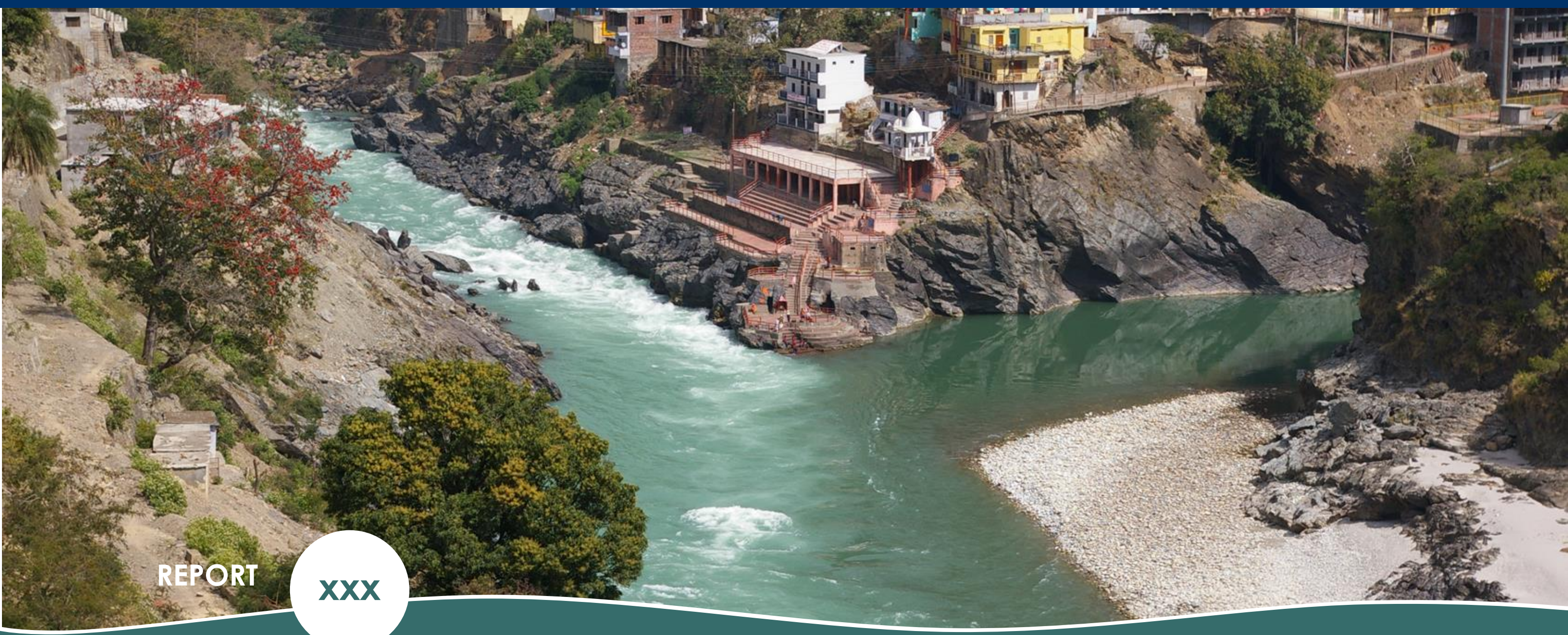
Water Allocation in Bhagirathi Basin, India



REPORT XXX

CLIENT SDC

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FutureWater Report xxx

Client
Swiss Development Cooperation (SDC)

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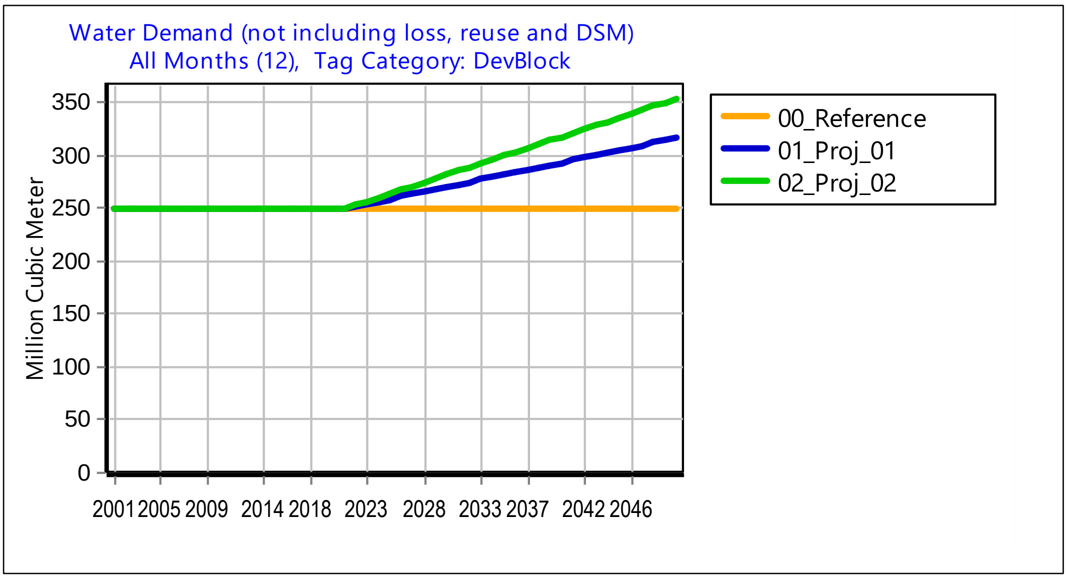
Water Demand (not including loss, reuse and DSM)
All Months (12), Tag Category: DevBlock
Million Cubic Meter
350
300
250
200
150
100
50
0
2001 2005 2009 2014 2018 2023 2028 2033 2037 2042 2046
00_Reference
01_Proj_01
02_Proj_02

1 Relevance

1.1 Moutains and climate change

Mountain regions occupy about one-quarter of the Earth's land surface and are home to 15% of the world's population. They supply half of the global population with fresh- water for domestic use and lowland irrigation in support of global food security. Mountains also provide some of the clearest indicators of global warming and their natural ecosystems act as early indicators of climate change. In the 20th century they experienced above-average warming, in comparison to the global mean. Mountain surface air temperature observations in Western North America, European Alps and High Mountain Asia show warming over recent decades at an average rate of 0.3ºC per decade, with a likely range of ± 0.2ºC, thereby outpacing the global warming rate 0.2 ± 0.1ºC per decade (IPCC, 2018)1. The warming rate over the last 50 years in the HKH has been 0.2˚C per decade.

Climate change is also making rainfall patterns irregular and is increasing the probability of extreme droughts and flooding events. High-resolution regional climate model for 2030's indicates that the annual rainfall in the Himalayan region may vary between 1268 ± 225.2 mm to 1604 ± 175.2 mm respectively, representing an increase in the range of 5 to 13%. Similarly, regional climate models have indicated an increase in summer precipitation of 4-40% by the end of this century. While the precipitation is increasing, it is projected that the number of rainy days may not increase, indicating an increase in rainfall intensity. Disasters associated with natural hazards not only jeopardize mountain people's livelihoods and the fruits of social and economic development, but also often strike people living in adjacent lowlands.

With the effects of climate change, there is an increase in temperatures, unpredictability of seasonal patterns (monsoon) and rapid and unprecedented glacier melting and changes in snow cover, leading to the development of large lakes in the higher mountain regions. This situation is further complicated by a reduction in the number of rainy days on one hand and increase in the intensity of rainfall over the last decade in the Himalayan region.

The Bhagirathi river valley in the Uttarakhand State is particularly prone to landslides and flash floods. The area has witnessed unexpected increase in extreme climate events in the recent years. Several landslide events are recorded in the valley in the past. Among them Kaunaldia Gad event and Varunavat event were reported by National Institute of Disaster Management (NIDM) as most destructive hazards. In 1978 due to cloud burst a flash flood along with heavy landslide was reported in Kaunaldia Gad (tributary of Bhagirathi River). In this event about 1.5 km long and 20m deep, lake was formed due to the large debris deposits. Again, on 24th September, 2003 a massive landslide was recorded near Varunavat Parvat.

1.2 Swiss Agency for Development and Cooperation's (SDC)

The Swiss Agency for Development and Cooperation's (SDCs) Global Programme Climate Change and Environment (GPCCE) India is supporting the operationalization of climate change adaptation actions in the mountain states of Himachal Pradesh, Uttarakhand and Sikkim through the phase two of the "Strengthening State Strategies for Climate Action"

(3SCA) project that was launched in 2020. This project involves strengthening capacities of public sector partners in planning and implementing relevant climate actions across select sectors including water, and disaster management, by leveraging the Swiss expertise in sustainable mountain development. Phase 1 of the 3SCA project (2016 to 2019) was implemented in the three Indian states of Madhya Pradesh, Sikkim, Uttarakhand.

The second phase of 3SCA (2020-23), known as the Strengthening Climate Change Adaptation in Himalayas (SCA-Himalayas), while building on the experience and achievements of Phase 1, aims to showcase mountain ecosystem appropriate scalable approaches for climate resilience in water and disaster risk management sectors; using these efforts to enhance the capacities of the institutions across the Indian Himalayan Region (IHR) to plan, implement and mainstream adaptation actions into their programmes and policy frameworks; and disseminating the experiences and lessons at the regional and global level. The overall goal of the program is to integrate climate actions into sub-national planning and implementation, benefitting local communities in India.

1.3 Project

A consortium of four partners and several sub-contractors is supporting SDC in achieving their overall goals. The consortium members are

- FutureWater, Netherlands
- Utrecht University, Netherlands
- The Energy and Resources Institute (TERI), India
- University of Geneva (UniGE), Switzerland

The project includes three outcomes:

- Outcome 1: Develop and validate an integrated climate resilient water resource management approach (**modeling**)
- Outcome 2; Increase technical and institutional capacity in the fields of hydrological modelling, IWRM and DSS;
- Outcome 3: Support the embedding of the IWRM approach tailored to glacier-fed Indian Himalayan subbasins in policies, and provide generic outputs and guidelines to facilitate upscaling to other subbasins in the Indian Himalayan Region.

Outcome 1 (**modeling**) will be achieved by developing and applying three hydrological models:

- (i) a high resolution glacio-hydrological model for the Dokriani glacier catchment (SPHY-Dokriani).
- (ii) a distributed glacio-hydrological model that covers the Bhagirathi subbasin (SPHY-Bhagirathi).
- (iii) a **water allocation model** that overlays the SPHY-Bhagirathi model in the downstream parts of the basin, where water demands are located (WEAP Bhagirathi).

This modelling toolset is forced with downscaled climate change projections and socio-economic projections to simulate future changes in water supply and demand in the subbasin. On the basis of stakeholder inputs, adaptation options are identified and implemented in the water allocation model for scenario analysis.

This report presents the results of the component (iii) of the modeling outcome: development, application and scenario analysis of a water allocation model.

