholders on the research objectives and methodologies, collect the feedbacks on their concerns and needs and convey the research results and key messages.

To enable the policy makers, relevant stakeholders and investors to explore the data and associated results, we developed a free on-line tool for spatial visualisation of the results on water supply, water demand, water supply-demand balance and water risks for existing and planned thermal power plants in India at the district level.

We conducted two case studies for India and Bangladesh. For India, four sub-basins, namely Chambal, Damodar, Gandak and Yamuna, were selected. From the supply side, the results show that overall water availability will increase in future in the four sub-basins, particularly in Chambal, Damodar and Gandak. However, water availability in Yamuna will decrease in the far future (2071-2100).

Water availability will vary from month to month depending on the physical conditions such as precipitation, evapotranspiration and surface runoff, etc. It will increase in Damodar and Gandak in both the dry and the wet seasons; however, it will decrease Chambal and Yamuna in the dry season. At the district level, water availability in most districts in the four sub-basins will increase.

From the demand side, future water demand will increase due to population growth, industrial development, and increase in power generation and irrigation. Out of the four sub-basins, Chambal will have the smallest water demand and Yamuna will have the largest. In all four sub-basins, irrigation water demand will dominate followed by domestic water demand, and this trend will continue until 2050. Damodar will have the highest energy water demand followed by Gandak. Energy water demand will greatly increase in Gandak.

For the water supply-demand balance at the sub-basin level, Chambal and Damodar will have water surplus in the future. Chambal will have the largest water surplus among the four selected sub-basins. Yamuna and Gandak will face serious water deficit in the future, particularly the Yamuna sub-basin.

At the district level, most of the districts in Chambal and Damodar, particularly in Chambal, will have water surplus. However, most of the districts in Gandak and Yamuna will face water deficit in the future. Particularly in Gandak, there will be many planned thermal power installations, operations of which will face severe water shortage.

The spatial distribution of water supply-demand balance at the district level can be used as an important indicator to assess the location and technologies for future power plants. The district-level analysis indicates that many of the existing and planned power plants are located in areas under high or moderate water stress. Specifically, most of the existing power plants and planned power plants in Yamuna and Gandak, a few plants in the upper part of Chambal and a few plants in the middle and right part and the lower part of Damodar will face high risks of water shortage. Relevant governmental organisations such as development and planning organisations and energy planning organisations as well as investors need to be highly cognisant of this situation to prevent new installations being locked-in in water-stressed locations. If new capacity has not yet been installed, alternative locations with a water surplus should be considered. Among the four sub-basins, most of the districts in the middle and lower part of Chambal and the districts located in the upper part of Damodar (the yellow area) can be considered as alternative locations for new installations.

The results of the project and the Water-Energy Nexus Assessment web tool can inform relevant governmental decision makers, energy planners and investors about where risks of water shortage will be for existing and planned power plants and help them identify suitable locations for new thermal power installations to ensure sufficient water will be available for cooling in the thermal power plants.

For Bangladesh, the case study was conducted for the Ganges basin within the border of Bangladesh. From the supply side, the results show that the Ganges flow will increase significantly in the future especially during the pre-monsoon (April to May) and the monsoon months (June to September). There will be a decrease of inflow during the post-monsoon period (October-November). The results also show that winter flow may likely increase in the future due to the increase in winter precipitation (December- February) induced by climate change.

From the demand side, the results show that the power sector will become the largest water consumer if power plants are to be equipped with the open-loop cooling system. However, if the power plants will be installed with the close-loop cooling system, a significant amount of water can be saved. Selection of the proper cooling systems for thermal power generation will be critical in determining the total water demand and level of water stress in the country. Relevant policy makers, investors and energy project developers need to be highly aware of the substantial impacts of the selection of power generation technologies and the type of cooling system on the sustainability of water use.

While the hydrological modelling results show that annual water flow will increase in the coming decades, they also show that in the dry season (December-May) water flow will be very limited. Therefore, competition among major water users in the dry season will become more severe. Considering the potential impacts of climate change and more intensified competition over water use in the future, the power sector in Bangladesh should consider the development of relevant guidelines and start to regulate water use for power generation. Bangladesh can learn from the experiences in India, which set a maximum limit of 2.5 m^3/MWh on water use for thermal power plants, adopted in January 2017.

5. Future Directions

The present study can be further developed in the following areas. First, the Ganges River includes 19 sub-basins across the borders of three South Asian countries, Nepal, India and Bangladesh. Due to data availability and the scope of the present study, only a detailed case study for four selected sub-basins in India and a case study for Bangladesh covering the river basin within Bangladesh were conducted. It is necessary to extend the present study for a detailed assessment covering all 19 sub-basins, which would provide a fuller picture of the water-energy nexus in the Ganges basin. In addition, the detailed assessment at the district level for the four selected sub-basins in India can be applied to all 19 sub-basins in the Ganges.

The calibration and validation of the SWAT model for the assessment of water supply at the sub-basin level is very limited in the present study. Calibration and validation are critial factors influencing the reliability of the hydrological modelling results and should be improved further by using the observation data or other reference data from secondary sources.

Dissemination of the present study is limited through stakeholder consultation workshops and the IGES website. It could be further extended through relevant outreach events and publication in relevant journals and presentations at impactful global conferences.

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7. Appendices

Appendix 1 Case study in Nepal: A synthesis from literature review

1. Introduction

The entire area of Nepal falls under the Ganges basin, occupying 14% of the basin area. In terms of its contribution to the flow of the Ganges, the rivers in Nepal contribute 46% in the monsoon season and as much as 71% in the lean season (Dungel and Pun, 2009). In Nepal, the annual renewable surface water available and annual renewable groundwater potential is estimated as 225 BCM (WECS, 2003) and 12 BCM (WECS, 2004), respectively. Of the 225 BCM, only 15 BCM per annum is used for agriculture (95.9%), domestic purpose (3.8%) and industry (0.3%) (WECS, 2011). Per capita availability of water in Nepal is 8,900 m^3/year, which is about five times the threshold water requirement of 1,700 m^3/capita per year (UNDP, 2006).

Nepal has high physiographic diversity, ranging from altitudes of less than 100 m in the Terai region to 4,877 m in the hilly region and more than 8,000 m in the mountain regions. These three regions are located parallel to each other from east to west. Monsoon rainfall is prominent from June to September and constitutes 80% of the annual rainfall. The monsoon in Nepal starts in mid-June from the eastern regions and gradually moves to the western regions and then finally reaches the far western regions in half a month. Of the total annual rainfall, the monsoon alone constitutes 80% of the rainfall starting from mid-June to September. However, there is significant regional variation in the annual precipitation within the country. According to WECS (2000), the Central Region of Nepal along the southern slopes of Annapurna Himalaya receives the highest mean annual precipitation of more than 6,000 mm, whereas the North-Central areas around the Tibetan plateau receive less than 250 mm precipitation annually. Snow contributes 10% to the total precipitation in Nepal (UNEP, 2001) and falls mostly in the northern and western mountainous regions in Nepal. Glaciers cover about 3.6% of the area of Nepal (Mool et al., 2001).

Characterised by extreme altitudinal variation within very short lateral distances, Nepal is heavily dependent on water to generate energy and irrigate crops as well as supply for domestic and industrial uses. With climate change and population growth, water shortage for power generation and food production are becoming more acute. However, water requirements for crop irrigation and power generation vary spatially.

Nepal ranks as 4th most vulnerable country from the impacts of climate change (World Bank, 2013). Water resource, food and agriculture are important sectors being affected by climate variability and change. The Himalayas in Nepal have witnessed the impacts of climate change, such as glacier melting and associated impacts on water availability in the Ganges basin. The decadal annual precipitation of 80 monitoring stations has shown a decreasing trend in average precipitation in Nepal at a rate of 9.8 mm/decade (MoPE, 2004).

More than 6,000 rivers flow through Nepal, which make it a water rich country (Chaulagain, 2009). Rivers in Nepal have been categorised into small, medium and large rivers based on their water source and discharge. About 78%, 9% and 13% of the average flow in the country is available from large, medium and small rivers, respectively (WECS, 2011). Only four rivers, Koshi, Gandaki, Karnali and Mahakali, are large rivers (**Figure A1-1**) and all of them are part of the Ganges basin. The large rivers originate from the Himalayas and are snow fed with significant discharge even in the dry season. These perennial rivers are the major sources of water for drinking, irrigation, industrial processing and hydropower generation (Chaulagain, 2009). However, the stream flow data over the last 20 years has shown a downward trend in major rivers, particularly due to the gradual disappearance of glaciers, which may reduce the water availability for use in the future (Gautam and Achary, 2012).

The current river flow gradient and river width in the upstream from the hills and mountains in Nepal make it suitable for hydropower production. Technically, 40,000 MW of hydropower production is feasible. However, despite this potential, Nepal currently only has a total of 787 MW installed capacity while the annual peak demand in FY2014/15 was 1,286 MW (NEA, 2015). Fourty percent of the population has access to electricity. It is estimated that electricity demand in Nepal increased annually at an average rate of 9% and peak demand increased by 8.9% (NEA, 2015). Except for one hydropower plant, all other hydropower plants in Nepal are run-off-river (RoR) plants, the power generation of which is affected by decreased river discharge in the dry season. In this context, Nepal's power security is at high risk from impacts of seasonal water variability induced by climate change.

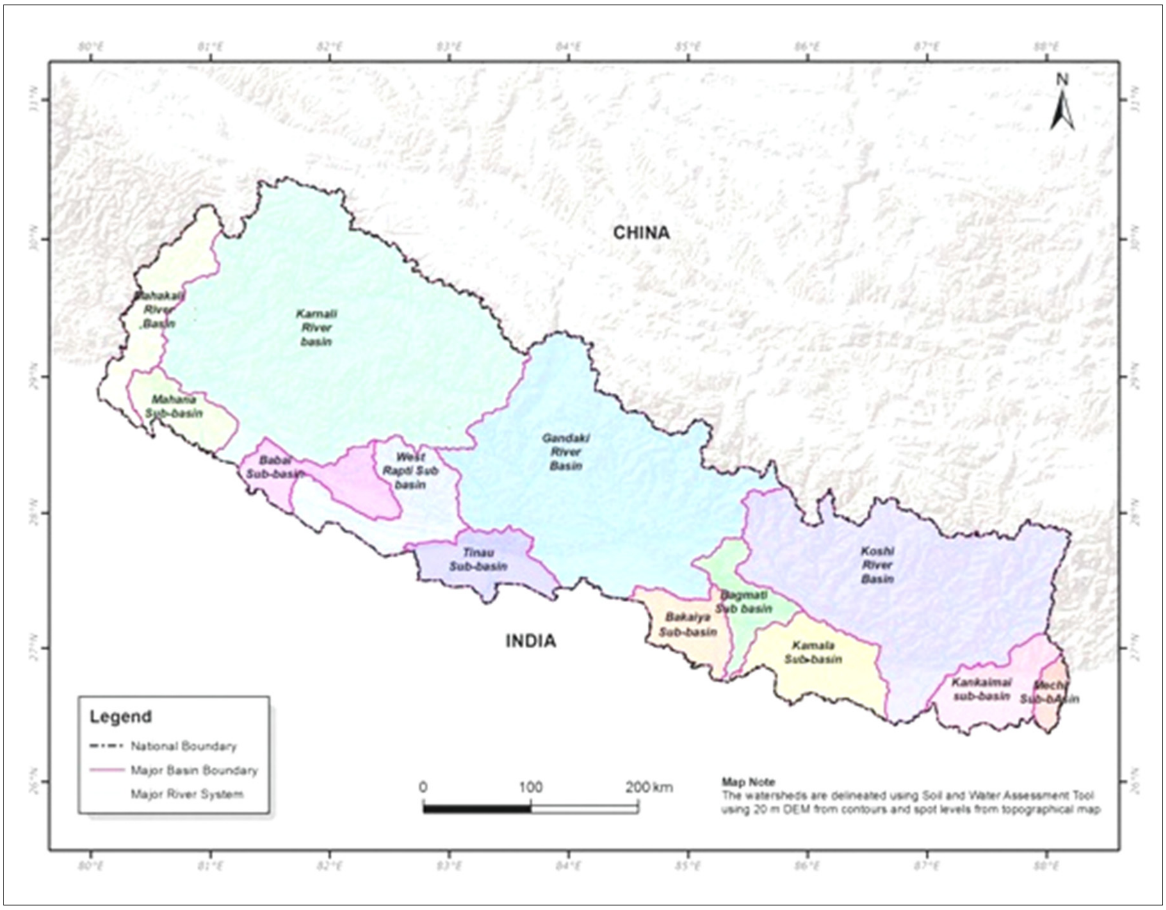

Figure A1-1 Major river basins in Nepal

Though 81% of irrigable land has access to water, water supply is uncertain due to the impacts from climate change and unmanaged water distribution. Of 2,642,000 ha (18%) of the land suitable for cultivation, Nepal has 1,766,000 ha (66.66%) potential for irrigation. So far, only 17% of the cultivated area has year-round irrigation and 42% of the cultivated area is rain fed (WECS, 2011). Water supply for domestic use (drinking water) and industrial use has been manageable and met the demand mainly due to low population and small-scale industrialisation.

Studies on water resources at the basin level in Nepal are scent, possibly due to the lack of hydro-meteorological data or poor data quality. Koshi river basin is the most abundantly studied basin. This case study will contribute to understanding the water resource situation in Nepal at the basin level.

Water resource, mainly used for the domestic sector (drinking), irrigation and the industrial sector, is not adequately utilised, especially for the latter two users. This case study intends to contribute to the development of methods for estimation and projection of water demand from domestic, irrigation and industrial sectors. Water demand will be estimated and projected for major river basins.

Study on the water availability in the river basins and impacts of climate change on water resource availability will help understand the nexus between climate change and water. The extension of the climate-water nexus study to include hydropower generation at the river basin level can be considered as the first of its kind for Nepal. It will enhance the scientific understanding of the climate-water-energy nexus for Nepal, which contributes to strengthening integrated water resource management and harnessing the potential for cross-border collaboration with neighboring countries, particularly after Nepal has put related provisions such as the Power Trading Agreement (PTA) and the Project Development Agreement (PDA) into place.

All river basins in Nepal flow into the Ganges river basin. A major part of the snow-clad mountains of the Hindu Kush region lies within Nepal, which serves as the major source of fresh water in the Ganges basin. Snow cover and glaciers contribute to keeping a positive water balance in the basin throughout the year. Hydrology alterations in this region may impact the whole Ganges river basin and climate change has already been identified as a major threat. The current case study is therefore very important for estimating possible future water availability in the basin and related implications for the demand sectors.

2. Water availability and water demand assessment

Studies on water availability and water demand are important for optimal planning and management of water resources. Per capita water availability is generally estimated for the whole country, which may not be appropriate for the basin level. As water availability varies according to basin, it would be more appropriate to find such value basin-wise. Here, the study has been done at the basin level, and is important for the development of Integrated Water Resources Management (IWRM). Also, such study can be helpful in assessing possibilities of inter-basin water exchange schemes.

The total area of Nepal has been classified under three types of river basins based on their drainage area: the first type are the major river basins that include the basins Koshi, Gandaki and Karnali; the second type are the basins Kankai, Kamala, Bagmati, West Rapti, Babai and Mahakali. Some of these river basins originate in the Himalayas, and include snowmelt contribution while some originate in the hills. Besides these two types, there are numerous perennial and non-perennial river basins in the southern part of the country originating in the lower hills, collectively known as Southern Rivers (**Figure A1-2**).

A process, namely the assessment based on the area contributed, has been applied to find the individual districts (administrative division of Nepal) that can be grouped under the basins. As most of the data such as human population, cultivated area and production value, number of industries, etc., are determined with reference to the districts, it would be appropriate to group them under the basins.

The study of basin-wise sectoral water demand is based on the findings of individual districts and their summation according to the list above.

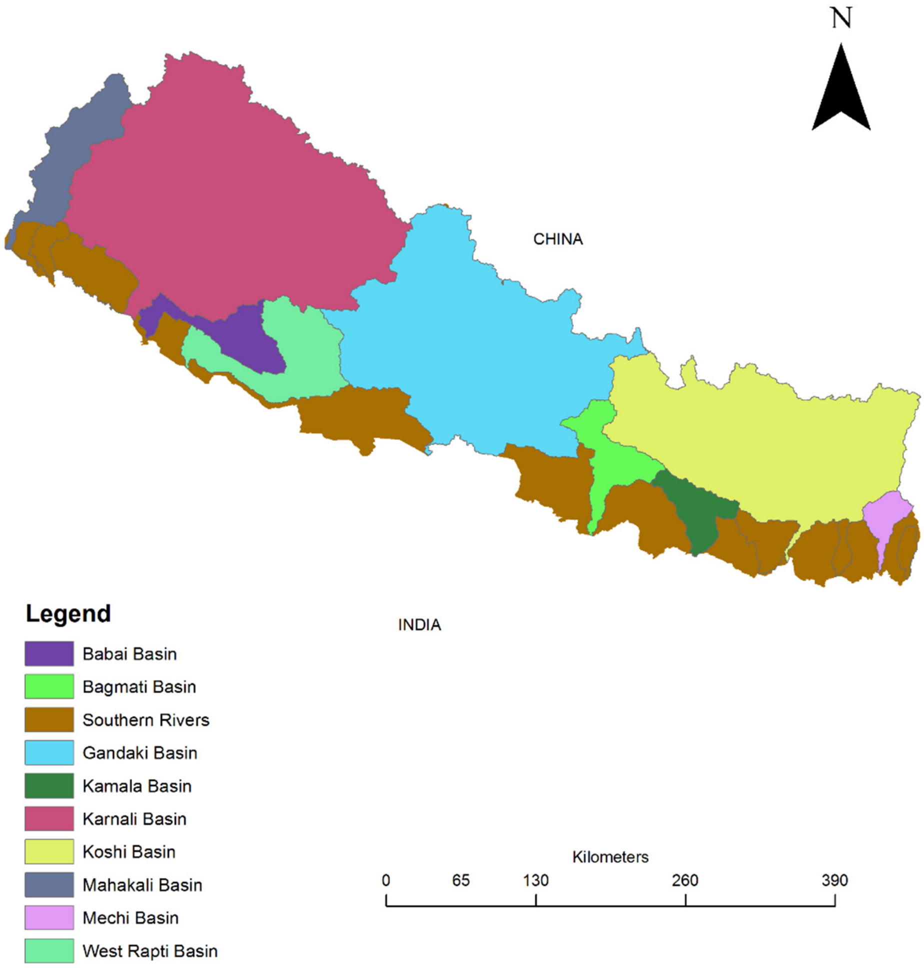

Figure A1-2 Major and minor river basins and southern river basins of Nepal

2.1 Assessment of water availability

The water availability in the river basins of Nepal has been studied from relevant papers and reports. Although some of the basins such as Bagmati, Koshi and Gandaki have been studied extensively in the past, the remainder have not been studied or documented to the same extent.

These river systems in Nepal are important mainly for irrigation, water supply and hydropower production. Agreements on river systems such as the Koshi Barrage Agreement (for flood control and water supply), the Gandaki Project, and the treaty on the integrated development of the Mahakali River, are important treaties between Nepal and India.

Major river basins (Mahakali, Karnali, Koshi, etc.) originate in the Himalayas and store huge amounts of fresh water in the form of snow and glaciers. Similarly, minor river basins (Bagmati, Rapti, etc.) are dependent on rainfall and groundwater sources; Southern rivers depend almost completely on rainfall. The values of total annual water availability in these basins is discussed below.

Water balance in the major river basins of Nepal is shown in **Figure A1-3** (WECS, 2011). The figure shows that water balance reaches zero in April for some basins but never becomes negative.

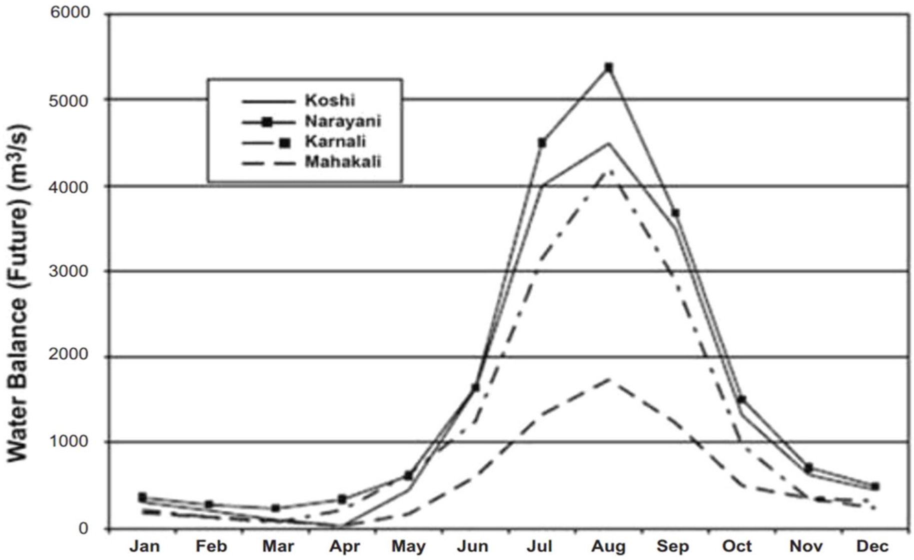

Figure A1-3 Water balance in major river basins of Nepal

Source: WECS, 2011

Water balance in the minor river basins of Nepal, shown in **Figure A1-4**, becomes negative during dry seasons (WECS, 2011). The water balance analysis of the major rivers of Nepal reveals that there is a possibility of positive water balance both during dry and wet months for rivers such as Koshi, Narayani (Gandaki), Karnali, and Mahakali. Meanwhile, water balance in minor rivers such as Kankai, Kamala is negative during dry months, as shown in **Figure A1-4**.

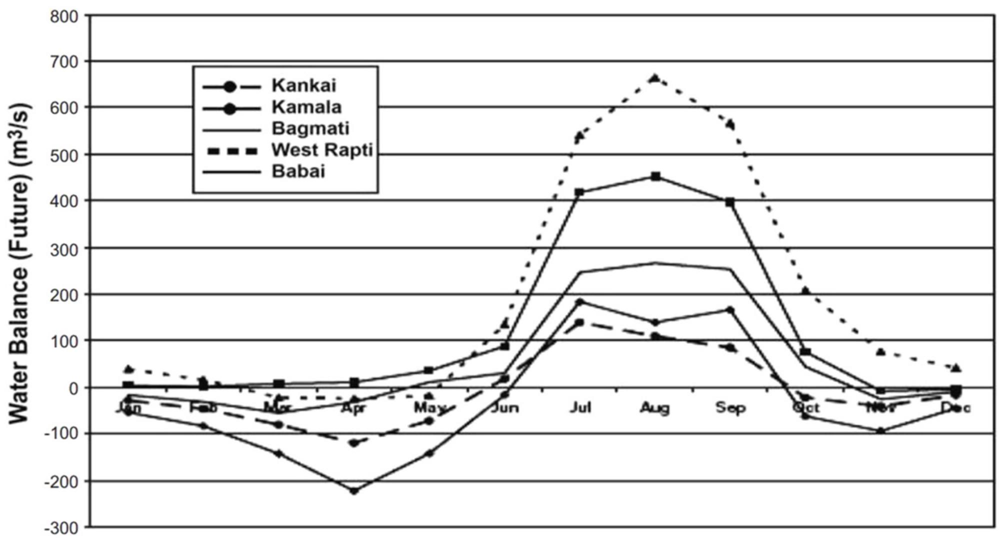

Figure A1-4 Water balance in minor river basins of Nepal

Source: WECS, 2011

2.2 Assessment of current and future water demand

Water demand in the river basins of Nepal has been calculated based on information available at the district level. **Table A1-1** lists different districts within relevant river basins and the area they account for. 'Y' and 'N' have been applied to refer to whether the district was included (Y) or not included (N) under the particular basin or others. The results are also depicted in the map (**Figure A1-5**).

For the three sectors (industry, domestic and agriculture), the current and future water demand has been calculated based on the methodology explained for each sector in the following sections.

Table A1-1 Percentage of the area of the administrative districts included within relevant river basins in Nepal

Districts	% area within the basin	Included-Y/ Not included-N	Districts	% area within the basin	Included-Y/ Not included-N
Mahakali Basin (1)			**Bagmati Basin (6)**		
Darchula	100	Y	Kathmandu	98	Y
Bajhang	2.8	N	Kavre	24.4	N
Baitadi	80.5	Y	Bhaktapur	98.4	Y
Doti	1.1	N	Makwanpur	26.6	N
Dadeldhura	77.3	Y	Lalitpur	100	Y
Kanchanpur	10.3	N	Sindhuli	38	N
Kailali	0.2	N	Rautahat	48.5	N
Karnali Basin (2)			Sarlahi	7	N
Humla	100	Y	Nawalparasi	30.7	N
Bajhang	97.2	Y	Kapilbastu	100	Y
Mugu	100	Y	Rupandehi	100	Y
Bajura	100	Y	Makwanpur	14.9	N
Baitadi	19.2	N	Parsa	100	Y
Dolpa	100	Y	Sindhuli	0.1	N
Jumla	100	Y	Panchthar	0	N
Kalikot	100	Y	Bara	100	Y
Doti	98.9	Y	Rautahat	51.5	Y
Dadeldhura	20.7	N	Dhankuta	2.6	N
Achham	100	Y	Sarlahi	93	Y
Dailekh	100	Y	Udayapur	46.2	Y
Jajarkot	100	Y	Mahottari	100	Y
Kailali	19.1	N	Ilam	31.1	N
Rukum	98.4	Y	Dhanusa	80.3	Y
Surkhet	100	Y	Siraha	38.9	N
Myagdi	16.3	N	Saptari	100	Y
Bardiya	27	N	Morang	100	Y
Salyan	34	N	Sunsari	83.3	Y
Baglung	17.4	N	Jhapa	93.5	Y
Rolpa	2.3	N	**Koshi Basin (7)**		
Babai Basin (3)			Sindhupalchok	100	Y
Surkhet	0.7	N	Dolakha	100	Y
Bardiya	36.9	Y	Solukhumbu	100	Y

Districts	% area within the basin	Included-Y/ Not included-N	Districts	% area within the basin	Included-Y/ Not included-N
Salyan	64.8	Y	Sankhuwasabha	100	Y
Rolpa	5.7	N	Taplejung	100	Y
Banke	2.4	N	Ramechhap	100	Y
Dang	39.7	N	Kathmandu	0.7	N
West Rapti Basin (4)			Kavre	75.6	Y
Rukum	1.5	N	Bhaktapur	1.6	N
Salyan	1.2	N	Lalitpur	0.2	N
Baglung	0	N	Okhaldhunga	100	Y
Rolpa	91.8	Y	Bhojpur	100	Y
Pyuthan	100	Y	Sindhuli	22.9	N
Banke	60.1	Y	Khotang	100	Y
Gulmi	3.3	N	Panchthar	100	Y
Dang	49.1	Y	Tehrathum	100	Y
Arghakhanchi	53.8	Y	Dhankuta	97.4	Y
Kapilbastu	0.2	N	Udayapur	33.3	N
Gandaki Basin (also called Narayani Basin) (5)			Ilam	0.3	N
Mustang	100	Y	Morang	0.1	N
Manang	100	Y	Sunsari	16.7	N
Myagdi	83.7	Y	**Kamala Basin (8)**		
Gorkha	100	Y	Sindhuli	39	Y
Baglung	82.5	Y	Udayapur	20.5	N
Kaski	100	Y	Mahottari	0.1	N
Lamjung	100	Y	Dhanusa	19.7	N
Parbat	100	Y	Siraha	61.1	Y
Rasuwa	100	Y	**Kankai Basin (9)**		
Dhading	100	Y	Panchthar	0.1	N
Gulmi	96.7	Y	Ilam	68.5	Y
Syangja	100	Y	Jhapa	6.5	N
Tanahu	100	Y	**Southern Rivers (10)**		
Arghakhanchi	32.7	N	Kanchanpur	87.4	Y
Nuwakot	100	Y	Kailali	80.7	Y
Palpa	59.5	Y	Bardiya	36.1	N
Chitwan	100	Y	Banke	37.5	N
Nawalparasi	69.3	Y	Dang	11.2	N
Makwanpur	58.5	Y	Arghakhanchi	13.6	N
			Palpa	40.5	N

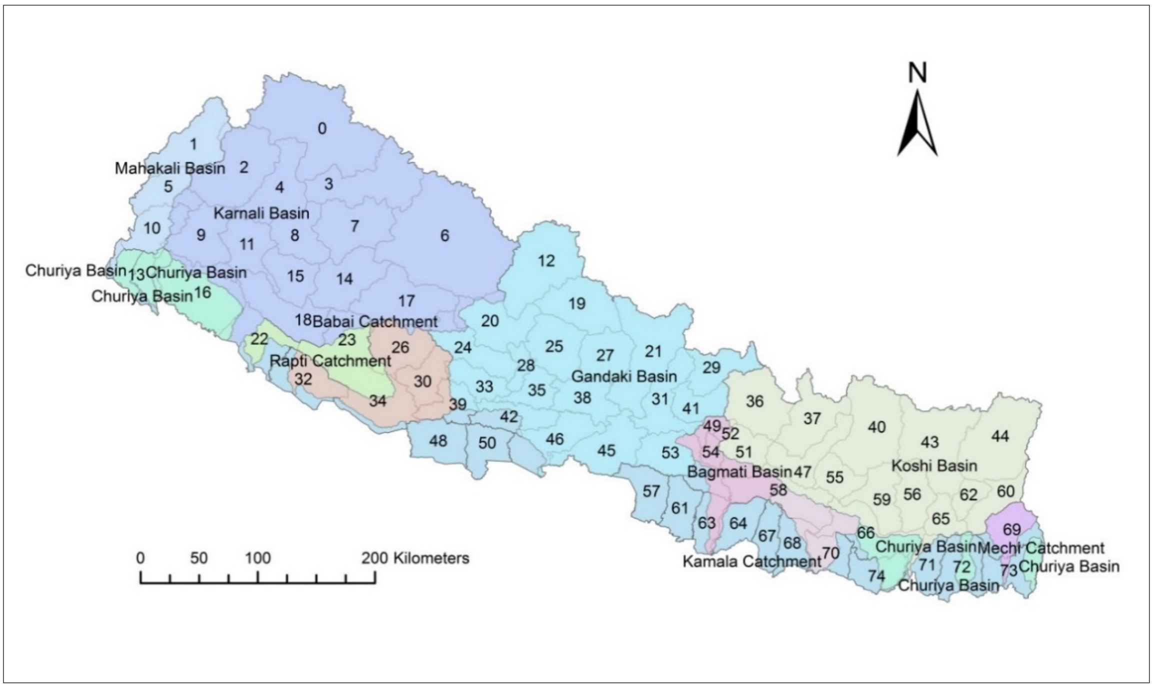

Figure A1-5 Nepal map showing all 75 administrative districts within basins

2.2.1 Domestic water demand

Domestic water demand is calculated based on liters per capita per day (lpcd) coefficients adopted from the guidelines and reports of the Government of Nepal (GoN). The population data was taken from the census report of the GoN. For future population projection, the growth rates have been calculated for individual districts over the past three decades (1981-2011) and the prediction was made to extrapolate the trend up to 2050 (see **Table A1-2**). The equation for estimating future population (*P*2) based on the exponential growth rate (*R*), the base-year population (*P*1) and time (*T*) is:

$$P2 = P1 * e^{(R*T)}$$

Table A1-2 Population growth (2011-2050) based on average exponential increase during 1981-2011

District	Average population increase (%) (1981-2011)	Population (Estimation based on 2011)				
		2017	2020	2030	2040	2050
Achham	1.1	275,012	284,223	317,212	354,029	395,120
Arghakhanchi	0.76	206,862	211,637	228,366	246,417	265,895
Baglung	0.74	280,784	287,075	309,080	332,773	358,281
Baitadi	1.12	268,386	277,582	310,572	347,484	388,782
Bajhang	1.51	213,685	223,598	260,083	302,521	351,884
Bajura	1.97	151,864	161,123	196,261	239,061	291,196
Banke	2.91	584,982	638,314	853,771	1,141,953	1,527,408
Bara	2.56	801,934	865,976	1,118,741	1,445,285	1,867,143
Bardiya	2.54	496,828	536,180	691,289	891,269	1,149,100

District	Average population increase (%) (1981-2011)	Population (Estimation based on 2011)				
		2017	2020	2030	2040	2050
Bhaktapur	2.15	346,630	369,741	458,496	568,557	705,038
Bhojpur	-0.18	180,479	179,497	176,263	173,087	169,968
Chitwan	2.68	681,158	738,183	965,052	1,261,645	1,649,392
Dadeldhura	1.64	156,796	164,707	194,078	228,686	269,466
Dailekh	1.51	286,554	299,813	348,601	405,329	471,287
Dang	2.43	639,400	687,796	877,172	1,118,690	1,426,707
Darchula	1.3	144,091	149,824	170,634	194,334	221,326
Dhading	1.08	358,465	370,217	412,248	459,049	511,164
Dhankuta	0.77	171,119	175,108	189,088	204,184	220,485
Dhanusa	1.86	843,667	891,965	1,073,830	1,292,776	1,556,363
Dolakha	0.71	194,725	198,943	213,672	229,491	246,481
Dolpa	1.7	40,639	42,765	50,685	60,073	71,200
Doti	1.08	225,925	233,366	259,987	289,644	322,685
Gorkha	0.53	279,800	284,274	299,713	315,990	333,151
Gulmi	0.54	289,421	294,166	310,552	327,850	346,112
Humla	3.06	61,111	66,988	90,977	123,556	167,802
Ilam	1.62	319,946	335,912	395,114	464,750	546,658
Jajarkot	1.82	191,038	201,742	241,946	290,162	347,987
Jhapa	1.76	902,989	951,858	1,134,672	1,352,598	1,612,378
Jumla	1.53	119,404	125,018	145,710	169,825	197,932
Kailali	3.67	966,822	1,079,371	1,558,058	2,249,037	3,246,457
Kalikot	1.49	149,737	156,572	181,692	210,842	244,668
Kanchanpur	3.27	549,207	605,893	840,615	1,166,268	1,618,078
Kapilbastu	2.5	664,553	716,343	919,937	1,181,395	1,517,163
Kaski	2.66	577,400	625,445	816,390	1,065,629	1,390,959
Kathmandu	4.73	2,316,414	2,669,447	4,283,228	6,872,602	11,027,351
Kavre	0.73	398,951	407,741	438,461	471,496	507,020
Khotang	-0.1	205,082	204,470	202,444	200,437	198,450
Lalitpur	3.11	564,050	619,145	844,710	1,152,453	1,572,312
Lamjung	0.31	170,897	172,506	177,980	183,628	189,454
Mahottari	1.84	700,952	740,795	890,698	1,070,934	1,287,642
Makwanpur	1.82	469,054	495,408	594,425	713,232	855,785
Manang	-0.24	6,445	6,400	6,249	6,103	5,959
Morang	1.97	1,086,455	1,152,579	1,403,463	1,708,956	2,080,947
Mugu	0.78	57,947	59,325	64,161	69,390	75,045
Mustang	0.13	13,559	13,613	13,793	13,977	14,162
Myagdi	0.53	117,320	119,205	125,706	132,563	139,793
Nawalparasi	2.45	745,283	802,057	1,024,435	1,308,469	1,671,254
Nuwakot	1.04	295,374	304,754	338,226	375,374	416,603
Okhaldhunga	0.24	150,144	151,236	154,934	158,722	162,602
Palpa	0.66	271,685	277,095	295,919	316,021	337,489
Panchthar	0.74	200,495	204,980	220,668	237,557	255,738
Parbat	0.44	150,526	152,534	159,421	166,619	174,143
Parsa	2.49	698,067	752,319	965,501	1,239,092	1,590,209
Pyuthan	1.23	245,587	254,826	288,207	325,961	368,661

District	Average population increase (%) (1981-2011)	Population (Estimation based on 2011)				
		2017	2020	2030	2040	2050
Ramechhap	0.76	212,071	216,946	234,022	252,442	272,311
Rasuwa	1.2	46,523	48,223	54,352	61,261	69,047
Rautahat	2.42	793,911	853,626	1,087,058	1,384,324	1,762,881
Rolpa	0.96	237,877	244,858	269,641	296,934	326,989
Rukum	1.51	228,400	239,013	278,082	323,536	376,421
Rupandehi	2.81	1,041,707	1,133,257	1,500,624	1,987,079	2,631,229
Salyan	1.55	266,152	278,861	325,775	380,580	444,606
Sankhuwasabha	0.68	165,361	168,774	180,665	193,395	207,022
Saptari	1.74	709,728	747,810	890,134	1,059,544	1,261,197
Sarlahi	2.19	877,934	937,613	1,167,429	1,453,573	1,809,854
Sindhuli	1.59	325,885	341,829	400,830	470,014	551,139
Sindhupalchok	0.71	300,390	306,891	329,596	353,979	380,167
Siraha	1.76	708,511	747,030	891,204	1,063,204	1,268,398
Solukhumbu	0.61	109,817	111,836	118,841	126,284	134,194
Sunsari	2.65	895,160	969,281	1,263,614	1,647,324	2,147,552
Surkhet	2.49	407,337	438,932	563,048	722,260	926,492
Syangja	0.21	292,743	294,557	300,687	306,943	313,330
Tanahu	1.23	348,078	361,176	408,505	462,034	522,579
Taplejung	0.18	128,841	129,536	131,882	134,270	136,702
Tehrathum	0.31	103,507	104,486	107,815	111,251	114,796
Udayapur	2.29	364,273	390,164	490,508	616,659	775,254

Based on the above population projection at the district level, water demand was calculated for individual basins (**Figure A1-6**). For 2017, daily per capita water demand of 45 lpcd (MoUD, 2005) and the nationwide water supply coverage rate in 2014, published by the National Management Information Project (NMIP) (NMIP, 2014), were used. Water supply coverage rate means the percntage of households that have access to the basic water supply through government or community-based initiatives. For 2020, 95% water supply coverage and 45 lpcd daily per capita water demand were used. For 2030, 2040 and 2050, 100% water supply coverage and the daily per capita water demand of 100 lpcd recommended by the World Health Organization were used.

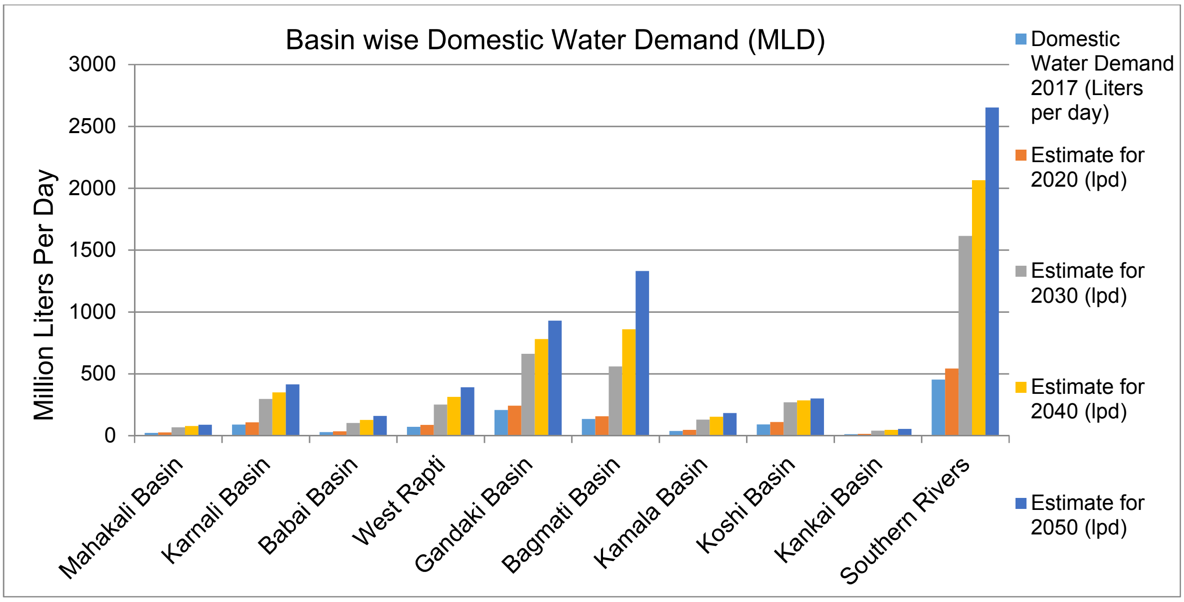

Figure A1-6 Basin-level domestic water demand (2017-2050)

Table A1-3 presents daily domestic water demand up to 2050 for different river basins in Nepal (see also **Figure A1-6**). Domestic water demand includes water for drinking and other household purposes.