Results of this component will contribute to the overall goal of the program ("to integrate climate actions into sub-national planning and implementation, benefitting local communities in India"). The goal for this specific component can therefore be defined as:

Application of a water allocation model to evaluate climate actions: case study Bhagirathi

2 Bhagirathi Basin

2.1 Overview

The Bhagirathi[1] is a turbulent Himalayan river in the Indian state of Uttarakhand, and one of the two headstreams of the Ganges (the other is the Alaknanda). The Ganges is the major river of Northern India and the holy river of Hinduism. Geographically speaking, the Ganga basin is spread over the region that includes India, Tibet, Nepal, and Bangladesh, covering an area of 10,86,000 km^2. In the Hindu faith, mythology, and culture, the Bhagirathi is considered the source stream of the Ganges. However, in hydrology, the other headstream, Alaknanda, is considered the source stream on account of its great length and discharge. The Bhagirathi and Alaknanda join at Devprayag in Garhwal and are thereafter known as the Ganges.

Bhagirathi basin is located in the state of Uttarakhand and located in two districts: District Uttar Kashi and Tehri District. The catchment[2] area of the Tehri Project is 6921.25 Sq. km. This area is divided into 16 sub-watersheds and 149 micro watersheds of which, 3557.99-sqkm are estimated to be snow bound, rocky, precipitous, alpine blanks or within the submergence area. Main purposes of catchments area treatment are to regulate the flow of water, prevention of soil erosion, to maximize the negative impact of the project itself on the catchment and to protect and regenerate vegetation in the catchment area and the water resources.

[1] Based on Wikipedia
[2] https://web.archive.org/web/20080825234641/http://gov.ua.nic.in/brvda/court_order6.html

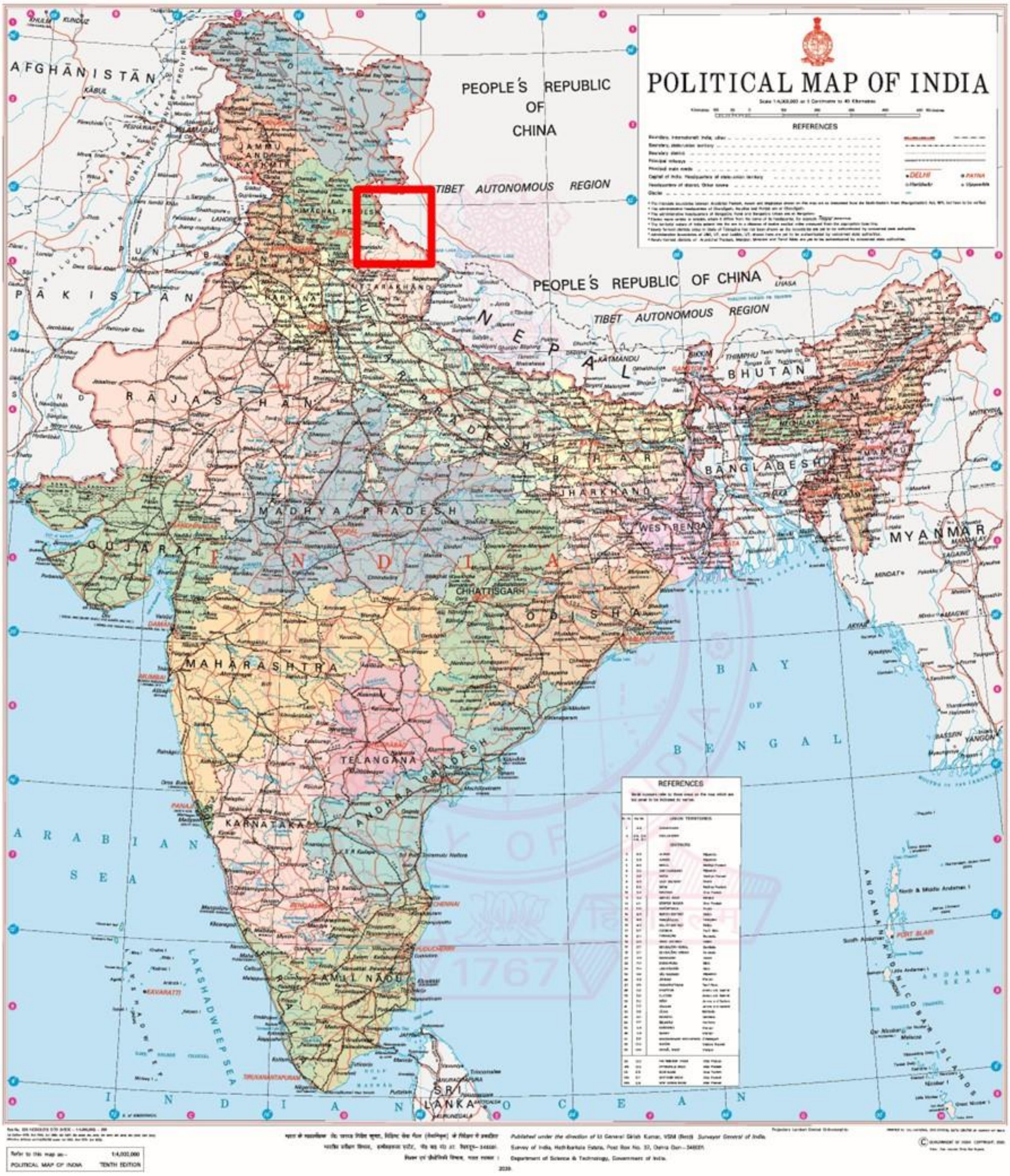

Figure 1. Overview of the three major rivers in the Hymalaya region: Ganges, Indus and Brahmaputra. Source: https://www.surveyofindia.gov.in/

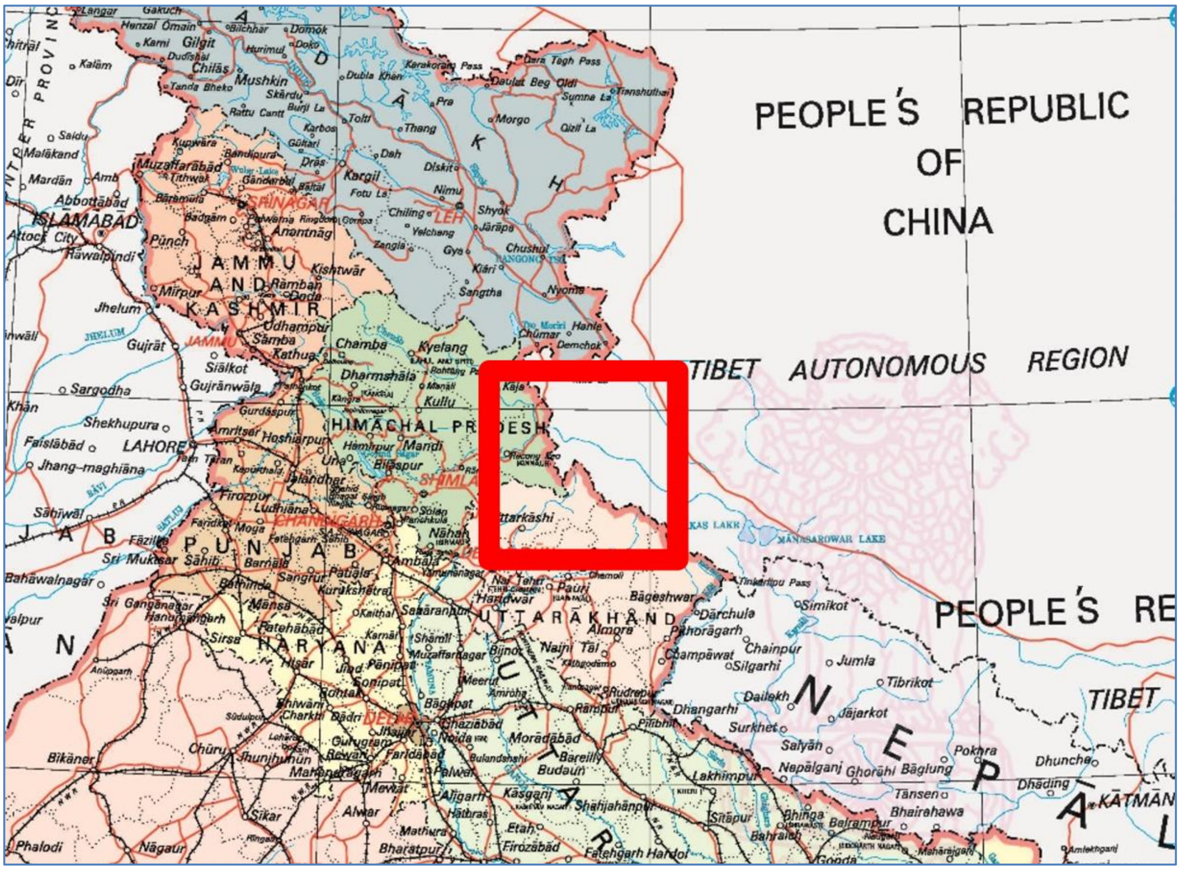

Figure 2. Location of Bhagirathi catchment in northern India in the state of Uttarakhand.
Source: https://www.surveyofindia.gov.in/
The boundaries, colors, denominations, and other information shown on any map in this work do not imply any judgment on the part of the authors concerning the legal status of any territory or the endorsement or acceptance of such boundaries.

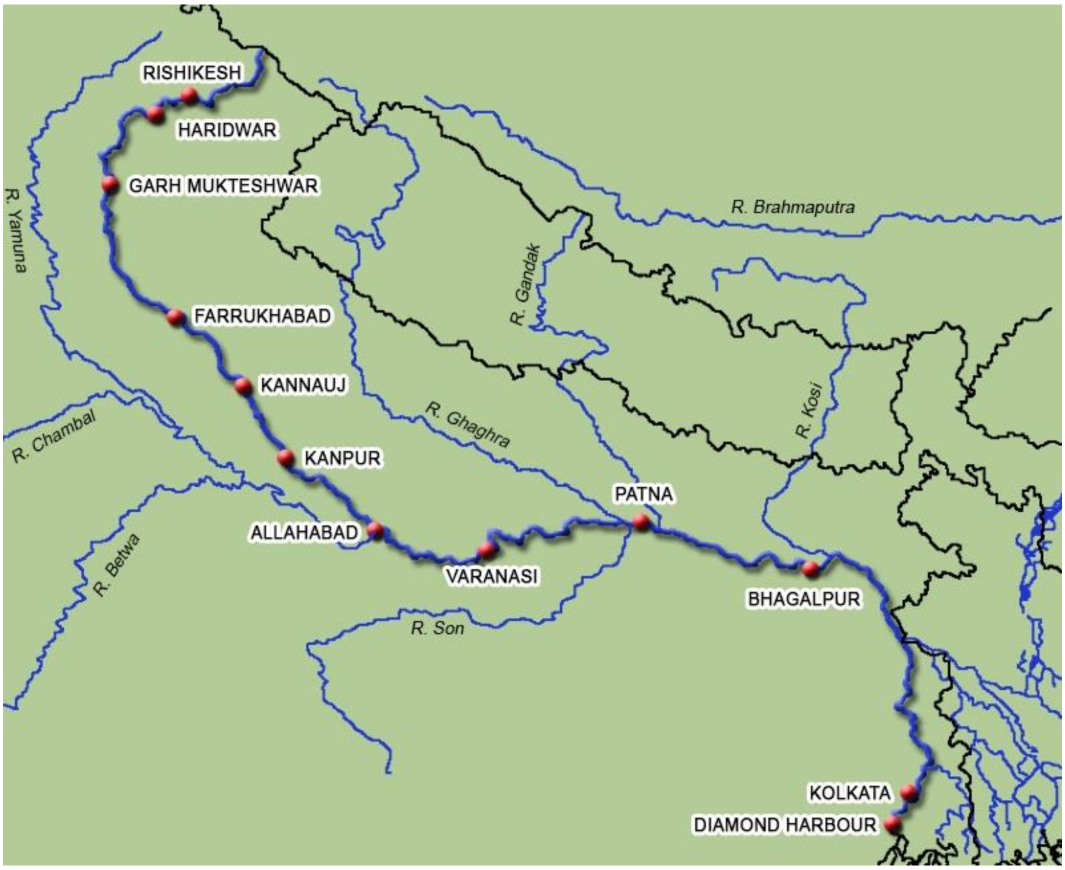

Figure 3. Some of the important cities beside the river Ganges as it travels through the northern plains of India and empties itself in the Bay of Bengal near Kolkata (formerly known as Calcutta). It provides water to an area of 8,61,452 Sq.km that is equivalent to almost 26% of the total geographical area in India. Source : https://monidipa.net/2018/02/21/traversing-the-ganges-from-old-times-to-new-part-i/

2.2 Dams

There are 17 dams along the Bhagirathi River, either in operation (#4), under construction (#1), planned (#8) or cancelled (#4) according to Wikipedia[1].