Table A1-3 Domestic water demand in litres per day (lpd)

River Basins	2017	2020	2030	2040	2050
Mahakali Basin	21,798,578	25,312,847	67,528,446	77,050,424	87,957,414
Karnali Basin	88,702,229	107,621,186	296,292,192	349,948,261	414,814,249
Babai Basin	28,451,153	34,843,004	101,706,364	127,184,945	159,370,669
West Rapti	70,602,122	87,100,208	251,715,779	312,995,489	391,565,870
Gandaki Basin	206,523,080	241,413,174	661,273,227	780,915,920	929,865,712
Bagmati Basin	134,336,252	156,393,696	558,643,458	859,361,228	1,330,470,070
Kamala Basin	36,944,936	46,548,738	129,203,399	153,321,732	181,953,721
Koshi Basin	90,184,985	109,459,047	269,835,008	284,659,405	300,593,522
Kankai Basin	11,083,240	14,360,233	39,511,379	46,474,960	54,665,818
Southern Rivers	452,953,551	542,069,791	1,613,778,430	2,065,367,865	2,652,216,300

2.2.2 Industrial water demand

Industrial facilities consume large amounts of water and the rate of consumption varies according to the type of products. In Nepal, the industrial sector has been growing in recent years. Although industrialisation started about 26 years ago, comprehensive information about employment, outputs, resource consumption and waste generation is poorly documented.

In this case study, industrial water use coefficients were used. The coefficients were estimated based on the total amount of water used by particular industrial sub-sectors in the form of 'liter per employee per Day (LED)'. LED includes both water used for production and water used by employees working at industrial facilities during their working hours.

The trend of annual industrial growth in all districts has been studied between 1991 and 2016 and the average growth rate was calculated (**Table A1-4**).

Table A1-4 Annual growth rate of industries in all districts in Nepal (1991-2016)

S.N.	Districts	Total industries	Average annual increase (%)	S.N.	Districts	Total industries	Average annual increase (%)
1	ACHHAM	4	8.7	39	LAMJUNG	26	16.9
2	ARGHAKHACHI	3	7.7	40	MAHOTTARI	5	9.6
3	BAGLUNG	10	12.9	41	MAKWANPUR	102	19.2
4	BAITADI	6	13.3	42	MANANG	1	4.2
5	BAJHANG	4	16.8	43	MORANG	233	8.5
6	BAJURA	1	4.2	44	MUGU	2	6.3
7	BANKE	72	12.5	45	MUSTANG	7	11.0
8	BARA	212	14.0	46	MYAGDI	14	16.4
9	BARDIYA	16	15.2	47	NAWALPARASI	105	16.7
10	BHAKTAPUR	150	8.9	48	NUWAKOT	39	14.2
11	BHOJPUR	7	6.8	49	OKHALDHUNDA	1	4.2
12	CHITWAN	174	10.8	50	PALPA	7	11.8
13	DADELDHURA	5	9.8	51	PANCHATHAR	9	16.9
14	DAILEKH	4	9.4	52	PARBAT	3	9.8
15	DANG	35	11.7	53	PARSA	148	9.3
16	DARCHULA	6	10.6	54	PYUTHAN	2	8.4
17	DHADING	50	27.4	55	RAMECHHAP	11	14.1
18	DHANKUTA	16	8.7	56	RASUWA	17	16.9
19	DHANUSHA	33	14.8	57	RAUTAHAT	9	5.3
20	DOLKHA	33	18.2	58	ROLPA	3	8.4
21	DOLPA	1	0.0	59	RUKUM	2	8.4
22	DOTI	6	10.8	60	RUPANDEHI	185	12.3
23	GORKHA	24	9.7	61	SALYAN	1	4.2
24	GULMI	5	9.8	62	SANKHUWASABHA	15	10.0
25	HUMLA	5	10.3	63	SAPTARI	12	9.6
26	ILAM	38	10.8	64	SARLAHI	16	5.2
27	JAJARKOT	3	8.4	65	SINDHULI	2	6.3
28	JHAPA	104	14.5	66	SINDHUPALCHOWK	44	14.8
29	JUMLA	0	0.0	67	SIRAHA	9	11.3
30	KAILALI	36	18.0	68	SOLUKHUMBU	35	14.9
31	KALIKOT	4	9.1	69	SUNSARI	124	9.9
32	KANCHANPUR	28	10.9	70	SURKHET	8	11.7
33	KAPILBASTU	31	13.2	71	SYANGJA	4	5.2
34	KASKI	329	13.6	72	TANAHU	18	15.6
35	KATHMANDU	2912	11.7	73	TAPLEJUNG	11	13.5
36	KAVRE	137	13.8	74	TEHRATHUM	5	9.9
37	KHOTANG	4	9.4	75	UDAYPUR	5	10.3
38	LALITPUR	726	15.3				

2.2.3 Agricultural water demand

The agricultural sector is the largest consumer of water resources in the world (**Figure A1-7**) and the trend will continue in the future. Both the industrial sector and the domestic sector have a water footprint in agricultural water. The agricultural sector effectively utilises rainfall and groundwater sources. For high productivity and production in non-rain fed areas or in the dry season, a large amount of water is required for irrigation.

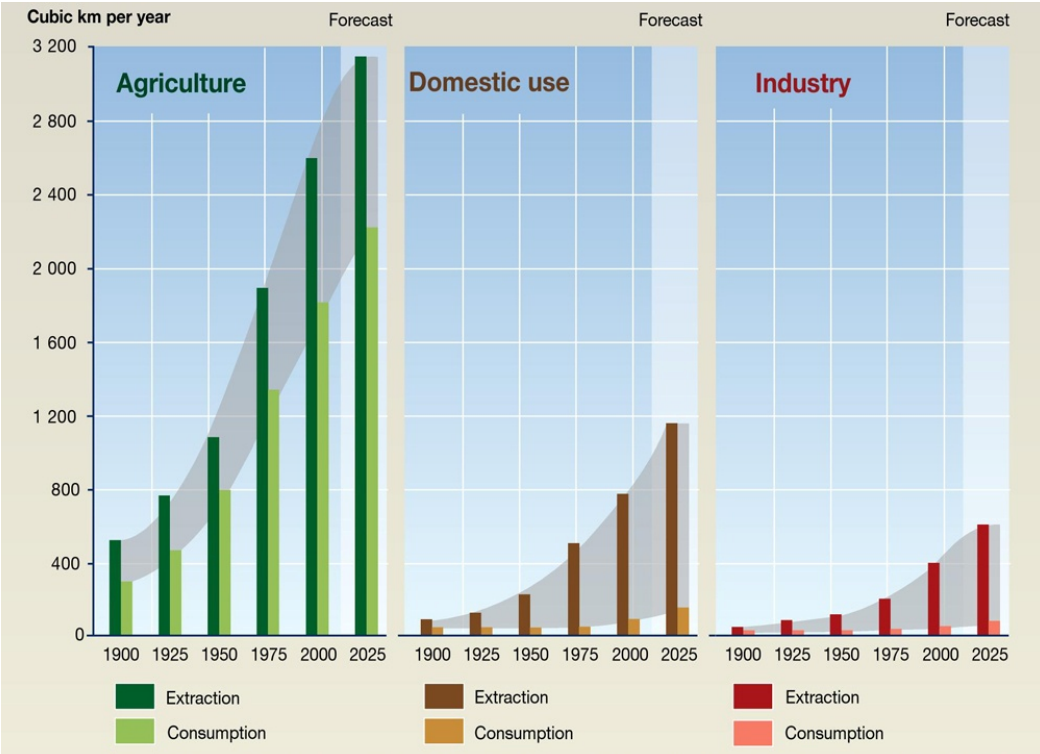

Figure A1-7 Trends in global water use

Source: Igor and Jeanna (2003)

In **Figure A1-7**, the shaded area in grey is the difference between water extraction and water consumption. In addition, the figure shows that the amount of water used for agriculture is the highest compared to domestic and industrial uses. In order to reduce the gaps in irrigation water supply and increase water irrigation efficiency, sewage from domestic water consumption can be reused for agriculture.

Agriculture is the backbone to Nepal's economy. Agricultural practices and technologies in Nepal still follow traditional norms, which require substantial improvement in terms of optimal water use. Large amounts of irrigable land for high value-added crops which generally require large amounts of water are generally not adapted by the farmers until now. Therefore, enhancement of irrigation systems to improve agriculture productivity will require a huge amount of water.

Agriculture is still practiced using traditional methods. Numerous farmers with land inherited from ancestors continue family traditions. The holdings are small in size and most keep livestock as a second source of income besides farming. In the estimation of agricultural water demand for individual basins, livestock water demand was added to the irrigation water demand to calculate the total agricultural water demand.

2.3 Assessment of water supply-demand gap

Water availability and water demand of the river basins in Nepal as discussed in previous sections are summarised in this section. Not all the available water can be used for the final demand and a certain amount is required for environmental needs. Some water projects in the basins are also targeted at people living in nearby basins or in neighboring countries. Under these circumstances, water supply-demand gaps assessed within the basin boundaries may not be sufficient to understand the overall picture.

Power supply and demand scenarios

Power supply is the backbone to national economic and social development. The history of power production in Nepal dates back to 1911 when the first hydropower station (the second one in Asia), Pharping Hydropower Station, was built. However, efforts in electrification and adequate electricity supply cannot keep up with rising demand and Nepal is continuously suffering from load shedding.

The load curve on November 11, 2015 provided by the Load Dispatch Center (LDC) of Nepal Electricity Authority (NEA) is presented in **Figure A1-8**. The figure shows energy sources currently available in Nepal and the gaps during the peak load hours.

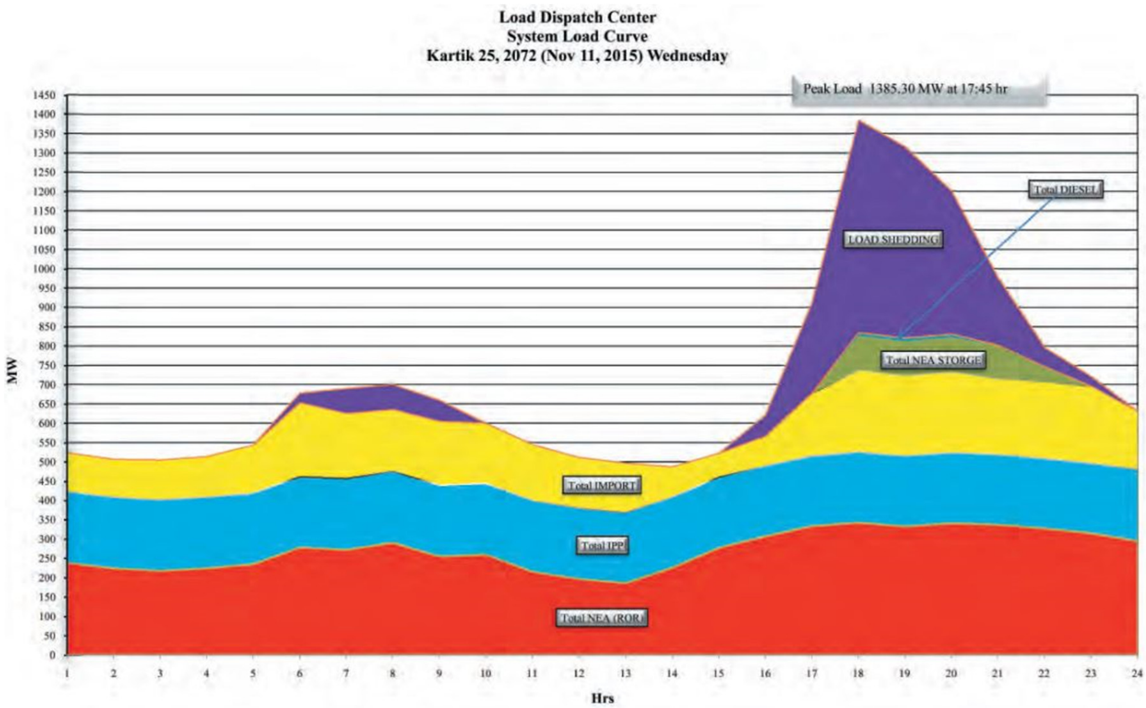

Figure A1-8 System load curve

Source: Nepal Electricity Authority, 2016

The current installed capacity in Nepal is 1,075 MW from hydropower. Thermal and solar plants with total capacity of 1,017 MW are under construction. Similarly, 2,920 MW hydropower mainly of reservoir types are proposed or planned for design and construction in the near future (NEA, 2018)

Electric energy consumption in Nepal is 139 kWh per capita (2014), which is significantly lower than the worldwide average of 3,128 kWh (IEA Statistics, 2014). The low per capita energy consumption is an indicator reflecting the scale of the economy and the condition of electric energy supply. GDP has not risen sufficiently in Nepal because many local industries suffer from serious shortage of electric energy and have to use expensive energy sources based on fossil fuels. Electrification in Nepal has not yet achieved 100% (**Figure A1-9**). The current very low per capita electricity consumption and potentially further improvement in electrification imply that demand for electric energy will increase many times over in the future.

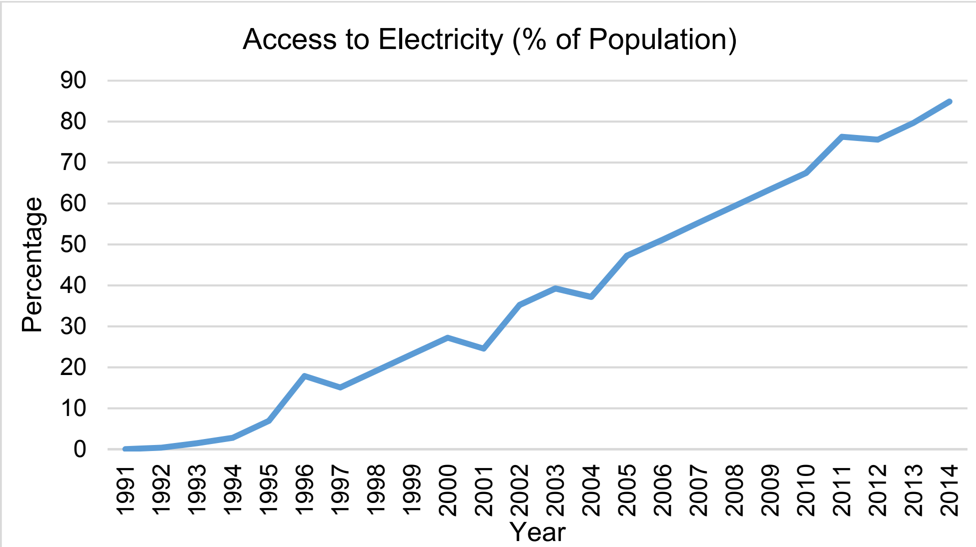

Figure A1-9 Electrification in Nepal

Source: The World Bank database.

The Water and Energy Commission Secretariat of the GoN conducted a study on electricity demand forecast up to 2040. The study estimated per capita electricity requirements in Nepal under a Business as Usual (BAU) scenario, a reference level economic scenario, and a high level economic scenario (**Table A1-5** and **Figure A1-10**). In addition, the estimates are also provided under different policy intervention scenarios.

Nepal has been facing an energy crisis over the past several decades. The installed capacity of all types of power plants is not enough to meet the power demand. Total energy imported from India during the year 2017-2018 was 2,582 GWh and increased year by year (A year in Review, Fiscal Year 2017/2018).

Table A1-5 Per Capita electricity demand under different scenarios

Year	BAU, 4.5%	Reference scenario, 7.2%	High scenario, 9.2%	Policy intervention, 7.2%	Policy intervention, 9.2%
2015	138	138	138	138	138
2020	271	291	304	531	547
2025	464	531	591	801	867
2030	716	891	1,067	1,261	1,474
2035	1,062	1,454	1,892	1,848	2,345
2040	1,536	2,361	3,388	2,927	4,118

Source: WECS, 2017.

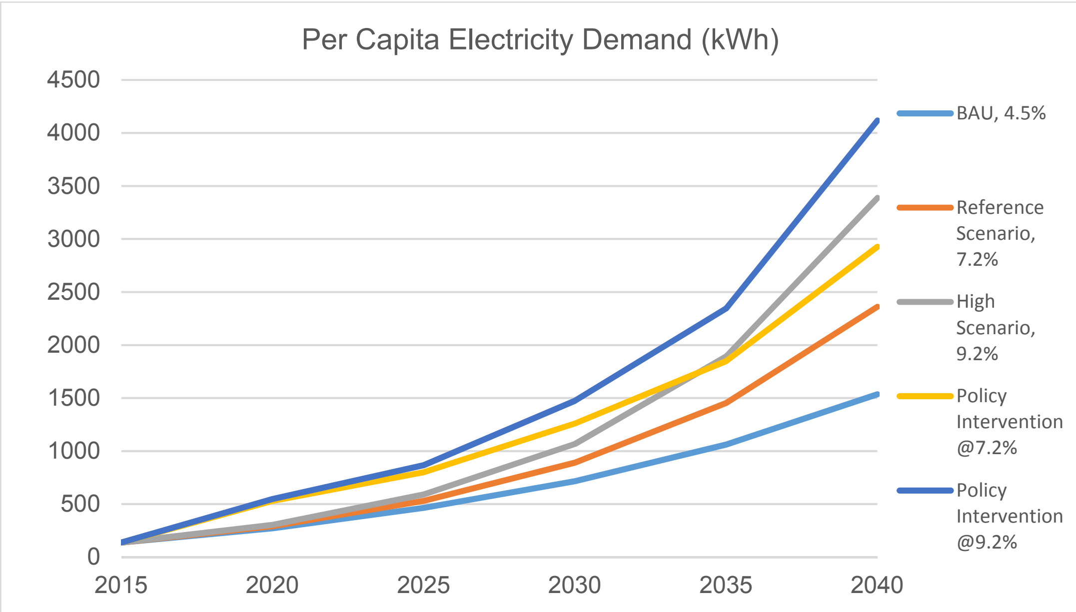

Figure A1-10 Per capita electricity demand 2015-2040

Source: WECS, 2017

2.4 Assessment of the challenges and opportunities in the hydropower sector in Nepal

Hydropower, a renewable source of energy generated from flowing water, is a sustainable source with low environmental impacts in terms of heat and pollutants, low investment operation and maintenance costs and flexible and reliable operations. However, large hydro dams have ecological impacts on hydrology and aquatic biodiversity. According to Bunn and Arthington (2002) there are three types of impacts, i.e., i) biotic responses to the altered flow regimes and associated changes in habitats; ii) life history responses to the altered flow regimes; and iii) biotic responses to the loss of longitudinal or lateral connectivity. The impacts of hydropower infrastructure have been reported in other literature. Dams alter the natural cycle of water flow and transform the biological and physical characteristics of the river channels and floodplains (Petts, 1984; Poff et al., 1997). The movement of sediments, nutrients and organisms between water and land may be restricted due to the reduction in overbank floods (Junk et al., 1989). The turbines in hydroelectric projects operated for water release from the reservoirs can harm fish and other biota (Dadswell, 1996).

Nepal has the highest per capita hydropower potential in the world and hydropower development can be a fundamental key to support Nepal's economic development, achieve the national goals and alleviate poverty (Adhikari, 2006). However, until now, Nepalese power supply has heavily relied on energy imports from India and purchases from independent power producers (IPPs) (Nepal Electricity Authority, 2017). Nepal has not yet realised the prospect of utilising its hydropower potential due to the lack of proper planning, insufficient investment in generation, transmission and distribution, inadequate policies and lack of legal and regulatory frameworks and associated policies and plans.

As per the 14th National Plan of the National Planning Commission, the total installed capacity will be 829 MW and the total length of transmission lines will be 2,848 km. It was aimed to increase electricity access to 87% of the population by the end of the 13th National Plan; however, only 74% has been achieved.

2.4.1 Assessment of the challenges of the hydropower sector in Nepal

Hydropower development can make significant contributions to national economic development. However, Nepal is now facing many technical and financial challenges which need to be addressed properly.

Technical challenges

Nepal is endowed with rich hydro resources but the country is still striving to achieve its economic prosperity due to limited hydropower development. Due to geology fragility, hydrologic variability, geotechnical constraints, difficult terrain and sparse hydro meteorological networks, etc., hydropower development is constrained. Some of the technical challenges in Nepal (Baral, 2014) are summarised as follows.

(i) Geology fragility

About 75% of Nepal is within the Himalayan region. The weak rock geological formation makes the Himalayas fragile. Because of this, it is very important to understand the geological fragility of the hydropower project sites and other factors that may assist in developing safer hydropower infrastructure, as well as in mitigating natural hazards and environmental degradation (Uprety, 2000).

(ii) Hydrologic variability

Nested in the Hindu Kush Himalayas, Nepal experienced a warming trend between 1977 to 1994 at a rate of 0.06 °C and projection shows that the mean temperature will further increase by 1.2 °C by 2050 and 3 °C by 2100 (MOEnv, 2012). Temperature increase has significantly retreated the glaciers and melted the ice which has been contributing to the increase in the size and volume of the glacial lakes and in turn posing a risk to Glacial Lake Outburst (GLOF) in the Himalayas. There are more than 2,000 glacial lakes in the Nepal Himalayas. As glacier retreating and ice melting will continue, dry-season flows fed by the glacier melts in the monsoon season will be reduced and can be further worsened by climate change which impacts the variability in river flows. As a result, river flows/discharges will be unreliable in the dry season in the Himalayas, which may pose serious risks to investment in hydropower development projects (Agrawal et. al., 2003).

(iii) High rate of sedimentation

Most of the hydropower plants in the Himalayan Rivers are affected by excessive sedimentation which primarily decreases the capacity (life) of the reservoir (by decreasing the dead storage capacity) and fundamentally causes erosion that reduces efficiency and life of the turbine components. Excessive amounts of sediments in the Himalayan Rivers are mainly due to weak rocks and extreme relief representing hard abrasive mineral/rock fragments, with the sediments depending on the distance traversed by particles, gradient of the river and the geological formation of the river course as well as the area of the catchment (Thapa et al., 2005). Sedimentation in the 1993 monsoon (March to December, 1993) in the Kulekhani reservoir was 519 ha-m, thereby decreasing the reservoir capacity by 5.2 MCM (Sthapit, 1996).

To mitigate excessive sedimentation it is important to strengthen sediment monitoring and implement necessary countermeasures such as watershed management and the construction of sediment traps and structures to control sediments within the reservoir and watershed.

(iv) Geopolitical situation and topographical constraints

Nepal is landlocked by its borders with India in the south, the east and the west and with China's Tibet Autonomous Region in the north. West Bengal’s narrow Siliguri Corridor separates Nepal and Bangladesh. Nepal stretches as an 800 km long, 150-250 km wide corridor along the Himalayan axis, with an area of 147,181 km^2. Due to the difficult terrain with dispersed settlements, long transmission lines are required and the costs of connection to national or regional grids could be two to five times as high as those of electricity generation by large and centraliced power plants (Rechsteiner, 2001). To mitigate this risk, it is needed to amend relevant strategies on the promotion of micro hydropower (with low cost).

(v) Lack of policy interventions regarding hydropower development

Nepal issued its first comprehensive regulation on hydropower development in the early 1990s. The regulation mainly reflected the need to address the demand and supply gaps in hydropower and control forest degradation. Other reasons include fund raising for infrastructure development from public and private sectors and the mobilisation of internal resources to develop hydropower. Pokharel (2001) proposed how to decide on the scale of hydropower projects based on the size of the river catchment areas (**Table A1-6**).

Table A1-6 Proposal for the scale of hydropower projects based on the size of the river catchment areas

River catchment area (km^2)	Size of hydropower plant	Purpose
< 300	Small	Localised approach to replace fossil fuels
300 -1000	Medium	Linked to the national grid
>1000	Large	Export-oriented projects

Source: Pokharel, 2001

(vi) Other challenges

Insufficient infrastructure, such as access to roads and transmission networks, is another challenge for hydropower development in Nepal. The institutional arrangement also needs to be strengthened to promote effective hydropower development. Isolated load centers which are not connected to the national or regional grids have discouraged hydropower developers due to additional costs to develop the transmission network. **Figure A1-11** portrays the problem tree together with the effects, core problems and their causes in the energy sector in Nepal.

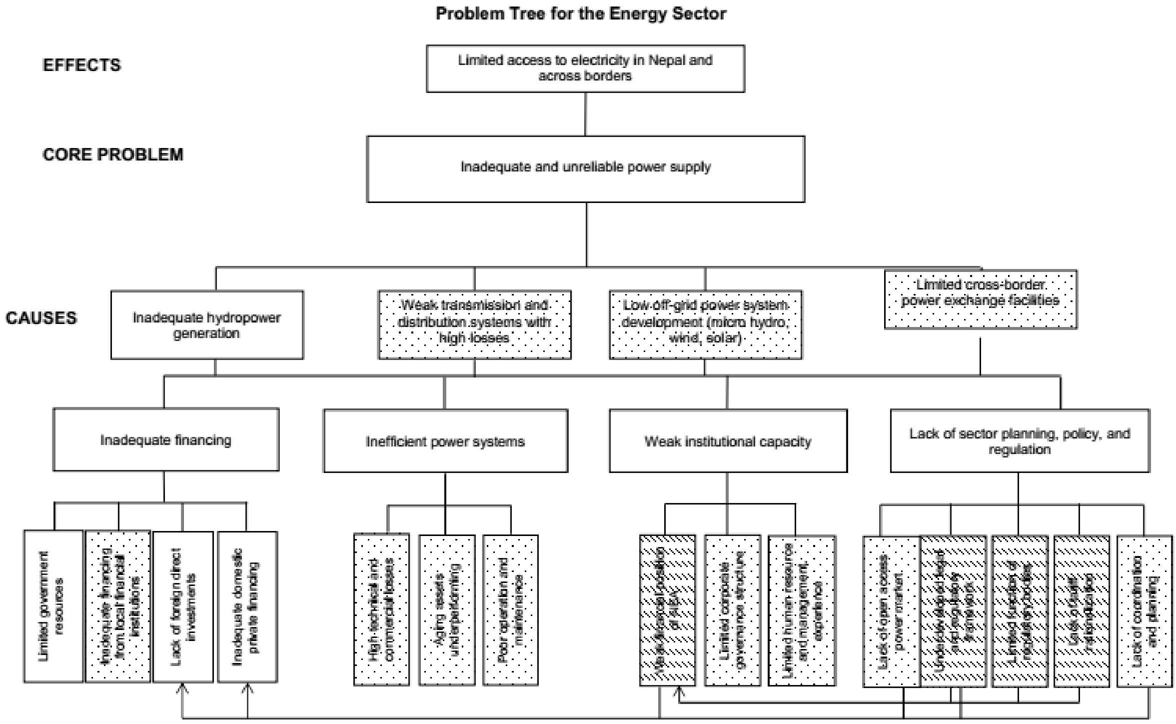

Figure A1-11 Problem tree for the energy sector

Source: ADB, 2013

Despite all these challenges, hydropower development is an effective way to boost economic development in Nepal (from the government's perspective) and generate multiple benefits through selling energy surplus (from the developers' perspective).

<u>Investment (financial) challenges</u>

Investment in the hydropower sector is heavily dependent on prudent management of various risks and mitigation of risks, including the introduction of an effective insurance program to effectively reduce risks (Shrestha, 2007).

There are some major constraints to mobilising funding sources from the financial intermediaries (FIs). Ramification of investment in the hydropower sector is an equity investment by entrepreneurs with complementary debt financing (generally accepted debt equity ratio is 70 to 30) from the FIs. An entrepreneur cannot implement a hydropower project just with an equity investment. It is also depends on the entrepreneur's ability to mobilise debt funding. Shrestha (2007) pointed out several constraints in mobilising the fund from the FIs including market failure and portfolio mismatch, lack of project finance instrument, lack of 'due diligence' capability of the FIs, foreign exchange risk, repatriation risk, sovereign risk, payment risk, hydrological risk, construction risk, local-level disputes and associated risks.

2.4.2 Opportunities for the hydropower sector in Nepal

Nepal faces many challenges (technically and financially) in the exploitation of its immense hydro resources as mentioned above. At the same time, there are many opportunities to harness the hydro potential.

(i) Abundant hydro resources

Nepal has high hydropower potential, which could be used as a main source for domestic energy supply and export revenues. It is estimated that Nepal has more than 80,000 MW of gross hydropower potential and 40,000 MW economically feasible potential, which is a significant energy resource. According to the World Bank Report (2014), the largest 23 dams in Nepal can serve an installed capacity of about 25,000 MW, producing 65 - 70 TWh of electricity annually with a net value of 5 billion USD per year. Compared with other countries, Nepal has high energy consumption in relation to its Gross Domestic Product (GDP) due to lack of a strategy for sustainable, effective and efficient energy use (www.energyefficiency.gov.np).

(ii) Possibility of big dams with large storage capacity

Many studies revealed that Nepal has the potential to build big dams with large storage capacities which can contribute to hydropower development and help flood control and flow regulation in respect to its downstream countries. This has been illustrated in the World Bank Report (2014) based on the modeling results (including water simulations and economic optimisation model) from the simulation of the baseline condition and future scenarios on the combination of three mega dams (Pancheswar Dam on the Mahakali/Sharda River, Chisapani Dam on the Karnali/Ghagara River and Koshi High Dam on the Koshi River) and other dams in Nepal.

According to the simulation results, the three mega dams with an installed capacity of 19,000 MW have a potential to produce 35 - 45 TWh of electricity annually. The remaining 11 dams corresponding to 4,600 MW installed capacity can generate at least 18 TWh electricity annually. In addition, 20 small dams can produce 26 - 30 TWh electricity per year. The current hydropower production in the Ganges basin in Nepal is only about 12 TWh annually and the current installed hydropower capacity is about 800 MW (Nepal Electricity Authority, 2017), which is projected to increase substantially to 1,800 MW by 2019-2020.

Due to the geopolitics and essentiality of trans-boundary negotiation it may take several years to design, build and operate hydropower projects in Nepal. Nepal has high potential to meet its own growing energy demand and at the same time to supply to neighbouring countries to partially meet the increasing regional energy demand. India currently has a big gap of about 100,000 MW in its energy demand, thus it would be beneficial for both India and Nepal to bilaterally collaborate in developing hydropower projects in both countries.

Installed capacity is the theoretical capacity of the turbines running at full design capacity throughout one year. Installed capacity is an important indicator for high peak load management. However, under the monsoonal climate, there will be insufficient river flow in many months of the year in the Ganges basin. Without large scale storage, hydro turbines cannot run at their full capacity. The actual power that can be generated is thus highly dependent on the water availability and is crucial for meeting the energy demand and to help power economic growth in Nepal.

For example, modelling results from the World Bank (2014) indicate that the Koshi High Dam with a potential installed capacity of 3,500 MW can produce more electricity than the Chisapani High Dam which has a potential installed capacity of more than 10,000 MW. Similarly, though the 20 small dams have a potential installed capacity of only one fourth that of the three mega dams, they can generate more than half of the country's total hydropower.

Figure A1-12 shows that with limited available storage and short monsoon season, the seasonal variations in hydropower production from the storage dams in the Ganges basin should be considered for the development of hydropower. This can be even more significant for the RoR hydro projects which do not have storage dams but are regulated by the upstream flows throughout the year. **Figure A1-13** illustrates that the actual power generation can be lower than the generation under the full installed capacity due to the seasonal fluctuations throughout the year.

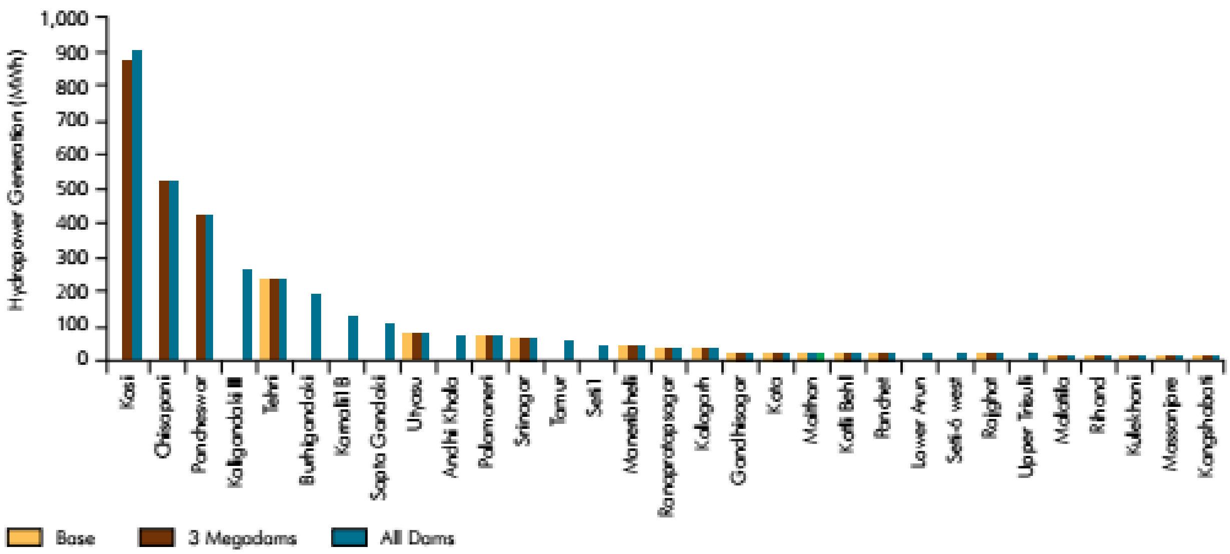

Figure A1-12 Hydropower potential in the Ganges basin

Source: World Bank, 2014

Other than seasonal variation, it is also important to know about yearly variations in the flows. Since hydropower production cannot be stored across years, strong fluctuations exist from year to year. The results from the World Bank report (World Bank, 2014) indicate that there is a significant potential for hydropower generation in Nepal in not only satisfying domestic and industrial energy demand but also providing an export surplus of electricity to other countries, such as India.

(iii) Possibility of multiple benefits from large-scale hydro projects

Many existing large-scale storage hydro projects, e.g., the Pancheswar Dam, Chisapani Dam and Koshi High Dam, can generate multiple benefits for Nepal. Similarly, the Budhigandaki Hydropower project, Dudhkoshi Storage Hydroelectric Project, Upper Arun Hydroelectric Project, Tamakoshi Hydroelectric Project, Andikhola Storage Hydroelectric Project, Uttar

Ganga Storage Hydroelectric Project, Tamor Storage Hydroelectric Project and the ChainpurSeti Hydroelectric Project, etc., can also be included as large-scale feasible projects in Nepal (Nepal Electricity Authority, 2017). Besides electricity generation, large scale hydro projects can also be utilised for other purposes including irrigation, drinking water supply, flood control and water navigation, etc. There are numerous cases in the world where downstream population or downstream countries have benefitted from large hydroelectric projects in the upstream. For example, in the Mekong River Basin, Cambodia, Laos, Thailand and Viet Nam have benefitted from the multiple use of hydropower projects for flood control, irrigation and water navigation, etc.

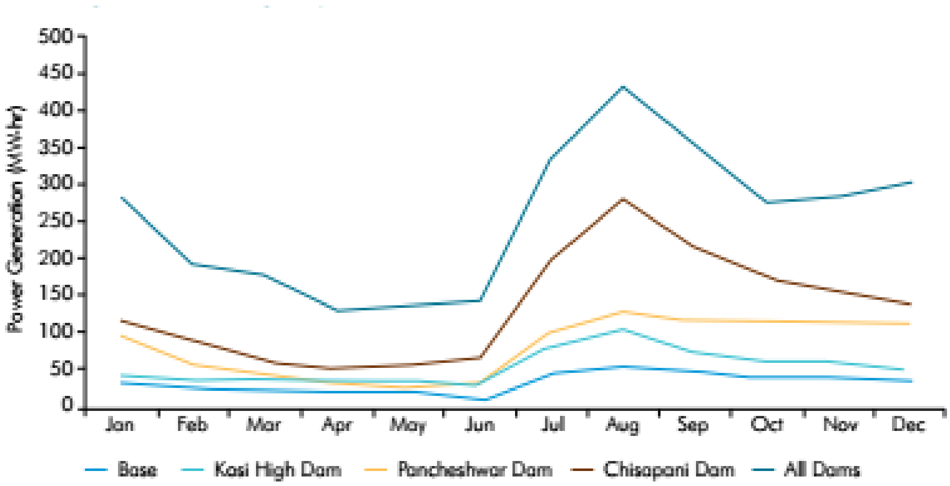

Figure A1-13 Monthly hydropower generation based on the modelling results

Source: World Bank, 2014

(iv) Export of surplus energy to neightbouring countries

There is a high potential in Nepal's hydropower generation for exporting the surplus energy generated to other countries. Neighbouring countries like India, Pakistan, Bangladesh and Bhutan can import the surplus energy from Nepal if strong diplomatic and economic ties are formed. India has developed large hydropower projects in Bhutan which provide electricity to India. In the same way, Nepal and India should build mutual trust and reach a common understanding over cross-border energy trading between the two countries. India's economy is one of the largest in the world and its energy demand will increase with rapid economic growth. India should thus take the initiative to establish trading relations with Nepal for the transmission of surplus energy from Nepal to India based on respecting Nepal's right on deciding upon the usage of the upstream water and respect of the right to access international water bodies.

(v) Cross-border grid and integration of the south Asian pool

Cross-border grid connections are increasingly being put in place in many parts of the world. For example, cross-border grid connections exist in Europe, Southern Africa and North America. Development of cross-border grid connection networks can help promote effective utilisation of untapped hydropower, promote and facilitate power trading and ultimately contribute to regional economic growth.

Cross-border power trading has taken place in South Asia, albeit at a slow pace (Janardhanan and Mitra, 2018). In 2011, the Energy Center was established in New Delhi under the Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC) to coordinate, facilitate and strengthen the cooperation in the energy sector in the region covering Bangladesh, Bhutan, India, and Nepal. The Center was established with the main objective of developing cross-border energy trading and a regional market for transmission of the hydropower generated from Bhutan and Nepal to India and Bangladesh. Cross-border energy trading can provide win-win solutions for the riparian countries in the Ganges basin. For example, the grid connections built in Bangladesh can be utilised to transmit the electricity generated from India to Bangladesh (the north-eastern parts) and can be used to transmit the electricity from India to Nepal. These cross-border grid connections can also be helpful for load shifting due to different time zones in these South Asian countries (Pokhrel, 2001).

(vi) Upstream benefits and advantages

Being an upstream country, Nepal has plentiful benefits and advantages. The amount of discharge and heads are important parameters for the designing and development of hydro projects. Nepal is endowed with topographical steep gradients, meandering nature of rivers in hills, easily available high heads and naturally existing rocky dams which makes it a feasible place for hydropower generation. In addition, perennial rivers enable to have the minimum required average flow in the rivers all year round. Comparing the two resources, high heads are Nepal's unique natural endowment with which the country can tap undeveloped hydro resources to a great extent.

One of the fundamental upstream benefits is less sedimentation. High sedimentation is a great obstacle to storage-based hydro projects as it can decrease the lifetime of the reservoir and deteriorate turbine components. Sedimentation in the Nepalese watersheds has been significantly acknowledged in the world community (Carson, 1985). Construction of relevant structures in the upstream can help lower the rate of sedimentation.

(vii) Replacement of fossil fuel-based energy

The Paris Agreement provides a strong message on building a low carbon society and hydropower can play a critical role in achieving the targets set by the Agreement. The current fuel mix in the Ganges basin is dominated by high carbon fossil fuels. Exploitation of the untapped hydropower resources through regional cooperation can provide multiple benefits including diversification of energy resources, minimising the risks of thermal power generation due to water shortage and contributing to low-carbon development in the region. A study by Timilsina et al. (2015) showed that full operation of cross-border power trading in South Asia could replace 63 GW of fossil fuel-based thermal power plants.

(viii) *Achieving economic prosperity and the Sustainable Development Goals (SDGs)*

The SDGs in Nepal's context have gained great momentum through the submission of its Voluntary National Review, entitled "*Eradicating Poverty and Promoting Prosperity in Nepal*". Mainstreaming the SDGs into Nepal's Governmental planning and budget began for the 14th National Plan (2016/17-2018/19). For energy sector, the Government of Nepal and the private sector collaboratively held a Power Summit in 2016 to attract investors to hydro project development. During the Summit, the Government of Nepal gave an assurance that it would provide preferable conditions for investors and simplify relevant administrative procedures through the formation of a coordination committee. Furthermore, the Government of Nepal has been making efforts to adjust electricity tariffs based on the power purchase agreement rate. The Government has provided an incentive of 5 million Nepali Rupee per MW to private hydropower developers as well as tax exemptions. Investors from China, India, Bangladesh, Singapore, Germany, the UK and Norway showed keen interest in this respect.

3. Conclusions

Nepal has a great amount of hydro resource endowment. Perennial rivers, topographical steep gradients, easily available high heads, naturally existing huge rocky dams, possibility of the cascade projects, etc., provide Nepal a solid foundation for the development of many large-scale hydro projects. Nepal's economic growth is highly dependent on the proper utilisation of its hydro resources. However, a lot of constraints remain, which require a good enabling environment to be built to attract more investment to the hydropower sector.