2.2.1 Tehri Dam

The Tehri Dam is the tallest dam in India. It is a multi-purpose rock and earth-fill embankment dam. It is the primary dam of the THDC India Ltd. and the Tehri hydroelectric complex. Phase 1 was completed in 2006. The Tehri Dam withholds a reservoir for irrigation, municipal water supply and the generation of 1,000 megawatts of hydroelectricity. The dam creates a reservoir of 4.0 cubic kilometers with a surface area of 52 km^2.

The Tehri Dam and the Tehri Pumped Storage Hydroelectric Power Plant are part of the Tehri Hydropower Complex which also includes the 400 MW Koteshwar Dam. Tehri pumped storage plant (4 X 250 MW) has variable speed features which can optimize the round trip

[1] https://en.wikipedia.org/wiki/Bhagirathi_River

efficiency under varying water levels in its reservoirs. Power is distributed to Uttar Pradesh, Uttarakhand, Punjab, Delhi, Haryana, Jammu and Kashmir, Chandigarh, Rajasthan and Himachal Pradesh.

The complex will afford irrigation to an area of 270,000 hectares, irrigation stabilization to an area of 600,000 hectares (1,500,000 acres), and a supply of 1.2×10^6 m^3 of drinking water per day to the industrialized areas of Delhi, Uttar Pradesh and Uttarakhand. The total expenditure for this project was USD 1 billion[1].

So total water demand downstream that should be originating from Tehri Dam is:

Drinking: 1.2 MCM/d = 438 MCM/year

Irrigation: 270,000 ha * 5 mm/day = 13.5 MCM/day = 4,928 MCM/year

Note that total downstream water requirements are much higher. According to (Amarasinghe et al., 2016) the total irrigated area in the entire Ganges Basin is about 40 Mha. (Amarasinghe et al., 2007) estimated the following trends for the entire country in terms of total water needs: 2000: 680 BCM/y; 2025: 833 BCM/y, and 2050: 900 BCM/y.

The Tehri dam[1], in the north of India, was commissioned in 2006 to provide water for electricity generation, irrigation and drinking water. It has a sediment trap efficiency of 95 per cent and was designed to offset 150 years of sedimentation. Watershed management is the principle measure in use for reducing the sediment inflow into the Tehri reservoir.

The Tehri reservoir serves multiple purposes besides storing water to produce 6,200 GWh of annual electricity generation. It provides irrigation to an additional area of 270,000 hectares as well as supporting the existing irrigated area of 604,000 hectares. It supplies clean drinking water to about 4 million people in Delhi and 3 million people in Uttar Pradesh and Uttarakhand. And last but not least, the Tehri reservoir has a flood control pool capacity of 219.65 Mm3.

The Tehri dam, a 260.5 m-high earth and rockfill dam, impounds water 44 km along Bhagirathi River and 25 km along Bhilangana River, creating a dead storage of 925 Mm3 and live storage of 2,615 Mm3, making a total storage capacity of 3,540 Mm3. Impoundment commenced in 2005. The Tehri reservoir operates between a 835 masl maximum operating level and a 740 masl minimum operating level. The crest elevation is 815 masl and together the chute spillway (see figure 2) and the four vertical shaft spillways have a discharge capacity of 15,540 m3/s.

https://thdc.co.in/sites/default/files/Role%20of%20Tehri%20Dam%20in%20prevention%20of%20Flood.pdf
Apart from irrigation, 300 m3/s drinking for Delhi and 200 m3/s for drinking UP

[1] https://www.hydropower.org/sediment-management-case-studies/india-tehri

2.2.2 Koteshwar Dam

The Koteshwar Dam is a gravity dam on the Bhagirathi River, located 22 km downstream of the Tehri Dam in Tehri District, Uttarakhand, India. The dam is part of the Tehri Hydropower Complex and serves to regulate the Tehri Dam's tailrace for irrigation and create the lower reservoir of the Tehri Pumped Storage Power Station. In addition, the dam has a 400 MW (4x100 MW) run-of-the-river power station. The project was approved in 2000 and its first generator was commissioned on 27 March 2011, the second on 30 March 2011. The construction site had been inundated in September 2010 by floods. The diversion tunnel was later blocked heaving/collapse of the hill in December 2010. The spillway was commissioned in Jan, 2011. The last two generators were made operational in March 2012.

The dam is 97.5 m tall and 300 m long. It has a structural volume of 560,000 m^3 and its crest lies at an elevation of 618.5 m above sea level. The dam's spillway consists of four 18 m wide and 16 m tall radial gates. When the reservoir is at flood level, the spillway has a discharge capacity of 13,240 m^3/s. Receiving water from Tehri Dam and collecting it from an overall 7,691 km^2 catchment area, the dam creates a reservoir with a 88,900,000 m^3 capacity, of which 35,000,000 m^3 is active (or "useful"). The reservoir's surface area is 29 km^2 and at full pool, it lies at an elevation of 612.5 m. The dam's power station is a run-of-the-river type and uses the active storage in the reservoir which can draw the lake down 30 m from full pool. The power house is located on the right bank of the river below the dam and contains 4 x 100 MW Francis turbine-generators. The height of the dam allows for a maximum 75 m of hydraulic head.

2.2.3 Maneri Bhali Stage – I

The Maneri Dam is a concrete gravity dam on the Bhagirathi River located at Maneri, 8.5 kilometres (5.3 mi) east of Uttarkashi in Uttarkashi district, Uttarakhand[1]. The primary purpose of the dam is to divert water into a tunnel which feeds the 90 megawatts (120,000 hp) run-of-the-river Tiloth Power Plant.

The power station is stage one of the Maneri Bhali Hydroelectric Project which was planned in the 1960s. It was completed and commissioned in 1984. Dharasu Power Station, the second stage, was halted in 1990 due to funding issues and was not restarted until 2002.[1] It was eventually completed and commissioned by 2008.

The Maneri Dam is a 39 m (128 ft) tall and 127 m (417 ft) wide gravity dam with a structural volume of 13,700 m3 (17,919 cu yd). It's spillway is located on its crest and is controlled by four tainter gates. In addition to discharge tunnel, the spillway has a maximum discharge capacity of 5,000 m3/s (176,573 cu ft/s). The dam's reservoir has a 600,000 m3 (486 acre·ft) capacity, of which 510,000 m3 (413 acre·ft) is active (or "useful") capacity.[3] Water supplied to the power station is first diverted from the Bhagirathi River by the dam into a 8.6 km (5.3 mi) long tunnel directly behind the dam. The difference in elevation between the barrage and the power station affords a design hydraulic head of 147.5"m (484"ft) and gross head of 180 m (590 ft). Near the Tiloth Power Plant, the tunnel splits into three penstocks to power each

[1] https://en.wikipedia.org/wiki/Maneri_Dam

of the three 30 MW Francis turbine-generators before being discharged back into the river. The design discharge of the power station is 71.4 m3/s (2,521 cu ft/s).[4]

Table 1. Maneri Bhali Stage – I : Salient Features. Source: https://www.uttarakhandirrigation.com/maneri-bhali

Diversion Dam	
River	Bhagirathi
Location	Maneri
Height	39.0 m.
Power Tunnel	
Tunnel Length	8.6 km
Diameter	4.75 m
Penstok	
Diameter	2.5 m
Number	3
Power House	
Location	Uttarkashi
Head	180 m
Installed Capacity	90 MW
No. of Units	3
Cost	79.34 Crores.
Year of Completion	1984