Hydropower electricity will power Nepal's economic growth through industrialisation and job creation. On the one hand, hydropower generation can replace fossil fuel-based energy supply which can help mitigate the trade deficits with India. On the other hand, firewood consumption can be reduced substantially, contributing to deforestation prevention and ecological conservation.

The fuel mix of electric power supply to satisfy domestic demand is an important issue for the Government to work on. For hydropower projects, not only the public sector but also a lot of investors from the private sector both in Nepal and from overseas and international organisations are keen to invest. Favouable conditions and solid policies are needed to lay down the basis for attracting more investment and mitigating the related risks.

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Appendix 2 Summary of the 1st stakeholder workshop in India

Workshop on "Harnessing of Climate-Water-Energy Nexus for Resource Security in the Ganga River Basin"

Venue: *Committee Hall, Convention Centre, Jawaharlal Nehru University, New Delhi*
20th April 2015, Monday

Organisers:
Central University of Rajasthan (CURAJ)
Jawaharlal Nehru University (JNU)
Institute for Global Environmental Strategies (IGES)

Supported by:
Asia Pacific Network for Global Change Research (APN)

Workshop Proceeding

The Stakeholders' workshop on Harnessing of Climate-Water-Energy Nexus for Resource Security in the Ganga River Basin was held on 20 April 2015, at the Jawaharlal Nehru University, New Delhi.

Objectives of the Workshop

The purpose of workshop was to communicate the expected outcomes of this study and share the methodology framework to relevant stakeholders, and to hear their concerns on water and energy security, water resource management, conflicts among different consuming sectors, optimal allocation of water resources allocation issues, and what the major needs are for nexus assessment. Following were the specific objectives of the workshop:

a) To get feedback and input from key stakeholders on the methodological framework of the APN project
b) To review the state of resources and their management practices in each country
c) To discuss and explore ways to highlight and prioritise a nexus approach in energy planning and identify feasible actions to realise nexus synergies.

Welcome session

Professor K.C. Sharma, Head, Department of Environmental Science, Central University of Rajasthan (CURAJ), welcomed the delegates and key resource speakers of the workshop. He briefly introduced the various academic programmes and research activities which are taking place in the CURaj. He also stated that he hopes to hear fruitful and active discussions in each session with participation from many different institutions.

Dr. Nanda Kumar, Regional Director, IGES-South Asia, welcomed the workshop participants and expressed the importance of water-energy-climate nexus in the present situation and stated that this nexus should be considered at the policy level. He informed the participants about the expansion plan of IGES in different geographical areas and future activities in India. On behalf of IGES, he thanks and welcomed all for this one-day event.

Professor AL. Ramanathan, School of Environmental Science, JNU, provided a welcome on behalf of JNU and informed about the institutes' multidisciplinary aspects in both academic as well as research areas. He also thanked the workshop organisers for highlighting the importance of sectors like energy and for developing a water-energy nexus in the region. JNU works on the climate related to the Ganges, both upstream and downstream. There is a need to develop strong linkage between researchers from various sectors to develop comprehensive policy in water and energy sectors.



Prof. K.C. Sharma (CURAJ) ***Dr. Nanda Kumar (IGES)*** ***Prof. AL. Ramanathan (JNU)***

Session- Project Introduction

Dr. Devesh Sharma, project collaborator (India), briefly introduced the project development, objectives and expected outcomes of the workshop to the participants. He said that the uniqueness of this project is to develop linkage between water and energy sectors in the Ganga river basin and further at the sub-basin level. He focussed on the workshop objectives. He also explained that stakeholder interaction and input is very important for the workshop methodology and framework. There is also a need to understand the present status of the river basin from the perspective of three sectors, i.e., water, energy and agriculture. He also highlighted that selection of sub-basins is another key objective of the workshop which must be based on certain logical criteria such as resource scarcity, location of power plants, etc. Dr. Sharma stressed that group discussion is an important tool and will be used in the workshop to identify criteria for sub-basin selection, how energy and water is linked, how power plants depend on water resources and to be aware of existing and future challenges for the power sector.


Dr. Devesh Sharma (CURAJ) ***Dr. Bijon K. Mitra (IGES)***

Dr. Bijon K. Mitra, policy researcher, IGES, introduced the purpose of the workshop to the participants. He briefly mentioned about the background behind the project development and also about the three collaborators. He also acknowledges the support of APN for financial support to conduct this project. He said that it is good opportunity to interact with different stakeholders and their views are useful to further improve the methodology of the project. He shared information on the previous national-level studies in India and Thailand. Based on previous experience, it was realised that there is strong linkage between water and energy and further that these should be linked with river basins. Considering the river basin as a hydrological unit, planning and policy should be developed at the basin level for sustainable development. In his presentation, he justified the importance of the Ganga river basin in South Asia and why this particular river is selected for the project. He mentioned that Ganga is a strategic basin in South Asia because of its catchment area, population growth and economic development, and because it is a good source of water in the region. It contributes about 30% of total water resources. In the energy sector, thermal power plants are the main source in this region and 40% of India's thermal power plants are located in this river basin. The economic contribution of this river basin is 1.1% of global GDP, which will increase to 3% by 2050. As any negative effect in this basin will heavily impact on the overall development situation, it is required to assess resource security in terms of water and energy sectors. He also focussed on the water security status of this river basin for present and future scenarios. Further, population growth, rapid urbanisation, and climate change will put additional pressures on the resources. Energy security is also an important concern for South Asia. Annual growth in electricity is expected to be 5%. These two securities are inter-dependent. The water requirement of thermal power plants is dependent on the fuel type and efficiency of the plant. Over 75% of installed power plants are located in areas with absolute water scarcity and water stress, and 35% of thermal power plants are located in the Ganga river basin. This is also one reason for selecting the Ganga river basin for this study. He also warned that conventional approaches will not be able to ensure resource security and little surface water will be left to meet additional demand beyond 2040. He then shared the key research questions with participants.

- How much water is used by electricity generation in South Asian countries?
- What are the driving factors of high water footprint for the electricity sector in the region?
- Can current policies overcome water conflict between electricity and other users?
- What types of technology can be intervened to deal with the water constraint situation?
- How can regional cooperation address the nexus approach to promote synergies between water and energy sectors throughout the river basin?

Based on the above research questions, the following objectives were prepared;

- Establishing a quantitative resource link between water and energy on the supply side of energy in the Ganges River basin.
- Providing guidance on an integrated assessment of the water-energy nexus for the planning of and investment in large-scale water management and energy development projects.
- Demonstrating the effects of water availability on long-term energy scenario development and subsequent impacts on energy technology choice.
- Supporting cross-border cooperation by seeking synergies between water and energy sectors in supporting the achievement of sustainable development at the river basin level.

Session on Methodological framework of quantitative assessment of water energy nexus

Dr. Devesh Sharma, Indian collaborator, started his presentation by highlighting the integrated and multidisciplinary approach used in the methodology framework and also the importance of the stakeholders' workshop during the project duration. He raised a question about the importance of pre-processing of data and quality checking in the hydrological model as hydrology is more dependent on the data input. Identification of sub basins should be based on certain criterions. He mentioned about the basic formulation of the SWAT model and fundamental concept of hydrologic response unit (HRU). It is important to understand the behaviour of sub basin in terms of soil, land use, topography and precipitation, as well as focus on the data types and various sources from where data can be procured and used in the hydrological model. He also discussed about the bias present in the future climatic projections of GCMs/RCMs, meaning it is important to remove the bias by checking the quality of these future projections. He also highlighted limitations in the availability of datasets such as in discharge data in the Ganga basin, which is directly linked with the calibration process. Further, he also mentioned the methodology to be used for demand calculations in agriculture, industry and domestic sectors. Agricultural demand will be estimated with the CROPWAT tool, which requires meteorological, soil, crop and rainfall data. For domestic and industrial demand, a statistical approach will be used. In the statistical approach, it is important to identify the dependent variables to estimate water demand in domestic and industrial sectors. Finally, he showed the expected outcomes of the project, such as assessment of dynamic water-energy nexus under climate change scenarios at the sub-basin level for selected sub basins, outputs of which may be important for policy makers in integrating water and energy resources. Policy makers can use this information in the selection of power generation technologies, determination of energy mix, and planning of new power plants under water constraints at the sub-basin level. Soon after the presentation made by Dr. Devesh Sharma, some questions were raised in open discussion from the participants.

- How to account for flow from outside the sub-basin and how to integrate such into the hydrological model. There was a suggestion to consider some medium and extreme scenarios in the study or if secondary data sources are available.
- What kind of data will be used for calibration as discharge data is not in the public domain, which will need clearance from the ministry. There is a possibility to get reservoir water level data but it will also need approval and clearance from the related authority. There is a possibility to link available data with hydropower projects in the sub-basins.
- Whether it was possible to measure and monitor observed data at certain locations in the study area. Here again, the project duration and fund is too limited to cover such activities, and would require a few years of observations.
- Factors like location of existing thermal power plants and agriculturally-intense areas will be considered for the selection of sub-basins.
- There was also a concern raised by one participant on the matching of scale as datasets are available on two different geographical scales, i.e., district level and sub-basin level.
- Discussion on pollution created by thermal power plants and role of renewable energy in the future and kind of future power mix options will be considered.
- Issuance of pricing of water consumed in the power plant.
- There was also a suggestion that for energy in the Ganga basin, the focus should be on small hydro as there is huge potential for small hydro power projects.

Session-Review and Status of Resources in three sectors (Water, Energy and Agriculture)

Mr. Rajkiran V. Boli, Associate Professor, Administrative Staff College of India, started his presentation by explaining the different kinds of power plants. He also explained about why water is important in power plant operation and also different operations where water is required. He stated that water and energy are interlinked and depend on each other. Energy Production depends on water for cooling thermal power plants and extraction, transportation and processing of fuels. At the same time energy is also vital to providing freshwater, and needed to power systems that collect, transport, distribute and treat it. Energy generation and water consumption are of huge importance in India. As per the Central Electricity Authority (CEA) report, a typical 2 x 500 MW thermal power plant with wet ash disposal without recycling of ash pond requires 4,000 m^3/h of water. Of this, more than 80% is consumed in the cooling tower itself. He also showed the breakup of water consumption in such plants. He also presented the total installed capacity of India as of February 2015, i.e., 261,006 MW, with thermal generation representing 70% of the total capacity. Out of this, coal-based thermal power plants represent 87% of the total thermal capacity installed. He presented briefly on power scenarios and developments in the Ganga Basin. Most of the Ganga basin falls in the Northern region which has a high power deficit. Rapidly increasing population, rising standards of living and exponential growth in industrialisation and urbanisation will only increase pressure on the supply side to meet the energy demand. He focused on industrial development which is affecting the overall situation of water resources in the Ganga basin. Each day, more than 500 million liters of wastewater from industrial sources are dumped directly into the Ganga.

Dr. T.B.S Rajput, Emeritus Scientist, Water Technology Centre, IARI, started his presentation by explaining the evolution of Indian irrigation and development after its independence. He showed the water demand projection in various sectors to year 2025. He also talked about groundwater resource exploitation in India. He said there are various challenges and issues in the agricultural sector, like over-exploitation of groundwater, water-logging and soil salinity, isolated development and use of surface and groundwater resources, and increasing groundwater pollution. There is a need to rethink about the water distribution system and irrigation efficiency. What measures are required to improve the irrigation efficiency? During the presentation, he also introduced a study based on CROPWAT application for enhancing water use efficiency in canal command areas, and said that the CropWat software tool is useful for identifying the optimal date of sowing of wheat. He also presented some examples of on-farm water management methods like laser land leveling, pressurised irrigation systems, use of flow measuring instruments, soil moisture sensors for irrigation scheduling, etc. He briefly explained the spatial pattern of rice and wheat production in the Ganga river basin. To end, he presented a case study on climate change and the potential vulnerability in the Ganga basin. The impact of climate change on grain yield of crops was studied using A2-2080 and B2-2080 scenarios derived from PRECIS RCM to show the increase in vulnerability with time.

Prof. A.K. Gosain, Professor, Department of Civil Engineering, IIT Delhi, started with various issues which are related to water Resources Development. He emphasised sustainable development and water resources management. He also said that there is lack of awareness of environmental demand, which has many implications. Sustainability of the system depends on water demand. There are some key questions like how we can look at the total availability and demand, gap analysis, etc. A scientific base is essential to understand and properly analyse information, i.e., application and use of models. He explained the basic approach and background information of SWAT and types of datasets required to develop the model for river basins. He also shared his experience and outputs of the Ganga River Basin Management Plan (GRBMP) of IIT Consortium. He also showed another research study, on the Delhi urban drainage system. Most of the drains are flowing with sewage throughout the year. Groundwater is becoming contaminated with these drains. He highlighted some major hydrological studies performed at IIT, Delhi including *India's National Communications (NATCOM) to UNFCCC Coordinated by MoEF* (2004 and 2012). This study was conducted for the whole country to quantify the impact of climate change and results of the study are available on the website.

Mr. Rajkiran V. Bilolikar ***Dr. T.B.S. Rajput*** ***Prof. A.K. Gosain***

Group Discussion 1: Selection of sub-basins

Based on the interaction with participants and their views, following factors were identified to select the sub-basins at the initial level.

- State of water availability
- Level of water demand of major consumers
- Level of existing/planned thermal power capacity
- Level of energy demand in the sub-basin
- Data Availability – discharge
- Planned document for power plant
- Economic – industrial corridor
- Urbanisation
- Intensive agriculture areas
- Population density
- Contrast – to identify the sub-basins which can provide different perspectives on the water-energy nexus in the Ganga basin

Considering all the above-mentioned points, it was realised that there is a need to prioritise the factors and develop some criteria to identify the sub-basins. Following are the factors which are required for the selection:

1) State of water availability
2) Economic – industrial corridor and existing/planned power plants
3) Urbanisation
4) Intensive agriculture areas
5) Population density

Criterion for sub-basin selection

State of water availability (1)

Surplus/Availability

- *Industrial Development (2)*
- *Urbanisation (3)*
- *Irrigation (4)*
- *Population density (5)*

Deficit/Shortage

- *Industrial development (2)*
- *Urbanisation (3)*
- *Irrigation (4)*
- *Population density (5)*

<u>Group Discussion 2: Understand the Water energy nexus in energy planning</u>

Discussion was carried out in an open-ended format to solicit relevant opinions as well as information. Following points were noted from comments put forward by experts during the discussion:

1) The energy-water nexus is not viewed as an immediate issue of concern by electricity generators. This is mainly due to the fact that generators are pre-occupied with requirements to manage rather challenging short-term economic viability issues of the sector due to various external factors such as increasing fuel prices with low fixed sale prices. Thus, stakeholders viewed the project as timely and suggested that it should be promoted, along with other means, to raise the issue.
2) To analyse water use requirements from power production, stakeholders suggested including government projections in future energy mixes. While it is recognised that renewables will play a role, the role of coal and nuclear is suggested not to be downplayed given India's need to develop and availability of large coal and thorium reserves. The issue of scenarios with very high renewables viewed as impractical was raised. On cooling technologies in future thermal plants, stakeholders suggested that applicability of dry cooling in India may be limited or absent due to the hot and humid climate in large swaths of the country.
3) There was a suggestion to expand the project scope to include hydropower in the analysis given its role both in the current and future energy mix, and its dependence on surface water availability. The project team is aware of the context; however, given the focus of the study on water use by the power sector, it is considered as a component for further studies in this area.
4) Estimating future energy generation at the sub-basin scale is a challenge requiring a creative yet relatively straightforward method. Experts suggested using similar logic and method of using proxies as used in sub-basin selection.
5) Experts suggested that, discussions on how to minimise the nexus, or issues around policy and institutional arrangements to manage the nexus, should follow the results. Suggested emphasis at this stage is on the robustness of the method and underpinning data as much as possible.

Workshop Agenda

09:30-10:00	**Registration**
10:00-10:30	Welcome address by CURAJ (5 min)…………………………………………...*K.C. Sharma* Welcome address by IGES (5 min) ....*Nandakumar J.* Welcome address by JNU (5 min)………………………………………..*AL. Ramanathan* Introduction of participants (10 min) Workshop objective and agenda (5 min)………………………………*Devesh Sharma*
Session 1:	**Project Overview**
10:30-10:45	APN Project Overview- Background, Objectives, Expected Outcomes……………………………………………………………………………...*Bijon K Mitra*
10:45-11:00	Methodology and expected outcome of the case study in India…….…………………….……………………………………..………………….*Devesh Sharma*
11:00-11:25	Open discussion on the study proposal and expectations
11:25-11:45	Group photograph and networking break
Session 2	**State of resources and management with focus on water energy and food security in Ganga River basin**
11:45-12:05	Overview on Energy supply and demand: Present and Future……………………………………………………………………..….Rajkiran V. Bilolikar
12:05-12:25	Trends of agriculture and agricultural practices in Ganga River basin: present and future situation ……………………………………………………….……………*TBS Rajput*
12:25-12:45	Water Resources Situation in the Ganga River Basin: Present and Future Situation…………………….…………………………………………………….……….*AK Gosain*
13:05-13:30	Q&A
13:30-14:30	**Lunch**
Session 3	**Focused group discussion**
14:30-15:30	<u>Focused group discussion 1: Sub-basin selection</u> **<u>Facilitator: Devesh Sharma</u>** • Selection criteria • Shortlisting of sub-basins for study
15:30-16:30	<u>Focused group discussion 2:</u> Water energy nexus in energy planning **<u>Facilitator: Pranab Jyoti Baruah</u>** • Practical challenges and stakeholder suggestions - Spatial water availability and power plant planning - Institutional and policy arrangements to enhance nexus synergies. • Way forward to minimise/manage the nexus – stakeholder perspective
16:30-16:45	Tea/Coffee break
16:45-17:10	Wrap-up (Reports from group discussion)
17:10-17:15	Closing remarks

Workshop Participants

S. No.	Resource persons	Organisation	Email
1	Prof. AL. Ramanathan	SES, JNU	alrjnu@gmail.com
2	Dr. Rajmohan Natarajan	International water management institute	r.natarajan@cgiar.org
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4	Prof. Suresh Jain	TERI University	suresh.jain@teri.res.in
5	Dr. Purnamita DasGupta	The Institute of Economic Growth	pdg@iegindia.org
6	Dr. Chetana Chaudhari	The Institute of Economic Growth	chetana.chaudhuri@gmail.com
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15	Dr. Devesh Sharma	CURAJ	deveshsharma@curaj.ac.in
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Appendix 3 Summary of the 1st stakeholder workshop in Bangladesh

Workshop on "Harnessing of Climate-Water-Energy Nexus for Resource Security in the Ganges River Basin"

Venue: DCE Seminar Room, Institute Building, Bangladesh University of Engineering & Technology
14th June 2015, Sunday

Organisers:
Institute of Water & Flood Management, BUET
Institute for Global Environmental Strategies (IGES)

Supported by:
Asia Pacific Network for Global Change Research (APN)

Workshop Proceedings

The Stakeholders' workshop on Harnessing of Climate-Water-Energy Nexus for Resource Security in the Ganga River Basin was held on 14 June 2015, at Bangladesh University of Engineering & Technology, Dhaka.

Objectives of the Workshop

The purpose of the workshop was to communicate the expected outcomes of this study and share the methodology framework to relevant stakeholders, and to get to know their concerns on water and energy security, water resource management, conflicts among different consuming sectors, optimal allocation of water resources, and what the major needs are for nexus assessment.

Following were the specific objectives of the workshop:

a) To get feedback and input from key stakeholders on the methodological framework of the APN project
b) To review the state of resources and their management practices in each country
c) To discuss and explore ways to highlight and prioritise a nexus approach in energy planning and identify feasible actions to realise nexus synergies.

Welcome session

Professor G M Tarekul Islam, Director, Institute of Water & Flood Management, Bangladesh University of Engineering & Technology welcomed the delegates and key resource speakers of the workshop. He briefly introduced the various academic programmes and research activities which are taking place in the IWFM. He also stated that he hopes to hear fruitful and active discussion in each session with participation from many different institutions.

Prof. G M Tarekul Islam (BUET)

Dr. Bijon KumarMitra, Researcher, IGES, Japan welcomed the workshop participants and expressed the importance of water-energy-climate nexus in the present situation and stated that this nexus should be considered at the policy level. He informed the audience about the importance of such project research for Bangladesh and how this region can gain from this study as a whole.

Dr. Bijon Kumar Mitra (IGES)

Dr. Md. Giashuddin Miah, Professor, BSMRAU and Member, APN Scientific Planning Group welcomed everyone attending the workshop. He iterated a brief overview of APN and its contribution towards research and development in developing countries. Being a member of project awarding committee of APN, he is committed to dedicating his utmost support for this project.

Prof. Md. Giashuddin Miah (BSMRAU)

Professor Khaleda Ekram, Honorable Vice-Chancellor, Bangladesh University of Engineering & Technology, thanked the organisers for arranging such an event. She emphasised the link between water, agriculture and energy. Pointing out the difference between efficiency and effectiveness, she also conveyed how local knowledge of developing countries needs to be involved for research and development purposes. On an ending note, she wished for the success of this workshop.

Prof. Khaleda Ekram (BUET)

Session- Project Overview and State of Water resources in Bangladesh with Special Focus in the Ganges River Basin

Chair: Md. Lutfor Rahman, Director, River Research Institute, Faridpur

Dr. Bijon Kumar Mitra, Researcher, IGES, Japan briefly introduced the APN project, "Assessment of Climate-Induced Long-term Water Availability in Ganges River Basin and Impacts on Energy Security in South Asia" to the workshop participants. He stated the strategic reason behind choosing the Ganges River Basin as the study area: water security in this region is facing a grave threat. Iterating that water and energy security are interdependent, he showed that conventional features of resource management in this region will no longer be sustainable. In his presentation, he showed that over 75% of the installed power plants in the river basin are located in areas with absolute water scarcity and water stress. Water conflicts in India are on the rise and may potentially affect Bangladesh in a similar way. He then shared the key research questions with participants.

- How much water is used for electricity generation in South Asian countries?
- What are the driving factors of high water footprint for the electricity sector in the region?
- Can current policies overcome water conflict between electricity and other users?
- What types of technology can intervene to deal with the water constraint situation?
- How can regional cooperation address the nexus approach to promote synergies between water and energy sectors throughout the river basin?

Based on the above research questions, following objectives were prepared;

i. Establishing a quantitative resource link between water and energy on the supply side of energy in the Ganges River basin.

ii. Providing guidance on an integrated assessment of the water-energy nexus for the planning of and investment in large-scale water management and energy development projects.
iii. Demonstrating the effects of the water availability on long-term energy scenario development and subsequent impacts on energy technology choice.
iv. Supporting cross-border cooperation by seeking the synergies between water and energy sectors in supporting the achievement of sustainable development at the river basin level.

After the end of this presentation, a question & answer session was held. Following points were identified:

- Food security was not accommodated in this study as lots of studies on food security have already been conducted in this region; not energy-water security.
- Many parameters could not be included in this project because of time and resource constraints, but they are expected to be covered in ongoing projects.
- In India no revenue is gained by the government from power plants for cooling water; same practice is applied in Bangladesh.
- Minimum environmental flow of rivers has been taken into account in this model.
- Biodiversity & ecological sustainability was accounted for in the model of this project.
- Treated wastewater may be used as cooling water for thermal power plants.

Professor G M Tarekul Islam, Director, Institute of Water & Flood Management, Bangladesh University of Engineering & Technology presented the "Methodology and Expected Outcome of the Case Study in Bangladesh." He started with an assessment of climate-induced long-term water availability in Ganges River Basin and impacts on Energy Security in South Asia and explained how power generation is having a detrimental effect on the ecosystem of this region. He also explained the changes of land use in the Ganges dependent areas, changes in dry season flow of the Ganges at Hardinge Bridge point and the tools that have been used for these purposes. The objectives of this study were delineated as:

- To set up a SWAT model and to calibrate and validate it over the Ganges river basin.
- To simulate the SWAT model for A2B2 scenarios from the regional climate model to capture uncertainty of future flow in the Ganges.

The possible outcomes were stated as;

- To assess water availability and water stress in Bangladesh for future climate scenarios.
- To obtain information about probable future annual discharge, surface runoff and base flow.

Assessment of current and future water demand for four sectors were:

i) Agriculture water use, in particular for irrigation;
ii) Industrial water use for manufacturing and service sectors;
iii) Water use for power generation; and
iv) Domestic water use.

The challenges surrounding the study were identified as:

- A transboundary river basin

- Data scarcity at the upstream catchment (observed hydro-meteorological data)
- A catchment with multi-water diversion and reservoir structure.

On the completion of this presentation, a question & answer session was held. The following points were made:

- Hardinge Bridge was considered as the gage station for Bangladesh.
- Salinity was not included in the model.
- Southwest region of Bangladesh was not considered in the study.
- Stress of water in the southwest region of Bangladesh can be assessed by an existing model, but it will not be used at this point.
- Rainfall data was input into the model.
- Data from India was not available and therefore Hardinge Bridge data were used for calibration and validation.
- Construction of barrage will change the whole scenario of this model. Old and new scenarios will be considered.
- Satellite data may not always be accurate and thus other data may be used in combination.
- Water demand varies for different energy sources; gas, coal and oil use cooling water in different ways in power plants.

Dr. Md. Giashuddin Miah, Professor, BSMRAU and Member, APN Scientific Planning Group introduced the participants to his presentation titled "Climate-Smart Technologies/Practices: Agroforestry as a Potential Opportunity." He started with demonstrating how increasing demand for food from limited land resources is affecting this region and stated that integrated action for agriculture/agroforestry is essential to achieve food security under unfavourable climate; climate-smart agriculture/agroforestry technologies that achieve the triple-win of food security, adaptation and mitigation. He stated that agroforestry is the intensive land management that optimises the benefits of interactions when trees and/or shrubs are deliberately combined with crops and/or livestock and the intentional mixing of trees and/or shrubs into crop/animal production systems to create environmental, economic and social benefits. At the end of his presentation, a brief question & answer session was held. The following points were made:

- Trees which interfere least with crops have been used in agroforestry.
- Climate and agroforestry are interlinked because increase in vegetation and greeneries will help in reducing global atmospheric carbon levels.
- Agroforestry uses partial shade condition which reduces evaporation and thus the water demand is also reduced.
- Farmers may gain widely from this type of agroforestry project.
- Soil health condition will improve by a big margin and water availability will be greater if agroforestry is used.
- Bangladesh's mango production has increased drastically because of the use of agroforestry.

Dr. Shamal Chandra Das, Executive Engineer, BWDB delivered his presentation on the challenges and measures of water resources management in Bangladesh. Starting with a brief review on the status of water resources in this nation, he then described the nature of the problems and challenges which Bangladesh faces in different seasons. According to him, Bangladesh Water Development Board have achieved a lot regarding integrating structural and non- structural measures in sustainable river management. He also iterated how climate change has been affecting Bangladesh and BWDB's efforts to adapt and mitigate accordingly. Following are the approaches which BWDB has adopted for countering the impacts of climate change:

- Systematic overall rehabilitation and improvement of all key structures, also making them withstand climate change
- Set the drainage channels grades to the current situation;
- Add more structures for water management to meet the effect of climate change.
- Carry out foreshore afforestation to reduce the impact of wave surges.
- Involve stakeholders to design and implement revamping through a participatory process.

Further challenges include:

- Long-term sustainability of TRM
- Sequential operation of the Tidal Basin
- Economic development of the area and water availability in the Basin
- Inter-sectoral conflicts (shrimp farming vs. agriculture)
- Land zoning/environmental management plan
- Impacts of climate change
- Establishment of the links between the Ganges Distributaries.

Way forward for water resources management in Bangladesh:

- Develop and implement flood forecasting technology for increasing lead time of forecast from present 5 days to 3 weeks (Under trial application)
- Develop storm surge forecasting technology (already developed, needs fine tuning)
- Implement river bank erosion monitoring, management and prediction technology (Erosion Early Warning System)
- It is imperative to have regional cooperation for river basin management targeting food security, energy security, environmental sustainability, adaptation to climate change
- Institutional framework for working out mechanisms for common basin management of common rivers need to be established;
- Joint Task Force for IWRM in Ganges Basin (Nepal, India, Bangladesh) and for Brahmaputra Basin (China, Bhutan, India, Bangladesh).

At the culmination of his presentation, a brief question and answer session was held; the following points were identified:

- Sectorial water demand data is available at BWDB.
- There are plans by BWDB to start participatory management in operation and maintenance in different projects.
- There are clear water allocation principles in the national water policy for different purposes during times of water crisis. However, implementation of such policy in Bangladesh is under doubt.
- Bottlenecks regarding acquisition of data from India has constrained flood forecasting lead time for Bangladesh.

Session on State of Resources and Management with Focus on Energy and Food Security in the Ganges River Basin

Chair: A. M. Monsurul Alam, Executive Director, Electricity Generation Company of Bangladesh (EGCB), Dhaka

Dr. Md. Ziaur Rahman Khan, Professor and Director, Centre for Energy Studies, BUET started the session with his presentation, "Overview on Energy Supply and Demand: Present and Future." A brief history of Bangladesh's energy resources and its current production, reserves consumption was discussed. Gas and coal were identified as key resources for thermal power stations in Bangladesh; demand and supply were discussed. Power System Master Plan (PSMP) was identified as the major future plan by the government of Bangladesh; the following goals were mentioned:

- The government has planned to set up a 4,000 MW nuclear power station by 2030.
- The government has planned to set up 4,000 MW and 20,000 MW coal based power stations by 2017 and 2030, respectively.
- The government has planned to extract 2,000 MW power from renewable sources by 2020.

Regional connectivity was iterated as one of the greater plans; Bangladesh has started to move towards regional power grid connectivity, the first manifestation of which has been the start of electricity import from India. India has agreed in principle to give Bangladesh corridor facilities for importing electricity from Nepal and Bhutan.

The following points were concluded:

- Meeting future energy demand will be a big challenge for a developing country like Bangladesh. The future growth of the nation is purely dependent on that.
- The Government of People's Republic of Bangladesh is working towards meeting the gap between energy supply and demand.
- The government is also encouraging efficient use of energy for ensuring energy security.
- The government has also planned to build a floating liquefied natural gas (LNG) terminal to facilitate import of LNG at Moheshkhali on a Built-own-Operate-Transfer (BOOT) basis.

At the end of this presentation, a brief question and answer session was held which was conducted by the honorable Chair. Following points were identified:

- Environmental impact assessment is done by EGCB.
- The temperature difference between incoming and outgoing cooling water for thermal power stations is about 3 degrees centigrade.
- Close-loop system is used nowadays for cooling water; inefficient open loop was used previously.
- Highly polluted river waters are having a detrimental effect on the operation and maintenance of power stations. Environmental impact assessment is being conducted on these matters by governmental and non-governmental organisations at different levels.
- Solar systems have been implemented successfully in certain parts of the country and their use in on the rise. Other renewable sources of energy are being looked at.

- Locations of power plants are influenced by a variety of factors; a systematic scoring method is applied.
- Transmission loss in Bangladesh is only 2.9%.
- Only close-loop cooling will be permitted from now on for thermal power plants.
- Cost difference between open loop and close-loop system is 20p/kwh; 83 taka/1,000 million BTU.
- Cooling water in winter season becomes very hard to acquire as pollutant concentration becomes very high in the rivers.

Focused Group Discussion

Facilitator**:** Dr. Bijon Kumar Mitra, Researcher, IGES, Japan

Following points were identified in the FGD:

- The power law of 1910 was modified and translated to Bengali in 1972; a thorough update is required.
- Water factors, water uses and environmental were not integrated into the law.
- Power master plan has been updated every 5 years since 1982.
- Standard of cooling water is missing in the master plan.
- Fuel mix of power plants is being experimented on to increase the efficiency.
- Power plants should not be set up in water scarce areas.
- Regional power connectivity may be looked at.
- Tripura power plant's excess is being supplied to Bangladesh.
- Brazilian hydropower companies are looking into Nepal and Bhutan for investment in hydroelectric power plants. Downstream countries may support these plans if they get electricity as an incentive.
- Ecosystem may be adversely affected by too much hydropower generation.
- Water and energy relations are not understandable to people unless they are educated or made aware about it.
- India's example may be used to explain and convince policymakers in Bangladesh.
- Political biasness may unfairly influence site selection of power plants.

Workshop Agenda

09:30-10:00	**Registration**
10:00-10:30	**Inauguration**
10:00-10:05	Welcome address by Dr. G M Tarekul Islam, Professor and Director, IWFM, BUET
10:05-10:15	Address by Dr. Bijon Kumar Mitra, Researcher, IGES, Japan
10:15-10:20	Address by Dr. Md. Giashuddin Miah, Professor, BSMRAU and Member, APN Scientific Planning Group
10:20-10:30	Address by the Chief Guest Prof. Khaleda Ekram, Hon'ble Vice Chancellor, BUET
10:30-11:00	**Group photograph and coffee break**
Session 1:	**Project overview and state of water resources in Bangladesh with special focus in the Ganges river basin** **Chair:** Dr. Sultan Ahmed, Director, Department of Environment
11:00-11:30	APN Project Overview- Background, Objectives, Expected Outcomes, Dr. Bijon Kumar Mitra, IGES, Japan
11:30-12:00	Methodology and Expected Outcome of the Case Study in Bangladesh, Dr. G M Tarekul Islam, Professor, IWFM, BUET
12:00-12:30	Water Resources Situation in Bangladesh: Present and Future Scenarios, Dr. Shamal Chandra Saha, Executive Engineer, BWDB
12:30-13:00	Q&A
13:00-14:00	**Lunch**
Session 2	**State of resources and management with focus on energy and food security in the Ganges river basin** **Chair:** A. M. Monsurul Alam, Executive Director, Electricity Generation Company of Bangladesh (EGCB)
14:00-14:30	Overview on Energy Supply and Demand: Present and Future Scenarios, Dr. Md. Ziaur Rahman Khan, Professor and Director, Centre for Energy Studies, BUET
14:00-14:30	Criteria for the Selection of Site and Technology for Power Plants, Mr. Ibrahim Ahmad Shafi Al Mohtad, Superintending Engineer, Electricity Generation Company of Bangladesh (EGCB)
14:30-15:00	Trends of Agriculture and Agricultural Practices in Bangladesh: Present and Future Scenarios, Dr. Md. Giashuddin Miah, Professor, Dept. of Agro-forestry and Environment, BSMRAU, Gazipur
15:00-15:15	Q&A

List of the participants of the stakeholder workshop on “Harnessing of Climate-Water-Energy Nexus for Resource Security in the Ganges River Basin”

Sl. No.	Names of the participants	Designation and Affiliation
1	Md. Sazzad Hossain	Executive Engineer Surface Water Processing Branch Bangladesh Water Development Board 72, Green Road, Dhaka 1205
2	Dr. Shamal Chandra Das	Executive Engineer Bangladesh Water Development Board 72, Green Road Dhaka 1205
3	Md. Mofazzal Hossain	Director Joint Rivers Commission 72, Green Road, Dhaka 1215
4	Saiful Alam	Director (Technical) Water Resources Planning Organization (WARPO), House 103, Road 1, Banani, Dhaka 1213, Bangladesh
5	Dr. Nurun Nahar	Senior Assistant Chief Programming Division, Planning Commission Sher-e Bangla Nagar, Dhaka
6	Dr. Md. Ziaur Rahman Khan	Professor and Director Centre for Energy Studies, Bangladesh University of Engineering and Technology (BUET), Dhaka 1000
7	Dr. Md. Obaidullah	Experimental Engineer Centre for Energy Studies, Bangladesh University of Engineering and Technology (BUET), Dhaka 1000
8	Md. Lutfor Rahman	Director River Research Institute, Faridpur
9	Saad Siddiqui	Principal Specialist and Head of Human Resources Division Institute of Water Modeling (IWM), House No. 496, Road No. 32, New DOHS, Mohakhali, Dhaka-1206
10	B.M. Tamim Al Hossain	Junior Specialist, Climate and Disaster Management Division Center for Environmental and Geographic Information Services (CEGIS), House # 6, Road # 23/C, Gulshan 1, Dhaka 1212
11	Tanvir Ahmed	Junior Specialist, Climate and Disaster Management Division Center for Environmental and Geographic Information Services (CEGIS), House # 6, Road # 23/C, Gulshan 1, Dhaka 1212
12	A. M. Monsurul Alam	Executive Director (Joint Secretary) Electricity Generation Company Ltd, BTMC Bhavan, 7-9 Kawran Bazar, Dhaka-1215, Bangladesh
13	Ibrahim Ahmad Shafi Al Mohtad	Superintending Engineer Electricity Generation Company of Bangladesh Limited, BTMC Bhaban, 7-9, Kawran Bazar Dhaka - 1215
14	Mr. Abdul Hye	Group Engineering Manager PENDEKAR ENERGY(L) LTD Meghnaghat Power Ltd. | Haripur Power Ltd | NEPC Consortium Power Ltd IDB Bhaban(11th Floor), Sher-e-Bangla Nagar | Dhaka – 1207, BANGLADESH
15	Dr. Md. Abdullah Elias Akhter	Scientist, Theoretical Division SAARC Meteorological Research Centre (SMRC) Plot No. E-4/C, Agargoan, Sher-E- Bangla Nagar Dhaka 1207, Bangladesh

Sl. No.	Names of the participants	Designation and Affiliation
16	Md. Rashedul Islam	Lecturer Institute of Water and Flood Management (IWFM) Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
17	Debanjali Saha	Lecturer Institute of Water and Flood Management (IWFM) Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
18	Shammi Haque	Lecturer Institute of Water and Flood Management (IWFM) Bangladesh University of Engineering and Technology (BUET) Dhaka 1000, Bangladesh
19	Dr. Md. Giashuddin Miah	Professor, Agroforestry and Environment Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur-1706, Bangladesh
20	Dr. Abul Fazal M. Saleh	Professor Institute of Water and Flood Management (IWFM) Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
21	Dr. Md. Munsur Rahman	Professor Institute of Water and Flood Management (IWFM) Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
22	Dr. Mohammad Rezaur Rahman	Professor Institute of Water and Flood Management (IWFM) Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
23	Mashrekur Rahman	Graduate Student Institute of Water and Flood Management (IWFM) Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
24	Aftabuzzaman Khan	Project Officer Regional Integrated Multi-Hazard Early Warning System (RIMES), Dhaka
25	Dr. Anisul Haque	Professor Institute of Water and Flood Management (IWFM) Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
26	Dr. Mohammed Abed Hossain	Associate Professor Institute of Water and Flood Management (IWFM) Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
27	Dr. Sujit Kumar Bala	Professor Institute of Water and Flood Management (IWFM) Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh
28	Dr. Bijon Kumer Mitra	Researcher, Water Resources Management Natural Resources and Ecosystem Service Group Institute for Global Environmental Strategies (IGES)
29	Dr. G M Tarekul Islam	Professor and Director Institute of Water and Flood Management (IWFM) Bangladesh University of Engineering and Technology (BUET), Dhaka 1000, Bangladesh

Appendix 4 Summary of the 1st stakeholder workshop in Nepal

IGES
Institute for Global Environmental Strategies

CREEW

APN
ASIA-PACIFIC NETWORK FOR GLOBAL CHANGE RESEARCH

Workshop on "Harnessing of Climate-Water-Energy Nexus for Resource Security in the Ganges River Basin"

Venue: Kiran Hall, Summit Hotel, Kupondole Height, Lalitpur
9 August 2015

Organisers:
Center of Research for Environment, Energy and Water (CREEW)
Institute for Global Environmental Strategies (IGES)

Supported by:
Asia Pacific Network for Global Change Research (APN)

INTRODUCTION

The country workshop on **'Harnessing of Climate-Water-Energy Nexus for resource security in the Ganga River Basin'** was held on 9 August 2015 at Summit Hotel, Kupondole Height, Lalitpur, Nepal.

The workshop was part of the project **'Assessment of Climate-Induced Long-term Water Availability in Ganges River Basin and Impacts on Energy Security in South Asia'** led by Institute for Global Environmental Strategies (IGES), Japan. The collaborating partners are Bangladesh University of Engineering and Technology (BUET), Central University of Rajasthan, India and Center of Research for Environment, Energy and Water (CREEW), Nepal.

The purpose of the stakeholder workshop was to bring together and engage a wide gamut of stakeholders-government agencies, academic and research communities, civil society, NGOs, international organisations and the private sector on a common platform to discuss ways to advance the nexus approach in resource management with a focus on water, energy and food security in the Ganga River basin. The specific objectives of the workshop were:

i) To get feedback and input from key stakeholders on the methodological framework of the APN project.

ii) To review the state of resources and their management practices in each country.