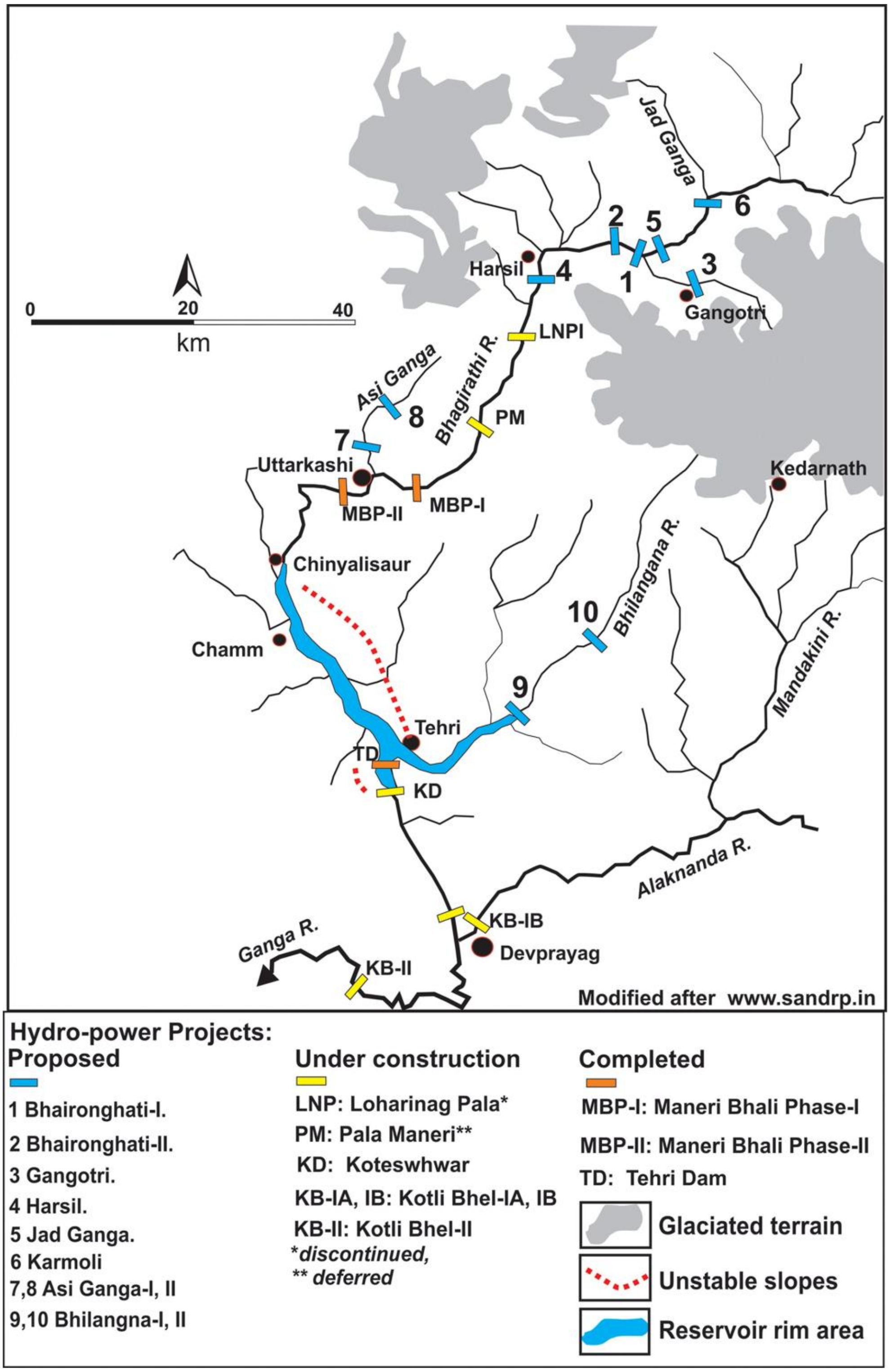

Figure 4. The drainage map of Bhagirathi river showing the distribution of proposed, under construction and completed hydropower projects. The Loharinag Pala is scrapped and Pala Maneri is deffered. Note the high concentration of barrages (bumper to bumper) between Harsil and Gangotri. Presently the large part of the river section is already inundated and if all the proposed projects become reality, the river will virtually be diverted into tunnels. Source: Sati et al., 2020.

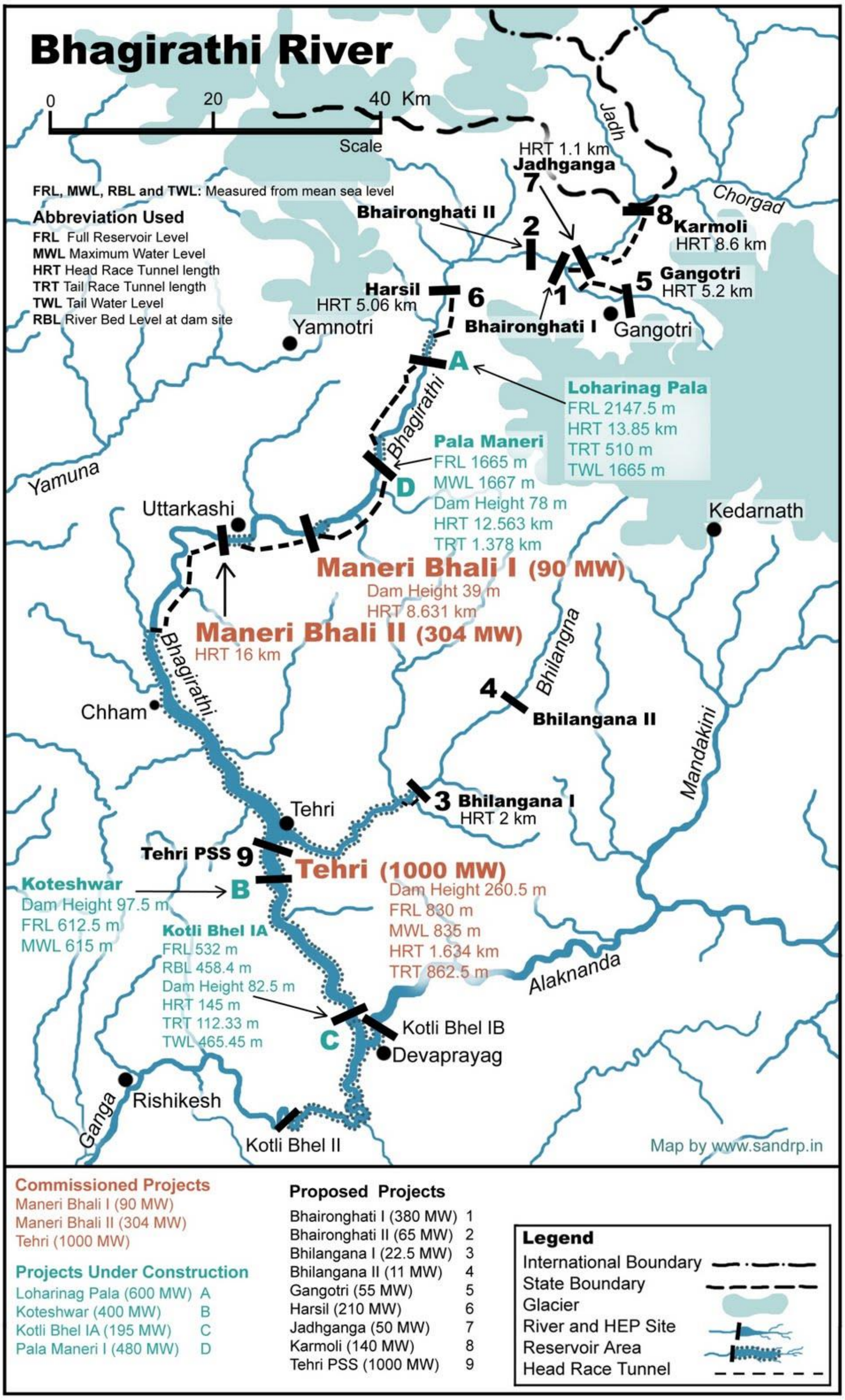

Figure 5. Existing, under construction and proposed dam projects om the Bhagirathi Catchment. Source : http://matuganga.blogspot.com/2011/12/dams-in-ganga-valley.html.

3 Methodology and Data

3.1 Water Allocation Modeling using WEAP

3.1.1 Model Selection

Selection of the most appropriate model for this specific project is an important decision to be taken. An assessment of relevant strengths and weaknesses for various well-known and established models is shown in Figure 6:

- Drought
- Floods
- Allocation
- Crops
- Complexity
- Scalable
- Scenarios

Since the project is focusing on water allocation and scenario analysis the WEAP model stands out. Scalability of the WEAP model is also a very relevant aspect of the current project. Since the complexity of the WEAP model, given its nice interface, is also relatively low, the model can also be used for training.

Some other strengths of WEAP not covered by those seven criteria yet important for the project:

- WEAP is used in over 180 countries and has many active users in India.
- WEAP can be automated and coupled with other models. Coupling with SPHY (also used in the project) has been successfully done in many other projects.
- WEAP has excellent (and free) training modules.
- WEAP is tailored towards starting in an explorative way and gradually including other components for more detailed analysis.
- WEAP is the de-facto standard for many developing and funding agencies to make investment decisions.
- WEAP is freely available

	Drought	Floods	Allocation	Crops	Complexity	Scalable	Scenarios
HEC-HMS	2	3	1	1	3	3	3
HEC-RAS	1	5	2	1	4	2	2
SPHY	3	4	2	2	2	4	4
WEAP	5	4	5	5	1	5	5
SWAT	4	3	3	3	2	4	3
SOURCE	4	4	4	2	4	5	4
SWMM	2	5	2	1	2	3	2
SOBEK	1	5	2	2	3	2	2
MIKE BASIN	4	3	4	2	2	4	4
MIKE SHE	3	3	3	3	5	2	1

Figure 6. Qualitative (expert based) assessment of some catchment scale models that might be used for the project. Scores 1 (=limited) to 5 (=well suited). Note that the color scale for "Complexity" is reversed to maintain green for "better" and red for "worse".

Figure 7. Number of members on the WEAP Forum. Source: https://www.weap21.org/index.asp?action=116

3.1.2 WEAP Summary

As presented above, there are various reasons for choosing the WEAP framework as the most relevant water allocation model to be used for the project. Most important is that WEAP is completely focused towards scenario analysis in a user-friendly approach. Second, WEAP is very scalable and a first-order setup of a particular region can be easily expanded when more data/resources are available. Third, WEAP is commonly used world-wide for IWRM analyses. Finally, WEAP is freely available for organizations in developing countries.

A detailed discussion on WEAP can be found in the WEAP manual which can be freely downloaded from the WEAP website (http://www.weap21.org/). In summary WEAP has the following features:

- Integrated Approach: Unique approach for conducting integrated water resources planning and impact assessments.
- Stakeholder Process: Transparent structure facilitates engagement of diverse stakeholders in an open process.
- Water Balance: A database maintains water demand and supply information to drive mass balance model on a link-node architecture.
- Simulation Based: Calculates water demand, supply, runoff, flooding, infiltration, crop requirements, flows, and storage, and pollution generation, treatment, discharge and in-stream water quality under varying hydrologic and policy scenarios.
- Hydrological Processes: Semi-distributed three-layer bucket approach (soil water, deep water, groundwater).
- Policy Scenarios: Evaluates a full range of water development and management options, and takes account of multiple and competing uses of water systems.

- User-friendly Interface: Graphical drag-and-drop GIS-based interface with flexible model output as maps, charts and tables.
- Model Integration: Links to other models and software, such as SPHY, SWAT, QUAL2K, MODFLOW, MODPATH, PEST, Excel, HEC-RAS and GAMS.

The WEAP model as used for this study has been expanded by adding “virtual tracers”. This is a quite innovative approach to track different sources and reuse of water. In the model user-specific virtual tracers are added to different sources of water to evaluate the mixing of return flows from each water user in sources of water supply to subsequent users (Simons et al., 2020). Tracers have been known for decades and used by hydrologists by injecting artificial dyes into streams to determine flow rate and movement. Harmless dyes can be tracked from the point of injection to the point of recovery, which may be kilometers downstream. Tracers can be therefore used to track sources of water (e.g. glacial melt, snow melt, rainfall runoff) as well as to follow reuse of water. Complete mixing is assumed. In this way, tracer concentrations can be used to recalculate the percentage attributed to each source of water.

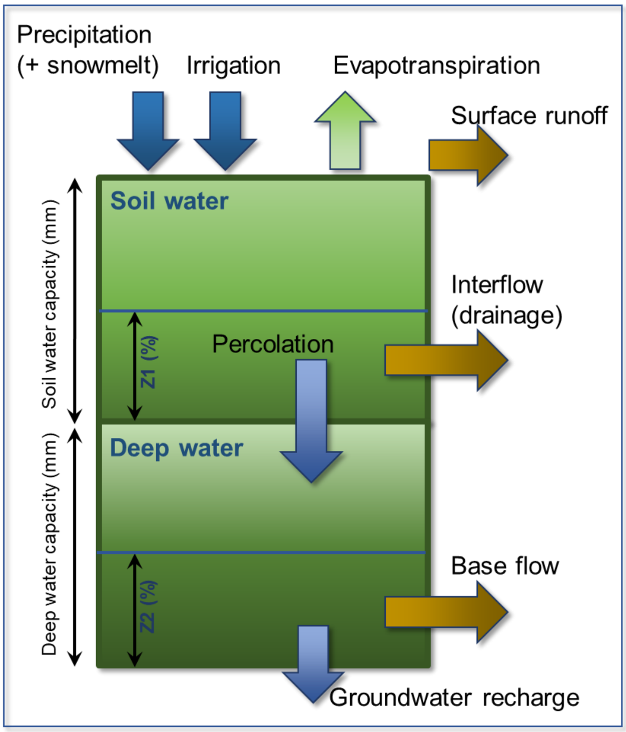

Figure 8. Processes included in the WEAP module that are calculated at the calculation unit-level.

Availability and access to good quality of data is essential for IWRM analysis using WEAP. Required input data can be divided into the following main categories:

- Model building
  - Static data[1]
    - Digital Elevation Model

[1] Nota that static data can still vary over longer time frames, but are fairly constant over days/weeks

        - Soils
        - Land use, land cover
        - Population
        - Reservoir operational rules
        - Allocation (priority) rules
    - Dynamic data
        - Climate (rainfall, temperature, windspeed, relative humidity)
        - Evapotranspiration by crops and natural vegetation
        - Water demands by all sectors
- Model validation/calibration
    - Stream flow
    - Reservoir releases
    - Hydropower generation

The WEAP framework is flexible in level of details of data availability. A typical example is that water demands can be included as a total amount of water, but can be also estimated by WEAP using population, their daily required intake and daily and/or monthly variation. Similarly, climate data can be entered at annual, monthly, 10-days or daily level. The more refined the input dataset is, the higher the reliable of the WEAP model scenarios will be.

This feature is very useful in areas with low data availability or where more and better quality data will become gradually available as the project progresses. The WEAP set-up gives the user the flexibility to add more detailed data when it becomes available, without having to start from scratch with every updated data set.

Sources of data can be various. Some input data will need to be locally sourced as those are not available in the public domain or are hard to detect from satellite (Figure 10). Other relevant input data for WEAP can originate from quickly accessible global data sources. In general, a WEAP model can be developed for any location on earth using quickly accessible data sources. Depending on the question and the detail required additional local data will increase the reliability of the results.

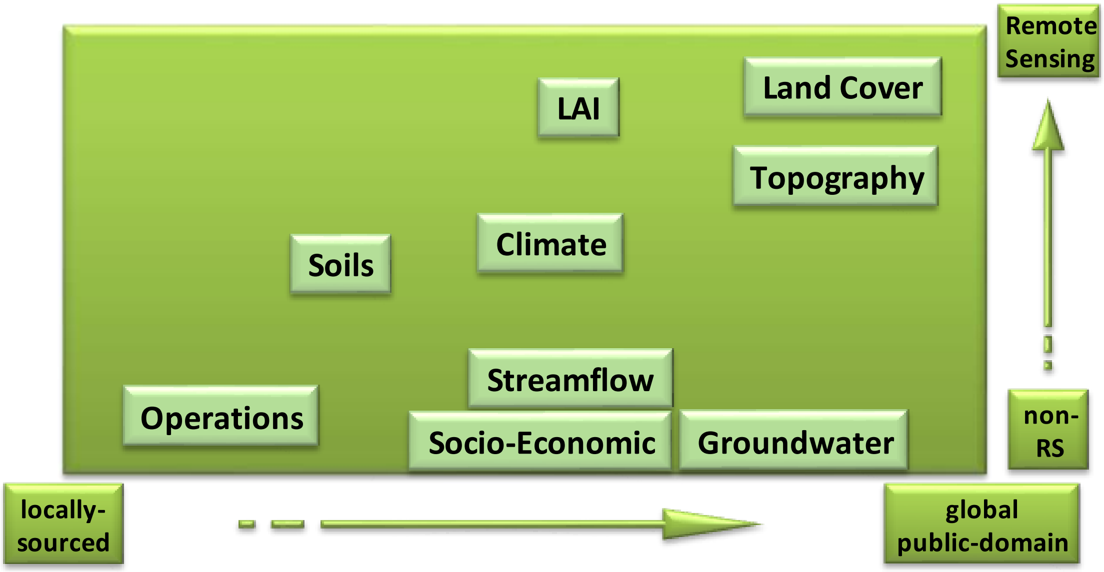

Figure 9: Development in data availability to support water allocation tools over the last 20 years.

3.2 Community Development Blocks

The Bhagirathi River Valley Authority (BRVA) of the Government of Uttarakhand uses so-called Community Development Blocks as base for studies and analysis[1]. Those Development Block are refined to ensure that hydrological as well as administrative boundaries are combined. Such an approach is used before and sometimes referred to as a water province, or a food producing unit (Veldkamp et al., 2015; Miina et al., 2016) and represents the intersection of the hydrological boundaries of river basins with the administrative boundaries of countries and provinces[2].

To ensure the consistency between the existing Development Blocks and the hydrological modeling undertaken with the SPHY model, some minor adjustments of the existing boundaries were made. At two locations the hydrological (catchment) boundary deviates substantially from the Development Block ones. In the north-west a tributary located in Himachal Pradesh was excluded from the Development Blocks. Inflow from this tributary is however considered in the modeling as water source. In the south are three Development Blocks (Chamba, Narendranagar, Devprayag) where some areas are located outside the catchment area. Water yield (runoff) from those areas is therefore not available from the SPHY model and will be assessed using WEAP' catchment model capability.

[1] https://brvda.uk.gov.in/pages/display/10-brvda--atlas
[2] Straatsma et al., 2018

In this study the same Development Blocks as defined by the BRVA were used for the water allocation modeling.

Original 10 Development Blocks. Bhatwrai divided in High and Low, so 11:

- Bhatwari_H
- Bhatwari_L
- Bhilangana
- Chamba
- Chinyalisaur
- Devprayag
- Dunda
- Jakhnidhar
- Narendranagar
- Pratapnagar
- Thauldhar

The linkage between those development blocks and the administrative boundaries has been assessed. The state of Uttarakhand is divided in two divisions: Garhwal Division and Kumaun Division Those divisions are further divided into Districts.

Table 2. The 2 Divisions and 13 Districts in Uttarakhand. The two Districts included in the water allocation analysis are indicated.

Division	Districts
Garhwal Division (#7)	Chamoli Dehradun Haridwar Pauri Garhwal Rudraprayag **Tehri Garhwal ←** **Uttarkashi ←**
Kumaon Division (#6)	Almora Bageshwar Champawat Nainital Pithoragarh Udham Singh Nagar

The Districts are divided in Subdistricts, often referred to as a Tehsil. Uttarakhand includes a total of 109 Tehsils.

Besides the above structure, some states have another administrative level, at the same level as the Districts; those are referred to as Community Development Blocks. Such a Community Development Block (CD Block) is a rural area administratively earmarked for planning and development. A CD Block is administered by a Block Development Officer, supported by several technical specialists and village-level workers. A CD Block covers several gram panchayats, the local administrative units at the village level. The entire state of Uttarakhand includes 95 CD Blocks. The two Districts the project is focusing on (Tehri Garhwal and Uttarkashi) include in total 15 CD Block. Since some of those Blocks are outside the Bhagirathi Basin a total of 10 Blocks are the focus of the water allocation analysis.

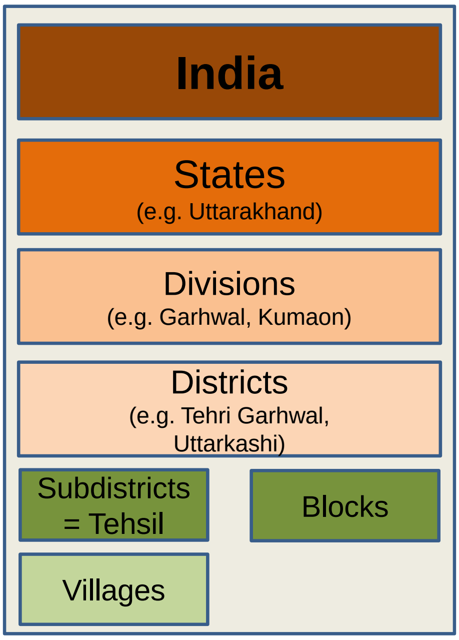

Figure 10.Simplified hierarchy levels in India's governmental structure as relevant for the current study.

Table 3. Names of Districts and Blocks in the study area. The 10 Blocks included in the water allocation analysis are indicated.

Districts	CD Blocks	Tehsils
Tehri Garhwal	**Bhilangna ←** **Chamba ←** **Devprayag (Hindolakhal) ←** **Jakhanidhar ←** Jaunpur Kirtinagar **Narendranagar ←** **Pratapnagar ←** **Thauldhar ←**	**??**
Uttarkashi	**Bhatwari ←** **Chinyalisau ←** **Dunda ←** Mori Naugaon Purola	Bhatwadi Chinyalisaud Dunda Mori Badkot Purola

As discussed above, the Development Block boundaries and the hydrological catchment boundaries deviate. Figure 11 indicates the main deviations with the SPHY boundaries. Those differences are mainly in North-Western part where a tributary of the Bhagirathi is outside the Bhatwari Block and even outside the Uttarkashi District. The water generated in this area and flowing into the Bhagirathi will be included in the water allocation analysis.

The second deviation between the hydrological and administrative boundaries is located in the South of the study area (Figure 11). The hydrological boundaries cross the Chamba, the Narendranagar and the Devprayag Blocks. So this means that water from outside Bhagirathi river is available to be used in those three development blocks.

Figure 11. Catchment boundary as used for the hydrological modelling by SPHY (purple, dotted) and the Development Blocks (purple, solid) used for the water allocation modelling. The red arrows indicate where the hydrological boundary differs from the Development Blocks.