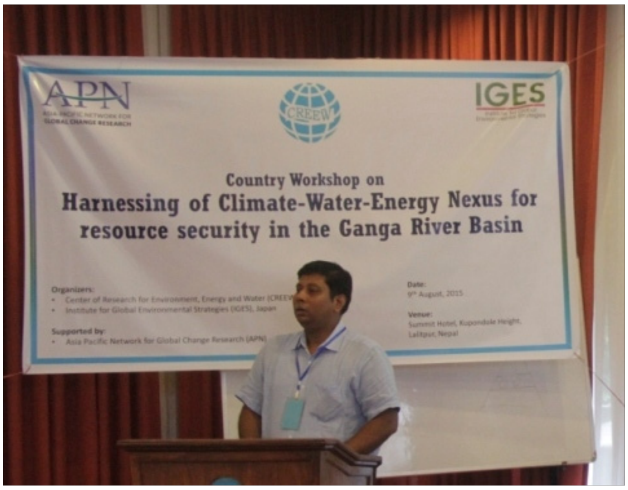
iii) To discuss and explore ways to highlight and prioritise the nexus approach in energy planning and identify feasible actions to realise nexus synergies.

Participants

Participants of the workshop

The event was attended by about 48 participants from relevant government organisations and their agencies, academic institutes, and other research institutes of non-government organisations. Participants from the government organisations and their agencies were Department of Irrigation (DOI), Groundwater Resources Development Board (GWRDB), Nepal Water Supply Corporation (NWSC), Department of Hydrology and Meteorology (DHM), Nepal Electricity Authority (NEA), Water and Energy Commission Secretariat (WECS), Department of Electricity Department (DOED), Kathmandu Upatyaka Khanepani Limited (KUKL). Amongst academic and research institutions were Nepal Academy of Science and

Technology (NAST), Institute of Engineering (IOE) of Tribhuvan University (TU), Central Department of Hydrology and Meteorology of TU, Kathmandu University (KU), Nepal Engineering College (NEC) of Pokhara University (PU), Asian Institute of Technology & Management (AITM); international organisations were Food and Agriculture Organization (FAO), International Centre for Integrated Mountain Development (ICIMOD); and research NGOs were The Small Earth Nepal (SEN), Nepal Development Research Institute (NDRI), Institute for Social and Environmental Transition – Nepal (ISET-Nepal) (*Please see ANNEX II*).



OPENING SESSION

Welcome speech

The opening session of the program was started with welcome remarks from Dr. Rabin Malla, Executive Director, CREEW (*Program schedule is attached in ANNEX I*). He welcomed all the participants and presenters who were mostly from related government institutions and agencies, research institutes, and universities. Also, he welcomed distinguished guest of the workshop, Dr. Bijon Kumer Mitra, Policy Researcher, Institute for Global Strategies (IGES), Japan. Moreover, he briefed objectives as to share the aim of the study and its major outputs to relevant stakeholders; to seek feedback and input from respective key stakeholders from Nepal on the methodological framework of the APN project; and then to secure water and energy supply security in the Ganga River Basin. He concluded by wishing for active participation, fruitful discussion and thanking all the participants for accepting the invitation of the organisers.

APN Project Overview-Background, Objectives, Expected Outcomes

Dr. Bijon Kumer Mitra, Policy Researcher, Institute for Global Environmental Strategies, (IGES), Japan

Dr. Bijon Kumer Mitra briefly introduced the participants about the purpose of the workshop. He briefly mentioned about the background behind the project development and also about the three collaborators. He said that it is a good opportunity to interact with stakeholders and their views are useful for further improving the methodology of the project. In his presentation, he justified the importance of Ganga river basin in South Asia and why this particular river is selected for the project. He mentioned that Ganga is a strategic basin in South Asia because of its catchment area, population growth and economic development, and as it is a good source of water in the region. It contributes about 30% to total water resources. In the energy sector, he said that thermal power plants are the main source of electricity in the region and that 40% of India's thermal power plants are located in this river basin. Dr. Mitra mentioned that as Nepal relies on hydropower it has also a big role to play for more hydropower generation for the region as well. Moreover, he highlighted that the outcome of the project would be to contribute to building regional cooperation in the climate-water-energy nexus. He then shared the key research questions with participants.

- How much water is used for electricity generation in South Asian countries?
- What are the driving factors of high water footprint for the electricity sector in the region?
- Can current policies overcome water conflict between electricity and other users?
- What types of technology can intervene to deal with the water constraint situation?
- How can regional cooperation address the nexus approach to promote synergies between water and energy sectors throughout the river basin?

Based on the above research questions, following objectives were prepared:

- Establishing a quantitative resource link between water and energy on the supply side of energy in the Ganges River basin.
- Providing guidance on an integrated assessment of the water-energy nexus for the planning of and investment in large-scale water management and energy development projects.
- Demonstrating the effects of water availability on long-term energy scenario development and subsequent impacts on energy technology choice.
- Supporting cross-border cooperation by seeking the synergies between water and energy sectors in supporting the achievement of sustainable development at the river basin level.

Open discussion

Er. Gautam Rajkarnikar from Department of Hydrology and Meteorology (DHM) inquired to presenter Dr. Bijon Kumer Mitra why he had chosen the Ganga River Basin despite many studies having been carried out in that basin. Dr. Mitra replied that water issues, water uses and water-energy linkage are very seldom covered. It accounts for 40% of the electricity generated from the Ganga basin. Nepal mainly depends on hydropower. Whereas in India, thermal plants and solar plants are being used and these occupy a huge land area. He also added that hydropower will be significant in the near future, and that Nepal will play big role in electricity generation.

Er. Jeebachh Mandal, Water and Energy Commission Secretariat (WECS), questioned Dr. Mitra regarding the difficulties in collecting discharge data from thermal plants. Dr. Mitra replied that power plant companies will not disclose such data. But in the case of Nepal, it is very easy to get data. He also suggested adding some parts from Tibet as well for the study since around 2-3% of the catchment lies in Tibet. Dr. Mitra replied that for now the addition was not possible because they are already in the middle of the project period but he promised to think about it in upcoming projects in the future.

SESSION I: Project overview

Chair: Dr. Kundan Lal Shrestha, Assistant Professor, Kathmandu University (KU)

Presentation: Methodology and expected outcome of the case study in Nepal

Er. Aashis Sapkota, Research Associate, Center of Research for Environment, Energy and Water (CREEW)

The presentation mainly focused on the methodology of the project in Nepal and its expected outcome. He discussed the calculation of current and future water demand for domestic purpose, irrigation purpose and industrial use. The methodology planned for the power plant survey was presented along with some sample questions. The execution of the SWAT model along with GCM and input data was also presented for discussion with the stakeholders. Expected outcomes of the project included assessment of the nexus between energy demands in the future.

Open discussion

Mr. Manoj Badu, Kathmandu University (KU) questioned Er. Aashis Sapkota about whether the study team has any intention to collect primary data for soil texture, land use and climate data or use secondary sources for modelling. He was curious as the basin was too big for simulation, thus collecting data will be crucial. Er. Sapkota replied that that part of the simulation has been planned for the second year and the study team will decide on a suitable methodology and database for the project. So, the comments and suggestions from the workshop will be a very important way forward in that regard.

Prof. Kundan Lal Shrestha from KU inquired that the current trend of establishment of industries is quite low but he was quite surprised to see Er. Sapkota's prediction on the future growth rate of industry. Er. Sapkota replied that growth until now was not so significant, but in future there will be huge scope for industrial growth. They have an optimistic outlook on industrial growth taking place at a healthy rate in the future.

Prof. Shrestha again added that the global climate model (GCM) has not given good outputs in the case of Nepal. So, he suggested a regional climate model (RCM) for this study. In return Dr. Mitra replied that in India and Bangladesh the collaborators are modelling with regional data. The same methodology will be applied in the case of Nepal. Dr. Shrestha also suggested simulating, if possible, extreme climatic events.

Mr. Prakash Gaudel, Nepal Electricity Authority (NEA), inquired that if there was any study in the upper basin it will definitely impact the lower basin and how this project would deal with such regional issues. Dr. Mitra replied saying that it was very challenging. He said we can approach some policy researchers concerning this issue. He also said that high-level discussions between Nepal, India and Bangladesh are underway to cope with it.

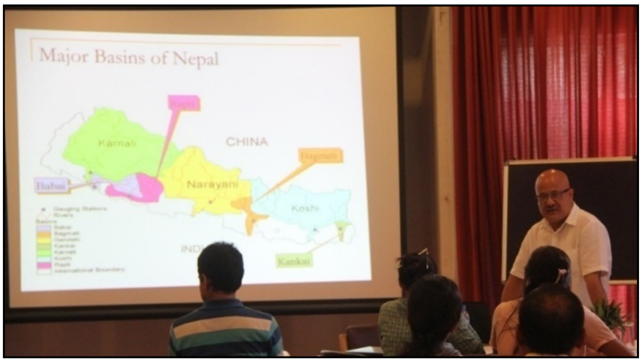
Dr. Mandan Lall Shrestha, Nepal Academy of Science and Technology (NAST), suggested that there are difficulties in implementing this type of project in our region. It is the same for this project as well as other projects so he requested to go along with the project and let the policy makers know about the difficulties. He also mentioned that these things must be included in the final report so that policy maker will have an idea of difficulties involved in the project.

State of Resources and Management with Focus on Water, Energy and Food Security in Ganga River Basin

TECHNICAL SESSION II A

Chair: Dr. Madan Lall Shrestha, Academician, Nepal Academy of Science and Technology (NAST)

Presentation: Climate Change and Water Resources in the Context of Nepal
Prof. Dr. Narendra Man Shakya, Institute of Engineering (IOE), Tribhuvan University (TU)

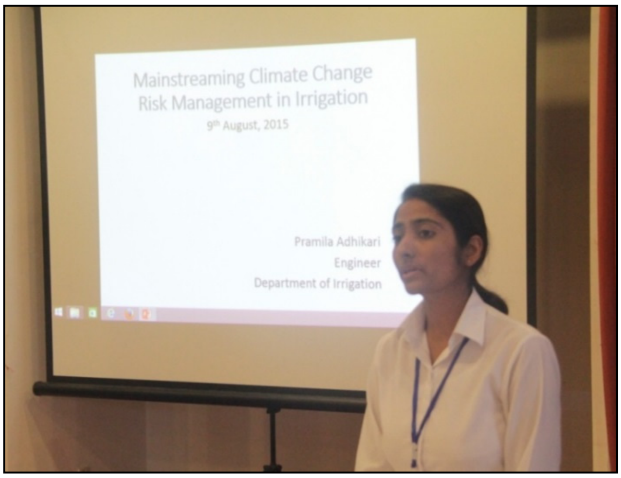


In the beginning of the presentation, Prof. Narendra Man Shakya, clarified the impact of climate change on the water resources of Nepal. He showed in his slides that the run-off coefficient of rivers was very high especially for rivers in the south. Also, he explained how the river discharge had changed from 1996 to 2005. During this period, it was shown that among the major rivers (except for Kamala and Kankai Rivers), Bagmati, West Rapti, Babai, Narayani, Koshi, Karnali and Mahakali have shown a positive discharge trend. He pointed out, using slides, that southern rivers have a big burden to support 42% of the agricultural area and 41% of the population of Nepal living in the southern plains with only 13% of the available water in Nepal. Furthermore, he presented a summary of glaciers, glacial lakes and GLOF in Nepal. In addition, he highlighted that:

- The number of glaciers increased but the total area decreased due to shrinking and defragmentation of glaciers
- The number of glacial lakes has been decreased but the total area is increasing due to merging and expansion of glacial lakes
- Possibility of high frequency GLOF in near future.

He further presented that the dependable flow of many river systems will decrease causing reduction in the energy generation of hydropower in the future. He said that increasing landslides and debris deposition within the watersheds is underway due to climate change. In one of the slides, he showed the increase in sediment concentration (ppm) during the mid-day period (09:00-15:00), which showed that the value of damage to the electromechanical components could be higher than the income generated by electricity. So, power plant operators might choose to shut down plants during those hours to avoid economic loss. However, he opined that it would not be beneficial for the energy balance in the system.

Presentation: Mainstreaming Climate Change Risk Management in Irrigation Climate Change and Water Resources in the context of Nepal
Er. Pramila Adhikari, Department of Irrigation (DOI)



Er. Adhikari presented the pilot project on Climate change risk management in the irrigation projects jointly developed by the Ministry of Science, Technology and Environment and Department of Irrigation. She started her presentation by explaining the expected outcomes of that project which are: integration of climate change risks into development projects and development and application of knowledge management tools. So, in order to achieve the above mentioned outcomes, she presented the methodology of a Department of Irrigation (DoI) pilot project. The methodologies were: implementation of Nepal's climate change policy, climate change vulnerability assessment, development of data support infrastructures, and establishment of an overall climate change risk management system. Similarly, she mentioned the climate change impact and vulnerability assessment steps. Moreover, she presented on the major climate change threats for irrigation such as: temperature, rainfall, wind, humidity, infiltration/runoff, surface hydrology and storms. Furthermore, she presented on the impact of climate change on the irrigation projects of different parts of Nepal such as: the rise in temperature leading to higher evaporation rates and irrigation demand in Dolakha district and so on. In addition, she also briefly presented the major climate change threats like flash floods, landslides, large scale extreme flooding, extreme drought, increased evaporation which have extreme effects on the irrigation system. Furthermore, she explained the climate change impact matrix which was formed by the relation of sensitivity system to climate threat and exposure of the system to climate threat. From this relation, a scale factor was developed. She also mentioned that, following the proposed methodologies, DoI had undertaken vulnerability assessments of irrigation systems in six districts: Banke, Chitwan, Mustang, Kathmandu, Dolakha and Panchthar of Nepal. In addition, she presented on the adaptation responses in intake, main canal, cross drainage and some common areas. To end, she talked about a specific vulnerability assessment matrix to be used while assessing a component of an irrigation system to exposure.

Open discussion

Prof. Rijan Bhakta Kayastha, KU, suggested Prof. Narendra Man Shakya use updated glacier data since the data of 2011 was already available. Furthermore, he was curious to know whether Prof. Shakya used re-analysed data or observed data for the study as it required much data for determining 8% snow and ice melt contribution in Koshi River Basin and for using the energy balance equation. Prof. Shakya replied that the study team is in the process of developing a new data set for the whole project and the analysis was based on the secondary data from Department of Hydrology and Meteorology (DHM). Er. Ram K. Kharbuja, from Department of Electricity Development (DOED), asked Prof. Shakya whether he had any flow duration curve data for snow-melt rivers since the scenario may differ between snow-fed rivers and rain-fed rivers. Furthermore, he inquired how the number of flood days will be affected due to climate change. Prof. Shakya replied that they have studied flow duration curves for Kaligandaki and Narayani basins. He further added that changes in rainfall changed in the return period of floods and they have analysis data for both average and extreme flood cases. In addition, he suggested the department to incorporate all the approaches.

Mr. Dibesh Shrestha, NDRI, put his curiosity to Prof. Shakya saying that despite a decrease in total area of snow and ice melting, the flow in Karnali and Mahakali was increasing. Further, he inquired as to whether the increase in the width of the hydrograph of Koshi River Basin meant the flow is increasing or not. Prof. Shakya replied that flow was increasing in the northern zone of Nepal due to melting of ice with the increase in temperature. The flow was high because of excessive melting of glaciers. In this context, hydropower can be generated there, but after say 40 - 50 years the river discharge will have decreased.

Mr. Manjeet Dhakal, Climate Analyst, inquired from Prof. Shakya as to whether the analysis on water availability carried out in the southern part of Nepal was hourly-based or daily-based data, and whether he had done any seasonal shift studies and whether the results of the present study were compared with the previous study data or not. Prof. Shakya replied that all-season analysis has been carried out and compared.

Similarly, Ms. Shobha K. Yadav, ISET-Nepal, asked Er. Pramila Adhikari about whether the methodologies she presented for vulnerability assessment of irrigation projects were originally developed or adapted from others. Er. Adhikari replied that the methodologies were developed by the Ministry of Science, Technology and Environment and Department of Irrigation (DOI) and they were revising it since lots of indicators were not included in their methodologies.

TECHNICAL SESSION II B

Chair: Prof. Dr. Hari Prasad Pandit, Institute of Engineering (IOE), Tribhuvan University (TU)

Presentation: Overview on Energy Supply and Demand: Present and Future

Er. Sher Singh Bhat, Deputy Managing Director (Generation Directorate), Nepal Electricity Authority (NEA)

Er. Bhat started his presentation by highlighting energy as a serious concern for all. Besides this, he also mentioned source- and sector-wise energy consumption in Nepal. He stated that to date, among South Asian countries, Nepal had ranked second last in electricity consumption after Afghanistan. He presented the electricity demand forecast starting from 2015/2016 to 2033/2034. The forecasted energy demand including loss will be 6,901 GWh for year 2015/2016 while it will be 36,36,6 GWh for year 2033/2034. Er. Bhat showed the capacity balance for the year 2015/16 during dry and wet seasons. According to the projections made, the electricity demand will be met by the hydro-electric projects under construction which are mostly river type projects but again the generated electricity will be in deficit due to increasing demand and reduced discharge in rivers during dry periods. This situation will lead Nepal to a hydro-electric deficit country in the future. He mentioned that, until electricity is not imported from neighboring countries, load shedding in Nepal will remain above 10 hours during the dry season even in 2018/19 despite a huge wet surplus. The solution to this is development of storage type hydro-electric plants which will be able to generate electricity even in dry periods and the surplus can be exported to the Indian market. Moreover, he presented the Nepal GDP and electricity demand growth rate and also hourly average load profile. He concluded his presentation by delivering an important message of *"*surplus management through integration with Indian system and market*"*.

Open discussion

Mr. Manjeet Dhakal, Climate Analyst, raised a question to Er. Sher Singh Bhat that he appeared to show future energy demand as somehow on the low side, and asked if he had considered the change in consumption culture in the future. Er. Bhat responded that they have taken care of different aspects and that that was the reason for the optimistic prediction. Again, Mr. Dhakal informed that the Clean Development Mechanism (CDM) has been successfully implemented in China and India. He inquired from Er. Bhat whether NEA has considered such mechanism for Nepal. Er. Bhat replied that CDM is not feasible for small projects. The process for gaining facilities is too expensive so it will be difficult for small projects. It is also something that cannot be conceived for projects that have already been implemented. However, he revealed that it might be possible for projects like Upper Karnali (900 MV) in the future.

Er. Umesh Babu Marahattha, Kathmandu Upatyaka Khanepani Limited (KUKL) suggested that a tariff system (hourly or seasonally) is a kind of solution for load shedding. Er. Bhat replied that even though it is a good solution it will take more time since all the household meters would have to be replaced.

Dr. Bijon Kumer Mitra (IGES) inquired from Er. Bhat whether there are any policies in Nepal which will encourage foreign investment in hydroelectricity projects. Dr. Bhat replied that a Foreign Direct Investment (FDI) policy is in place in Nepal but it was not effectively implemented. He further said that downstream countries will benefit during the wet season and it depends on the foreign currency in which the downstream countries are willing to pay. He also gave an example of Ethiopia where they are using domestically raised funds for construction of hydroelectricity projects. So, he opined, Nepal should use its own domestic fund and reduce dependency on FDI.

Dr. Dibya Ratna Kansakar, Department of Irrigation (DoI) suggested that forest resources are exploited a lot for domestic purposes. So, to minimise such activities, hydroelectricity if generated in surplus can be consumed for domestic use, pumping groundwater in the plains (terai) for irrigation and for different scale lift irrigation in the hills and mountains of Nepal.

SESSION III: Focused group discussion

Facilitator: Dr. Sujata Manandhar, Researcher, CREEW

Prof. Ashutosh K. Shukla, Nepal Engineering College, suggested including the study on eco-system on the Ganga River Basin under this project. Also, he suggested undertaking a study on other sub-basins too while looking at the whole basin and trying not to simplify the complex study of the basin.

Dr. Mitra, IGES, replied that the eco-system study and sub-basins study will not be carried out in this current study since the project had already completed a year. But he promised to include these studies in future projects.

Prof. Hari Prasad Pandit, IOE, suggested the study team refer to the World Bank Report of 2012 for improving the findings and recommendations of this project and to make it a professional report on regional co-operation to harness the Climate-Water-Energy Nexus for resource security in the Ganga River Basin.

CLOSING SESSION

Dr. Bijon K. Mitra (IGES, Japan) closed the program with his closing remarks. He extended a vote of thanks to all the participants from different organisations for their active participation and fruitful suggestions for this project. He promised to share the results of the study among the stakeholders after completion of the project.