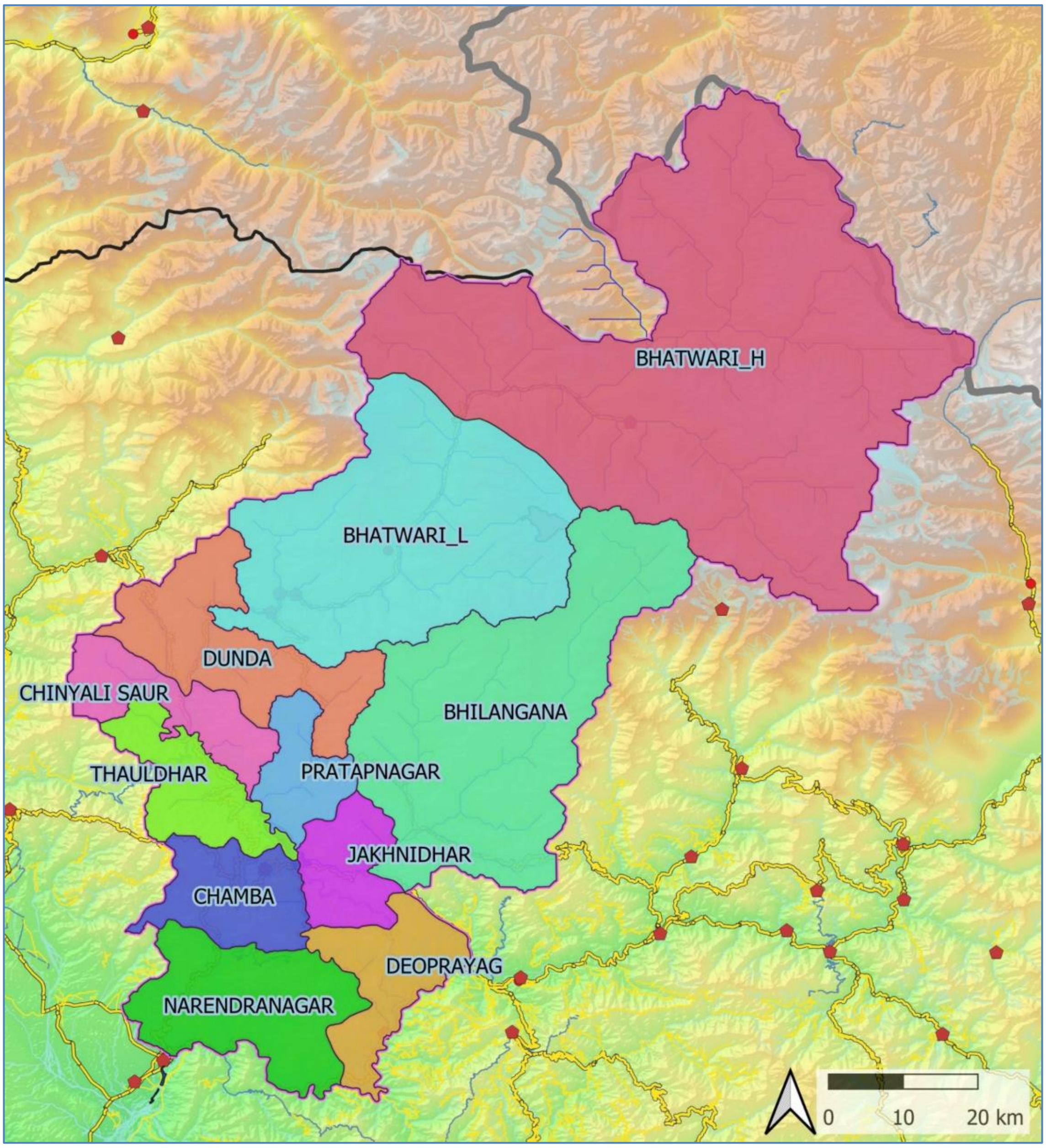

Figure 12. Overview of the 11 Development Blocks that are the base for the water allocation analysis. Yellow: Development Block boundaries; blue: Bhagirathi Basin boundary.

Box: Uttarakhand[1]
Key figures

[1] https://uk.gov.in/

Area:53,483 sq.km.
Population : 101.17 lakh (= 1,011,700 ~ 1.0 million)
Capital : Dehradun(Temporary)
Districts: 13
Literacy Rate: 79.63%

Uttarakhand was formed on the 9th November 2000 as the 27th State of India, when it was carved out of northern Uttar Pradesh. Located at the foothills of the Himalayan mountain ranges, it is largely a hilly State, having international boundaries with China (Tibet) in the north and Nepal in the east. On its north-west lies Himachal Pradesh, while on the south is Uttar Pradesh. It is rich in natural resources especially water and forests with many glaciers, rivers, dense forests and snow-clad mountain peaks. Char-dhams, the four most sacred and revered Hindu temples of Badrinath,Kedarnath, Gangotri and Yamunotri are nestled in the mighty mountains. It's truly God's Land (Dev Bhoomi). Dehradun is the Capital of Uttarakhand. It is one of the most beautiful resort in the submountain tracts of India, known for its scenic surroundings. The town lies in the Dun Valley, on the watershed of the Ganga and Yamuna rivers.

It is blessed with a rare bio-diversity, inter-alia, 175 rare species of aromatic & medicinal plants are found in the State. It has almost all major climatic zones, making it amenable to a variety of commercial opportunities in horticulture, floriculture and agriculture. It has a vast tourism potential in adventure, leisure, and eco-tourism.

The State is rich in mineral deposits like limestone, marble, rock phosphate, dolomite, magnesite, copper, gypsum, etc. The number of small scale industries is 25,294 providing employment to 63,599 persons. As many as 1802 heavy and medium industries with an investment of Rs 20,000 crore employ 5 lakh persons. Most of the industries are forest-based. There is a total of 54,047 handicraft units in the state.

With levels of literacy higher than the national average, the State has abundant availability of quality human resources. Within a short span of its existence, Uttarakhand has emerged as a significant destination for investments in manufacturing industry, tourism and infrastructure. Emphasis is on stimulating all three sectors of its economy (agriculture, industry and services),to their fullest potential in tandem with the geographic profile of the state. The Government of Uttarakhand has undertaken several policy measures and incentives in order to encourage inflow of investment into the various sectors of its economy.

Box: Tehri Garhwal District[1]

Key figures

Area:3642 km^2
Population: 618,931
Sub Division: 5
Tehsils: 12
Development Blocks: 9
Villages: 1868
Language: Hindi, Garhwali

[1] https://tehri.nic.in/

District Tehri Garhwal stretches from the snow clad Himalayan peaks of Thalaiya Sagar, Jonli and the Gangotri group all the way to the foothills near Rishikesh. The gushing Bhagirathi which runs through seems to divide the district into two, while the Bhilangna, Alaknanda, Ganga and Yamuna rivers border it on the east and west. Tehri Garhwal is surrounded by Uttarkashi district in the north, Pauri Garhwal district in the south, Rudraprayag district in the east, and Dehradun district in the west.

Box: Uttarkashi District[1]

Key figures

- Area: 8016 km^2
- Population: 330,009
- CD Blocks: 6
- Tahsils: 6
- Language:

Uttarkashi district was created on February 24, 1960 out of what then constituted the parganas of Rawain and Uttarkashi of Rawain tahsil of erstwhile Tehri Garhwal district. It sprawls in the extreme north-west corner of the state over an area of 8016 sq. kms. in the rugged terrain of the mystic Himalayas. On its north lie Himachal Pradesh State and the territory of Tibet and the district of Chamoli in the east. The district is named after its headquarters town Uttarkashi, an ancient place with rich cultural heritage and as the name suggests is the Kashi of north (Uttara) held almost as high a veneration as Kashi of the plain (Varanasi). Both the Kashi of the plain (Varanasi) as well as the Kashi of north are situated on the banks of the river Ganga (Bhagirathi). The area which is held sacred and known as Uttarkashi, lies between the rivers Syalam Gad also known as the Varuna and Kaligad also known as the Asi. The Varuna and the Asi are also the names of the rivers between which the Kashi of the plain lies. One of the holiest Ghats in Uttarkashi is Manikarnika so is the one by the same name in Varanasi. Both have temples dedicated to Vishwanath.

3.3 Data sets

3.3.1 Population

Population data is collected in India every 10 years. The Indian Census is the largest single source of a variety of statistical information on different characteristics of the people of India. With a history of more than 130 years, this reliable, time tested exercise has been bringing out a veritable wealth of statistics every 10 years, beginning from 1872 when the first census was conducted in India non-synchronously in different parts[2]. The latest completed one was done in 2011.

https://www.census2011.co.in/district.php

[1] https://uttarkashi.nic.in/
[2] https://censusindia.gov.in/2011-common/aboutus.html

Total population for the entire district:

- Tehri Garhwal Uttarakhand 618,931
- Uttarkashi Uttarakhand 330,086

Block name	**WEAP**	**PopTot**
Bhatwari_H	BhatH	28,203
Bhatwari_L	BhatL	28,203
Bhilangana	Bhila	109,756
Chamba	Chamb	50,950
Chiniyalisaur	Chiny	49,641
Devprayag	Devpr	51,482
Dunda	Dunda	59,843
Jakhnidhar	Jakhn	47,520
Narendranagar	Naren	81,604
Pratapnagar	Prata	62,618
Thauldhar	Thaul	43,403
TOTAL		**613,222**

3.3.2 Land cover and irrigation

3.3.3 Digital Elevation Model

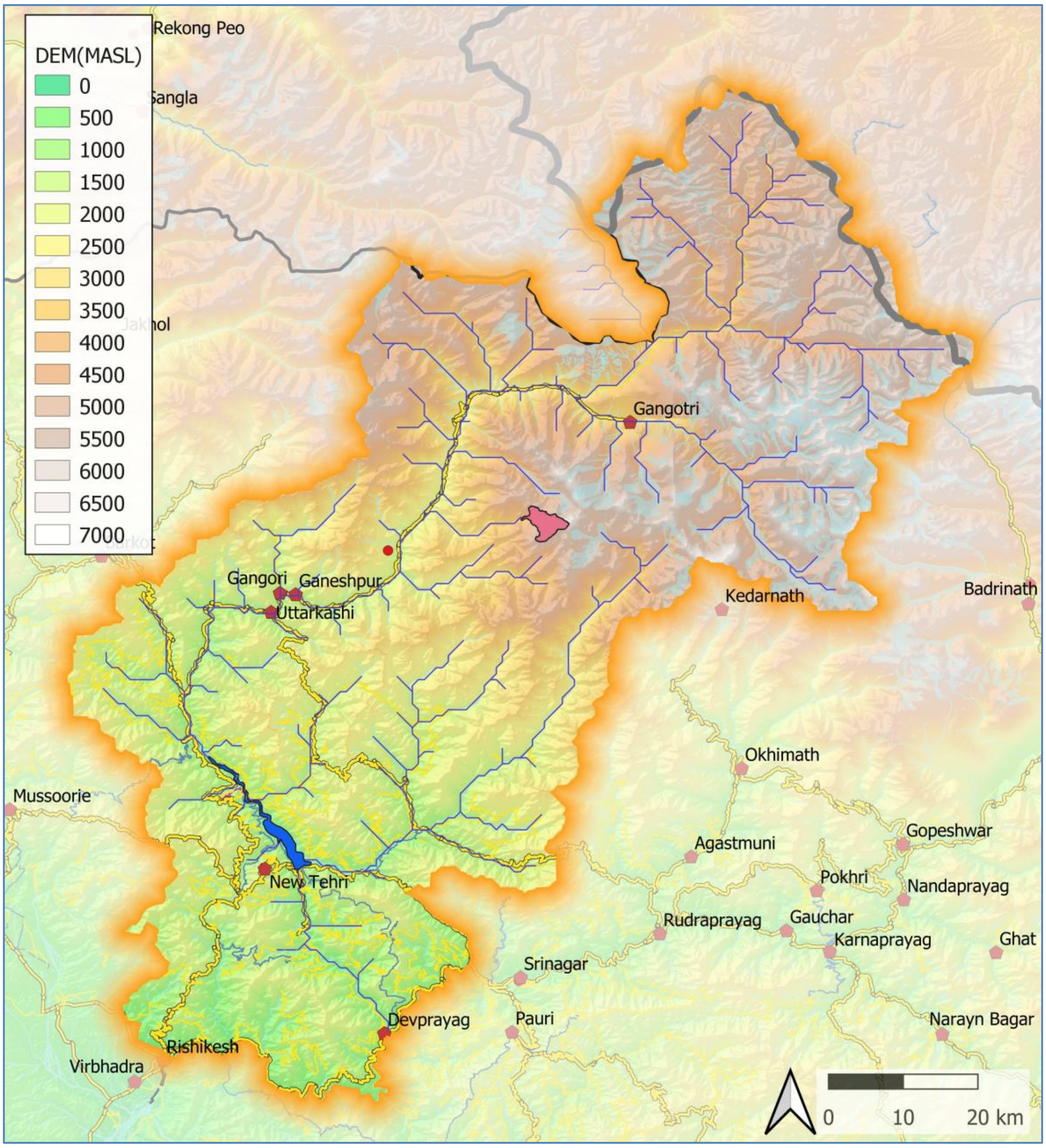

Figure 13. Digital Elevation Model of the Bhagirathi Basin and surroundings. Source: SRTM

3.3.4 Water Allocation and Consumption

Domestic

- Allocation: 125 liter per day per person (~45 m^3 per year)
- Consumption: 20%[1]

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[1] Those consumption and return flow data are based on expert knowledge. If more precise data is becoming available, then this can easily being implemented in WEAP as those values are implemented as so-called Key Assumptions

- Return flows: 80%

Industry

- For each 100 persons 1 “Industrial Unit” assumed
- Allocation per Industrial unit: 10 m^3 per day (~3650 m^3 per year)
- Consumption: 25%
- Return flows: 75%

Irrigation

- Allocation: 1000 mm per year = 10,000 m^3 per hectare
- Consumption: 60%
- Return flows: 40%

Irrigation water requirements are mainly in the kharif season and more recently also in the “summer” season. Kharif crops are usually sown at the beginning of the first rains during the advent of the south-west monsoon season (June), and they are harvested at the end of monsoon season (October–November). A second cropping season which is referred to as “summer season” (Singh, 2020). Planting for the summer season is in general in March, harvesting in May/June (Sharma, 2017). During the rabi season (November-May) wheat is the main crop in the lower areas.