Workshop agenda

OPENING SESSION		
10:00-10:05	Welcome address	Dr. Rabin Malla, Executive Director, CREEW
10:05-10:10	Welcome address	Dr. Bijon Kumer Mitra, Policy Researcher, Institute for Global Environmental Strategies (IGES), Japan
10:10-10:20	Introduction of participants	
10:20-10:25	Workshop objective and agenda	Dr. Rabin Malla, Executive Director, CREEW
SESSION I: Project overview		
Chair: Dr. Kundan Lal Shrestha, Assistant Professor, Kathmandu University (KU)		
10:25-10:40	APN Project Overview-Background, Objectives, Expected Outcomes	Dr. Bijon Kumer Mitra, Policy Researcher, IGES, Japan
10:40-10:55	Methodology and expected outcome of the case study in Nepal	Er. Aashis Sapkota, Research Associate, CREEW
10:55-11:30	Open discussion on the study proposal and expectations	
11:30-11:45	*Group photograph and coffee break*	
State of resources and management with focus on water energy and food security in Ganga River basin		
TECHNICAL SESSION II A		
Chair: Dr. Madan Lall Shrestha, Academician, Nepal Academy of Science and Technology (NAST)		
11:45-12:15	Climate Change and Water Resources in the Context of Nepal	Dr. Narendra Man Shakya, Professor, Institute of Engineering (IOE), Tribhuvan University (TU)
12:15-12:45	Mainstreaming Climate Change Risk Management in Irrigation	Er. Pramila Adhikari, Department of Irrigation (DoI)
12:45-13:00	Questions and discussion	
***Lunch Break* (13:00-14:00)**		
TECHNICAL SESSION II B		
Chair: Dr. Hari Prasad Pandit, Professor, IOE, TU		
14:00-14:30	**Overview on Energy Supply and Demand: Present and Future**	Er. Sher Singh Bhat, Deputy Managing Director (Generation Directorate), Nepal Electricity Authority (NEA)
14:30-15:00	**Development of Nepal's hydropower resources for energy security in the region: Prospects and Challenges**	Er. Jeebachh Mandal, Joint Secretary and, Dr. Sanjaya Sharma Joint Secretary; Water and Energy Commission Secretariat (WECS)
15:00-15:15	Questions and discussion	
***Coffee Break* (15:15-15:30)**		
SESSION III: Focused group discussion		
Facilitator: Dr. Sujata Manandhar, Researcher, CREEW		
15:30-16:30	**Focused group discussion: Water energy nexus in energy planning** - Practical challenges and stakeholder suggestions - Spatial water availability and power plant planning - Institutional and policy arrangements to enhance nexus synergies.	

	- Realising nexus in regional cooperation on resources security - Way forward to minimise/manage the nexus-stakeholder perspective	
16:30-17:00	Wrap-up (Report from focused group discussion)	
17:00-17:15	Closing remarks	Dr. Bijon Kumer Mitra, Policy Researcher, IGES, Japan

List of workshop participants

SN	Name	Organisations
Government organisations		
1	Er. Pramila Adhikari	Department of Irrigation (DoI)
2	Dr. Bhupendra Prasad	Nepal Water Supply Corporation (NWSC)
3	Er. Gautam Rajkarnikar	Department of Hydrology and Meteorology (DHM)
4	Prakash Gaudel	Nepal Electricity Authority (NEA)
5	Er. Jeebach Mandal	Water and Energy Commission Secretariat(WECS)
6	Er. Birat Gyawali	Department of Irrigation (DoI)
7	Er. Raj Kumar Gumanju	Department of Irrigation (DoI)
8	Er. Surya Dev Gupta	Department of Electricity Development (DOED)
9	Dr. Dibya Ratna Kansakar	Department of Irrigation (DoI)
10	Er. Tilak Mohan Bhandari	Kathmandu Upatyaka Khanepani Limited (KUKL)
11	Er. Bijaya Man Shrestha	Kathmandu Upatyaka Khanepani Limited (KUKL)
12	Er. Umesh Babu Marahatta	Kathmandu Upatyaka Khanepani Limited (KUKL)
13	Jagat Prasad Joshi	Groundwater Resources Development Board (GWRDB)
14	Er. Sher Singh Bhat	Nepal Electricity Authority (NEA)
15	Er. Ishwar Prasad	Nepal Water Supply Corporation (NWSC)
16	Er. Laxmi Devkota	Budigandaki
17	Er. Ram Gopal Kharbuja	Department of Electricity Development (DOED)
Academic/research institutions		
18	Dr. P.C. Jha	Institute of Engineering (IOE)/Tribhuvan University (TU)
19	Mohan Bdr. Chand	Kathmandu University (KU)
20	Dr. Archana Prasad	Central Department of Zoology (CDZ)/TU
21	Prof. Ashutosh Kumar Shukla	Nepal Engineering College (NEC)/ Pokhara University (PU)
22	Dr. Narayan Shrestha	Nepal Engineering College (NEC)/PU
23	Dr. Madan Lall Shrestha	Nepal Academy of Science and Technology (NAST)
24	Dr. Madhav Narayan Shrestha	Asian Institute of Technology & Management (AITM)
25	Dr. Tirtha Raj Adhikari	Tribhuvan University (TU)
26	Dr. Rijan Bhakta Kayastha	Kathmandu University (KU)
27	Manoj Badu	Kathmandu University (KU)
28	Dr. Narendra Man Shakya	Institute of Engineering (IOE)/TU
29	Dr. Kundan Lal Shrestha	Kathmandu University (KU)
30	Dr. Hari Prasad Pandit	Institute of Engineering (IOE)/TU
UN agencies and international organisations		
31	Dr. Bijon Kumer Mitra	Institute for Global Environmental Strategies (IGES), Japan
32	Bhim Nath Acharya	Food and Agriculture Organization (FAO)
33	Sonu Khanal	International Centre for Integrated Mountain Development (ICIMOD)
NGOs and Others		
34	Dibesh Shrestha	Nepal Development Research Institute (NDRI)
35	Dr. Jaya K. Gurung	Nepal Development Research Institute (NDRI)
36	Dilli Bhattarai	The Small Earth Nepal (SEN)
	Manjeet Dhakal	Freelance Climate Analyst
37	Shobha Kumari Yadav	Institute for Social and Environmental Transition –Nepal (ISET-Nepal)
38	Dr. K.N. Dulal	Center of Research for Environment, Energy and Water (CREEW)
39	Dr. Rabin Malla	CREEW
40	Dr. Sujata Manandhar	CREEW
41	Dr. Salina Shrestha	CREEW
42	Meera Prajapati	CREEW
43	Sarita Shrestha	CREEW
44	Aashis Sapkota	CREEW

45	Nihit Bhattarai	CREEW
46	Upendra Shahi	CREEW
47	Sangam Ghimire	CREEW

Appendix 5 Project workshop in Bangladesh was covered in the national newspaper

Prof Khaleda Ekram, Vice-Chancellor, BUET, delivering her inaugural speech as chief guest at a workshop on 'Assessment of Climate - Induced Long Term Water Availability in Ganges Basin and Impacts on Energy Security in South Asia' organized by Institute of Water and Flood Management (IWFM) on Sunday at the seminar room of IWFM, BUET. The function was addressed, among others, Dr Bijon Kumar Mitra, Researcher, IGES, Japan and Dr Md Giasuddin Miah, Professor, BSMRAU and member, APN Scientific Planning Group. The function was presided over by Prof Dr G M Tarekul Islam, Director, IWFM, BUET.

■ NN photo

Appendix 6 Agenda of the final project workshop in Bangladesh

Final Country Workshop of the Research Project on Assessment of Climate-Induced Long-term Water Availability in Ganges River Basin and Impacts on Energy Security in South Asia

Venue: Department of Environmental Science, Central University of Rajasthan
18 November 2018

Organisers: Bangladesh University of Engineering and Technology (BUET)
Institute for Global Environmental Strategies (IGES)
Supported by: Asia Pacific Network for Global Change Research (APN)

Workshop Program

0930-1000	**Registration**
10:00-10:30	Welcome address by BUET (5 min)……………………………. Prof. GM Tarekul Islam Welcome address by IGES (5 min)…………………………………… Bijon Kumer Mitra Chief Guest Speech (5 min)…………………Dr. Sujit Kumar Bala, Director, IWFM Introduction of participants (5 min) Workshop objective and agenda (10 min)..................................*Prof. GM Tarekul Islam*
10:30-10:40	**Group photograph**
Session 1:	**Project Overview**
10:40-11:00	APN Project Overview- Background, Objectives……………….*Bijon Kumer Mitra*
11:00-11:20	Coffee break
Session 2:	**Project Overview**
11:20-11:50	Water Resource Availability in Bangladesh……..………..*Prof. GM Tarekul Islam*
11:50-12:00	Q&A
12v00-12:30	Energy-Water Nexus tool for supporting power development plans……..………………………………………………………………….*Bijon Kumer Mitra*
12:30-12v40	Q&A
12:40-13:40	Interactive Discussion and Suggestions
13:40-13:50	Closing remarks
13:50-15:00	**Lunch and Networking**

Appendix 7 Agenda of the final project workshop in India

IGES Institute for Global Environmental Strategies | CREEW | APN ASIA-PACIFIC NETWORK FOR GLOBAL CHANGE RESEARCH

Workshop on
Harnessing of Climate-Water-Energy Nexus for Resource Security in the Ganga River Basin

20th November 2018 (*Tuesday*)

Venue: Department of Environmental Science, Central University of Rajasthan

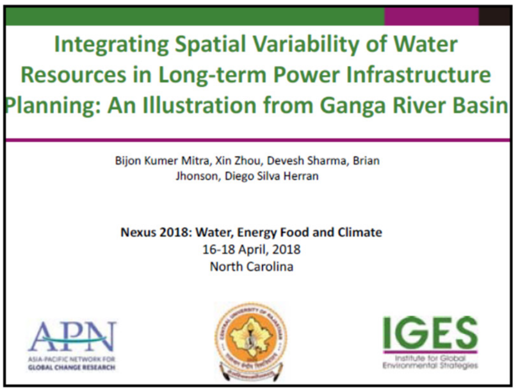
Organizers: Central University of Rajasthan (CURAJ), India
Collaborators: Institute for Global Environmental Strategies (IGES), Japan
Center of Research for Environment, Energy and Water (CREEW), Nepal
Supported by: Asia Pacific Network for Global Change Research (APN)

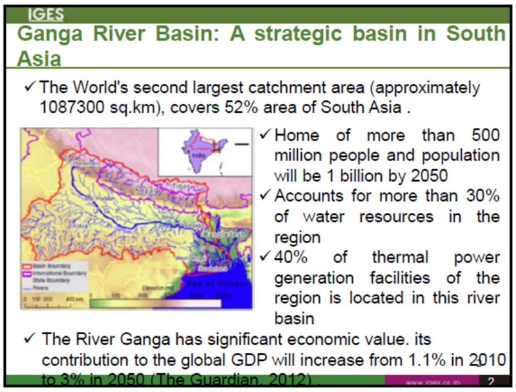
Workshop Program

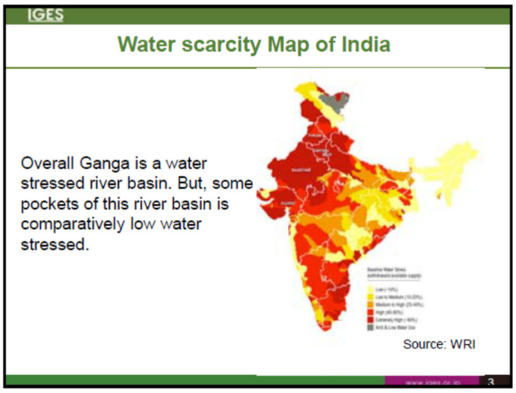
0930-1000	**Registration**	
	Opening Session	
1000-1005	Welcome Address (CURAJ)	Dr. Devesh Sharma, EVS, CURAJ
1005-1010	Welcome Address (IGES)	Dr. Bijon K Mitra (IGES, Japan)
1010-1015	Workshop Objective and Agenda	Dr. Devesh Sharma, EVS, CURAJ
1015-1020	Introduction of Participants	All Participants
1020-1025	Presidential Remarks	Dr. L. K. Sharma, Dean, SES, CURAJ
1025-1030	Vote of Thanks	Dr. Garima Kaushik, EVS, CURAJ
1030-1050	**Group photograph and networking break**	
	TECHNICAL SESSION ***Chair: Dr. Someshwar Das, Atmospheric Dept., CURAJ***	
1050-1110	Water-Energy Nexus and Application to South Asian Countries	Dr. Tomohiro Okadera *(NIES, Japan)*
1110-1130	Water Resources Situation in the Ganga Basin	Dr. B. R. Sharma *(IWMI, New Delhi)*
1130-1150	Water-Energy Nexus in Nepal	Dr. Rabin Mallala *(CREEW, Nepal)*
1150-1210	Agriculture and groundwater use in semi-arid regions-Implications for sustainability	Dr. RamKumar *(WoTR, Pune)*
	PROJECT SESSION ***Chair: Dr. B. R. Sharma, IWMI, New Delhi***	
1210-1220	Project Overview	Dr. Bijon K Mitra (IGES, Japan)
1220-1240	Water Resource Availability in Selected Sub-basins of Ganga Basin	Dr. Devesh Sharma (CURAJ, India)
1240-1300	Energy-Water Nexus Tool for Supporting Power Development Plans	Dr. Bijon K Mitra (IGES, Japan)
1300-1345	Discussion and Suggestions	
1345-1400	Closing Remarks	
1400-1500	**Lunch**	

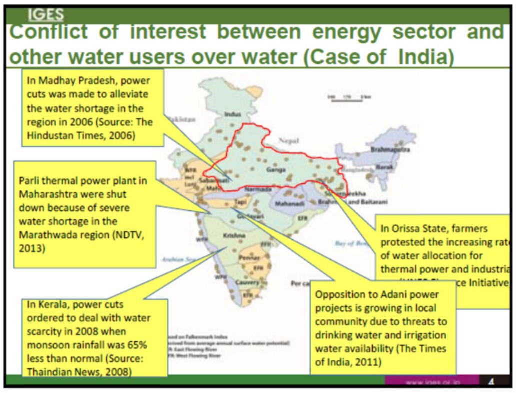
Appendix 8 Presentation at the 2018 Nexus Conference, North Carolina

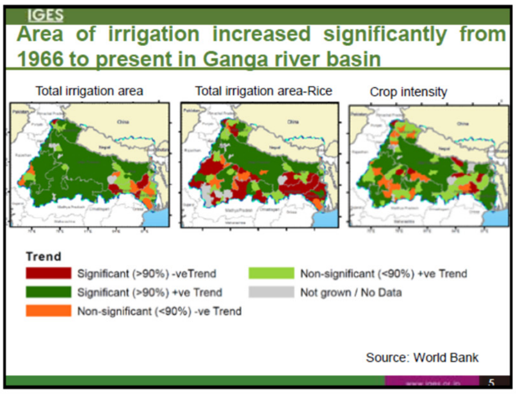
Abstract is available in the Conference abstract book.
https://waterinstitute.unc.edu/files/2018/10/CONFIDENTIAL_ABSTRACT-BOOK-FOR-NEXUS-2018.pdf

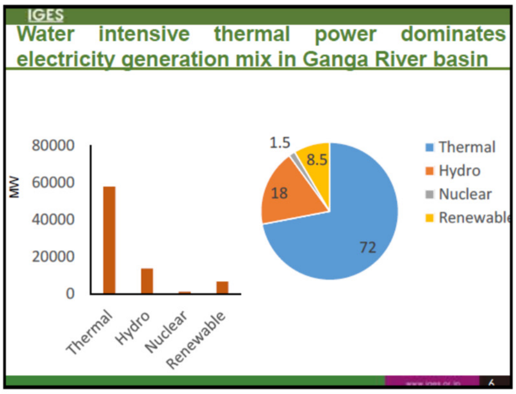












IGES

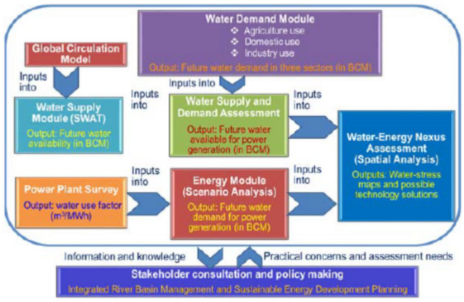
Aims of our research project

- ✓ Our research project "Assessment of Climate-Induced Long-term Water Availability in Ganges River Basin and Impacts on Energy Security in South Asia" aims to quantify the nexus of water and energy from both supply and demand sides and provide a scientific assessment on the long-term impacts of water availability on location-specific power generation scenarios and technology options.
- ✓ The water stress map for power generation can be used to guide feasible energy planning and help assess the risk of investment in energy development projects from water security perspective.

7

IGES

Analytical framework for an integrated assessment on water-energy nexus in the Ganges River Basin



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Stakeholder participation in the research works

Country workshop on Climate-Water-Energy Nexus, 20 April 2015, Delhi, India

Country workshop on Climate-Water-Energy Nexus, 9 August 2015, Kathmandu, Nepal

Country workshop on Climate-Water-Energy Nexus, 14 June 2015, Dhaka, Bangladesh

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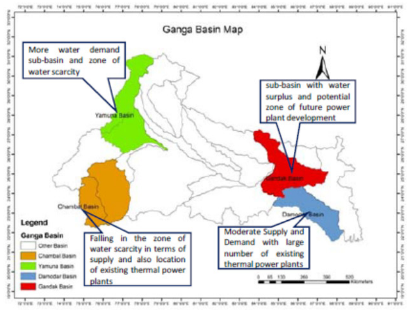
IGES

Selected sub-river basins of Ganga for study



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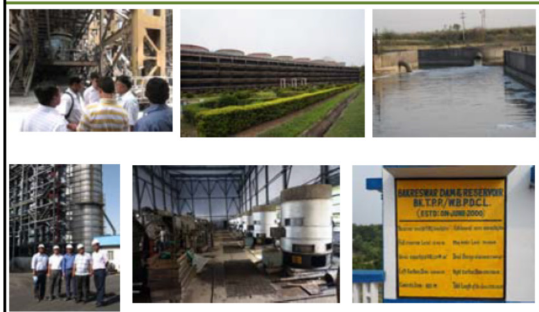
Power plant survey in India



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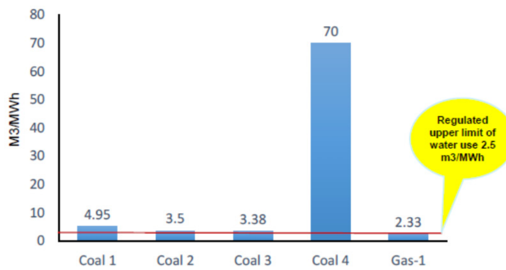
Results of power plant survey



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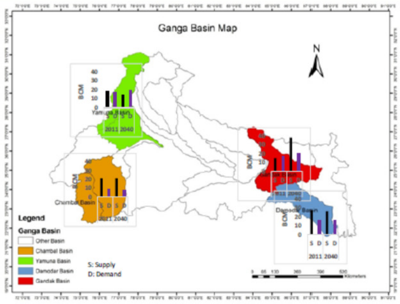
Water supply-demand projections for four selected sub-basins of Ganga River



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Key findings

- ✓ Water availability will decrease in Yamuna and Damodar sub-basins by 23% and 6%, respectively in 2040 . In contrast, water availability in Gandak sub-basin will increase by 153% in 2040 .
- ✓ In Yamuna sub-basin water demand will exceed water availability in 2040. This implies that water may become a constraint for the development of new thermal power infrastructure in the sub-basin.
- ✓ For Yamuna sub-basin, power supply may need to be provided from neighbouring sub-basins.
- ✓ In the coming years, Gandak will have significant increase in water availability and will have large amount of water surplus. Therefore, Gandak could be a suitable place for locating new thermal infrastructure and help alleviate water-stress pressure in Damodar where a number of thermal power plants are located.

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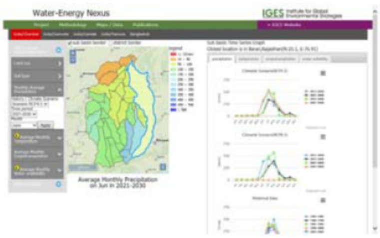
Web tool for supporting site-specific suitable power generation technologies



It would be an useful tool for decision makers and investors of power generation infrastructure development

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About IGES

The Institute for Global Environmental Strategies (IGES), established in March 1998 under an initiative of the Japanese government, is an international research institute conducting solution-oriented and innovative policy research for realising sustainable development both in the Asia-Pacific region and globally. IGES research focuses on climate change and energy, sustainable consumption and production, natural resource management, strategic and quantitative analysis, and sustainable governance.