Irrigation water requirements are quite diverse and location specific. In the WEAP model we consider the standard cropping pattern of rice-wheat which will capture the main irrigation requirements. For rice it was assumed that in June 200 mm is needed for puddling and for the months Jul-Oct 10 mm/day was assumed to be required to sustain crop growth. For wheat in November 5 mm/day was set as the irrigation requirements. After dormancy it was assumed that during Mar-May another 5 mm/day is needed.

Agriculture data from the Agriculture Department is used to abstract irrigated areas in the Bhagirathi Basin[1]. The data provides information on irrigated area split between various crops.

Table 4. Irrigated areas in hectare for each development block. Source: Agricultural Department Uttarakhand.

Abbr	*DevBlock*	*Rice (ha)*	*Wheat (ha)*	*Other Crops (ha)*	*TOTAL (ha)*
BhatH	Bhatwari_H	201	140	32	372
BhatL	Bhatwari_L	349	223	28	600
Bhila	Bhilangana	3250	2956	62	6268
Chamb	Chamba	432	265	37	734
Chini	Chiniyalisaur	698	446	56	1200
Devpr	Devprayag	182	156	15	353
Dunda	Dunda	1412	981	77	2470
Jakhn	Jakhnidhar	462	351	56	869
Naren	Narendranagar	465	411	104	980
Prata	Pratapnagar	1139	1157	21	2317

[1] [Agriculture data -Source Agriculture Department, Uttarakhand.docx]

Thaul	Thauldhar	263	98	56	417
TOT	**TOTAL**	**8853**	**7184**	**544**	**16580**

Table 5. Irrigation depth in millimetres per months for various crops.

Month	*Rice (mm/month)*	*Wheat (mm/month)*	*Others (mm/month)*
Jan			90
Feb			90
Mar		150	90
Apr		150	90
May		150	90
Jun	500		90
Jul	300		
Aug	300		
Sep	300		
Oct	300		90
Nov		150	90
Dec			90
Year	**1700**	**600**	**810**

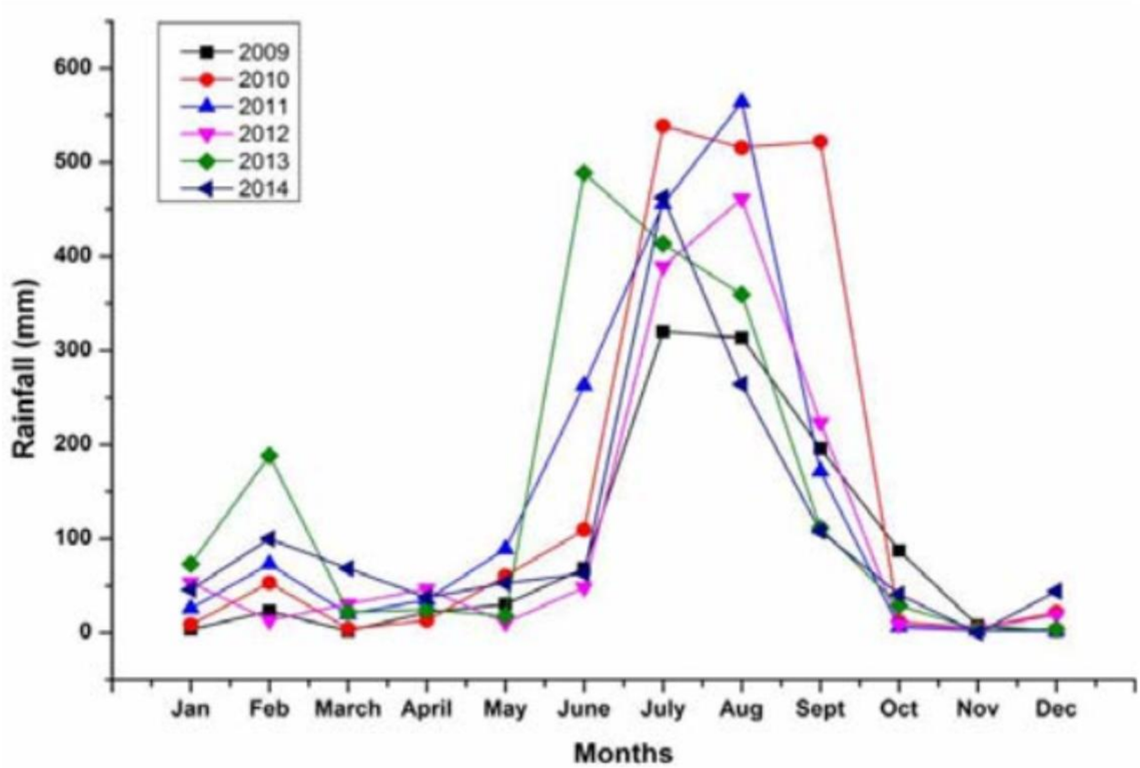
3.3.5 Water Accessibility

Access to water is significantly hindered by the proximity of users to water sources. In many regions, especially in developing countries, water sources can be kilometers away. The large-scale distribution of water through pumps and transmission canals is a critical infrastructure component that enables access to water across considerable distances. However, the efficiency of these systems is contingent on advanced engineering and substantial energy inputs. Transporting water over large distances requires significant energy, often derived from non-renewable sources, thus impacting the environment and entailing high operational costs. They also introduce challenges related to sustainability, maintenance, and resource management. Addressing these challenges is crucial for ensuring equitable and sustainable access to water for all.

Only some qualitative information on this “distance to source” is available for the Bhagirathi. Based on this information enhanced with expert knowledge a limiting factor on flow delivered to domestic, industrial and irrigation use was introduced in the WEAP analysis. For each Development Block the stream density was determined using the HydroSheds database. Those distances to nearest stream were converted to a limiting factor on water that can be delivered.

3.3.6 Climate

http://utrenvis.nic.in/rainfall%20data.html



Source: Vishwambhar Prasad Sati, 2018. Cloudburst-Triggered Natural Hazards in Uttarakhand Himalaya: Mechanism, Prevention, and Mitigation. World Academy of Science, Engineering and Technology. International Journal of Geological and Environmental Engineering. Vol:12, No:1, 2018

3.4 WEAP Water Allocation Model

The WEAP model was setup using the 11 Community Development Blocks (CDB) as presented above. For each of those 11 CDBs three demand sites and three supply sides were considered. The three demand sides were for Domestic (Dom), Industry (Ind) and Irrigation (Irr). The supply side was split into Snow, Rain and Glacial (Glac).

Water supply data was provided by the SPHY basin scale model for each of the 10 CDBs. Data were provided in millimeters per month for the three components (rain, snowmelt, glacial melt).

The model was setup for two time periods:

- Reference period: 1991–2020
- Future period: 2021–2050

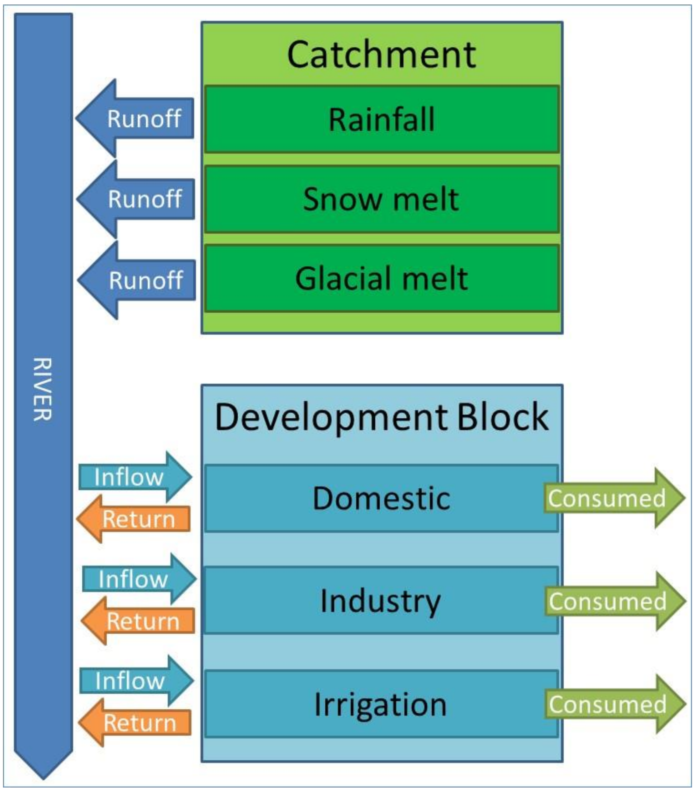


Figure 14. Schematic representation of one Community Development Block water flows as setup in the WEAP model.

Virtual tracers were used to follow the water for the three supply sides (rainfall, snow melt and glacial melt) and for the three return flows (domestic, industry and irrigation).

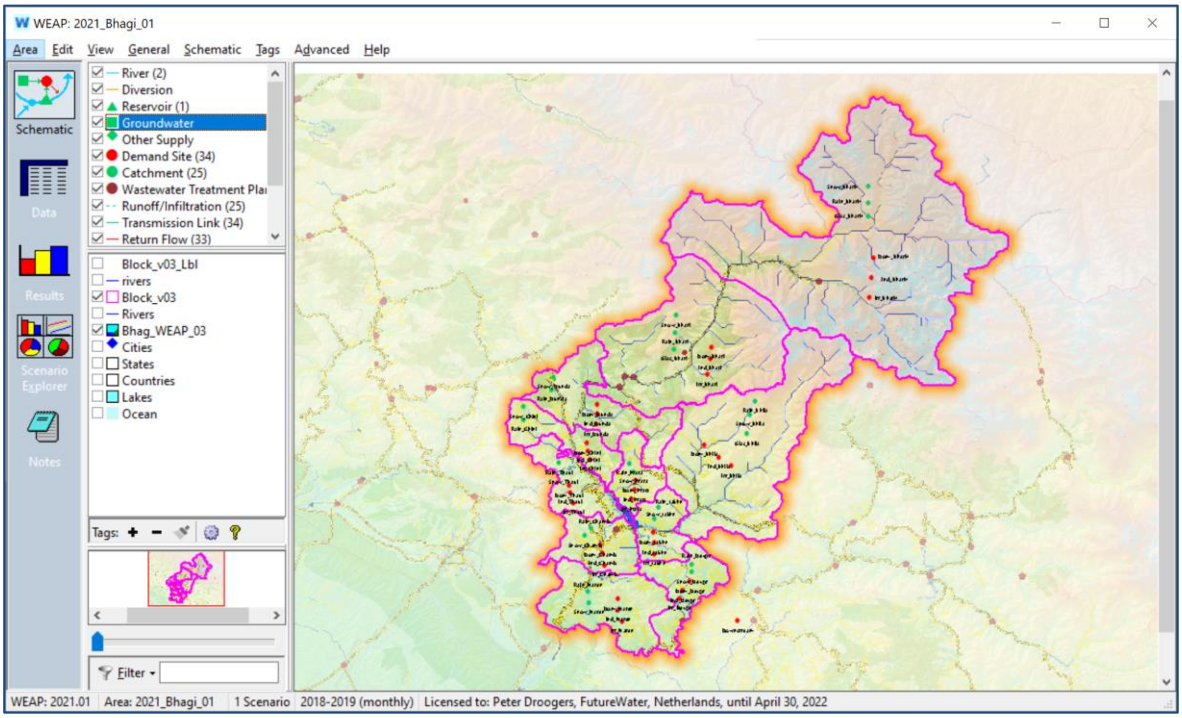


Figure 15. Screenshot of the WEAP model as developed for the Bhagirathi Basin to analyse water allocation scenarios.

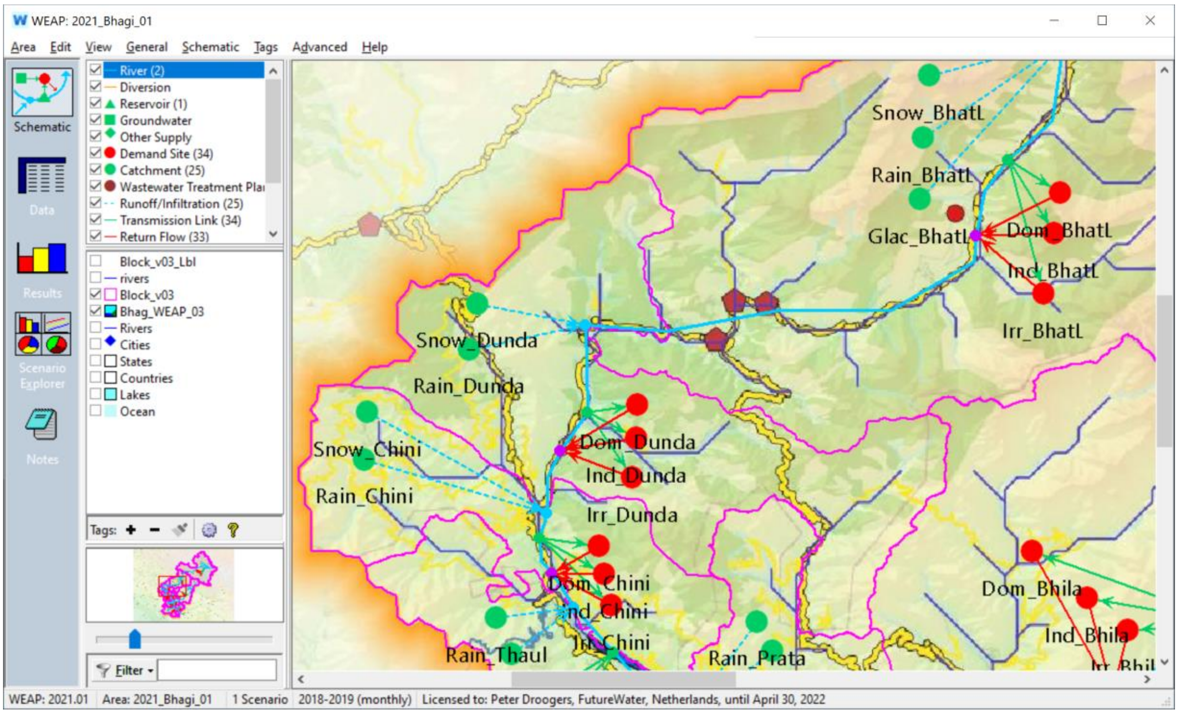
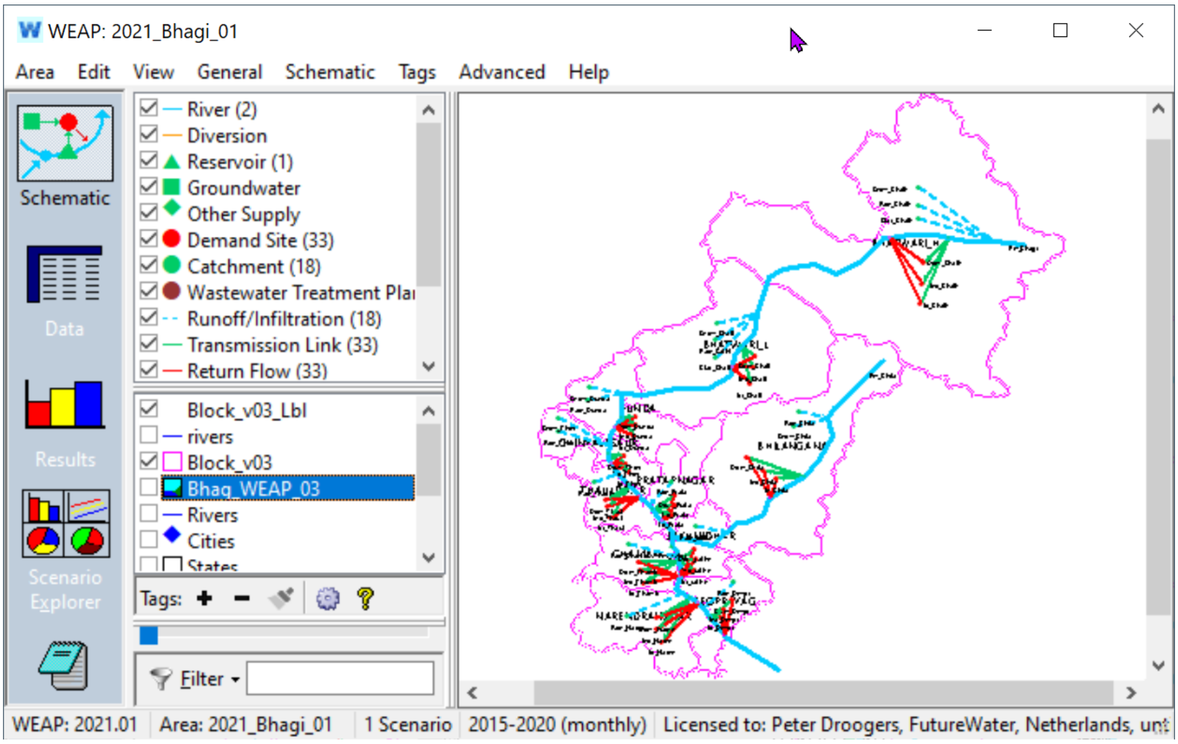


Figure 16. Same as Figure 14 zoomed at the western part of the Bhagirathi Basin.



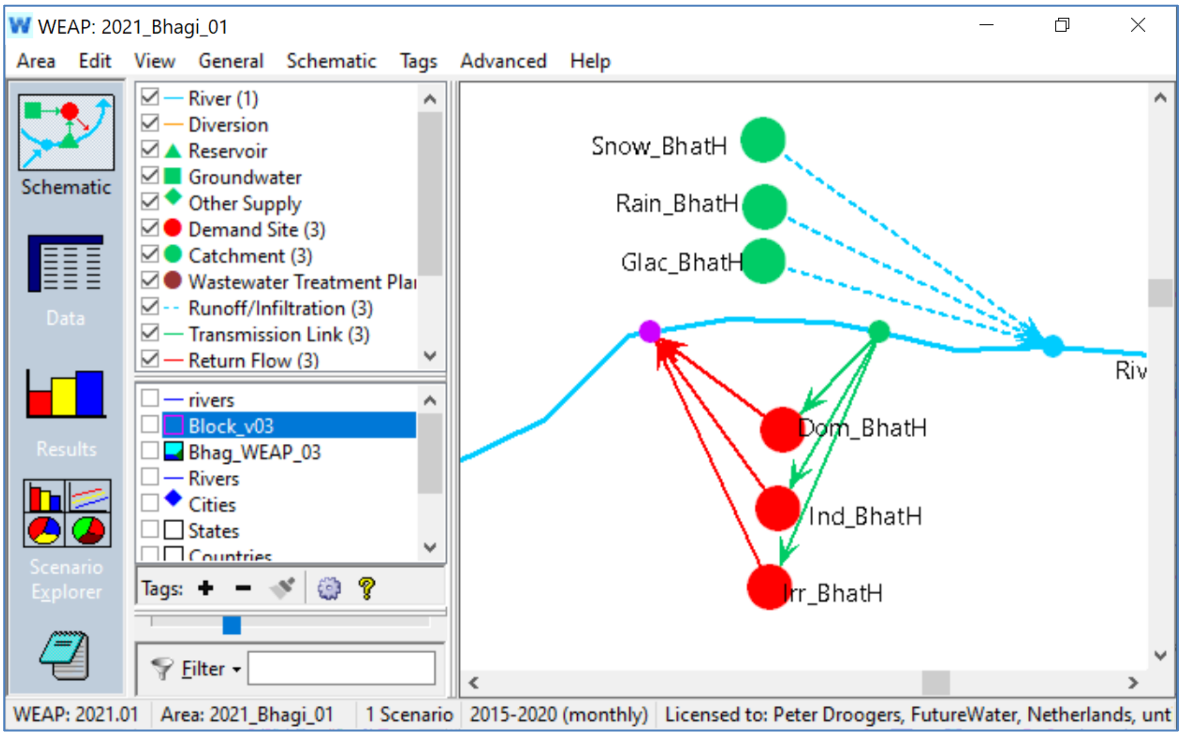


Figure 17. Screenshot of WEAP zoomed in on one Community Development Block.

4 Projections and Adaptation Options[1]

4.1 Current

4.1.1 Water Demand

Annual water demand within the basin for domestic use, industry and irrigation is about 250 MCM per year. About 80% of that water is allocated to be used in the irrigation sector. During the paddy season most of this irrigation water is needed, with a peak around June for puddling, seedbed preparation and transplantation Figure 18.

Water need for each of the eleven Community Development Blocks (CDB) depends predominantly on the irrigated area in the CDB and total population. Figure 19 indicates that the biggest water demand is for the Bhilangana CBD in the Tehri Garhwal District has the highest population amongst all the CDB and is also quite big (~ 1300 km^2).

Downstream water demands are huge and are over 5000 MCM per year as detailed in Chapter 2.2.1. Total water demand that should be delivered by the Bhagirathi Basin are much higher and are shown in Figure 20.

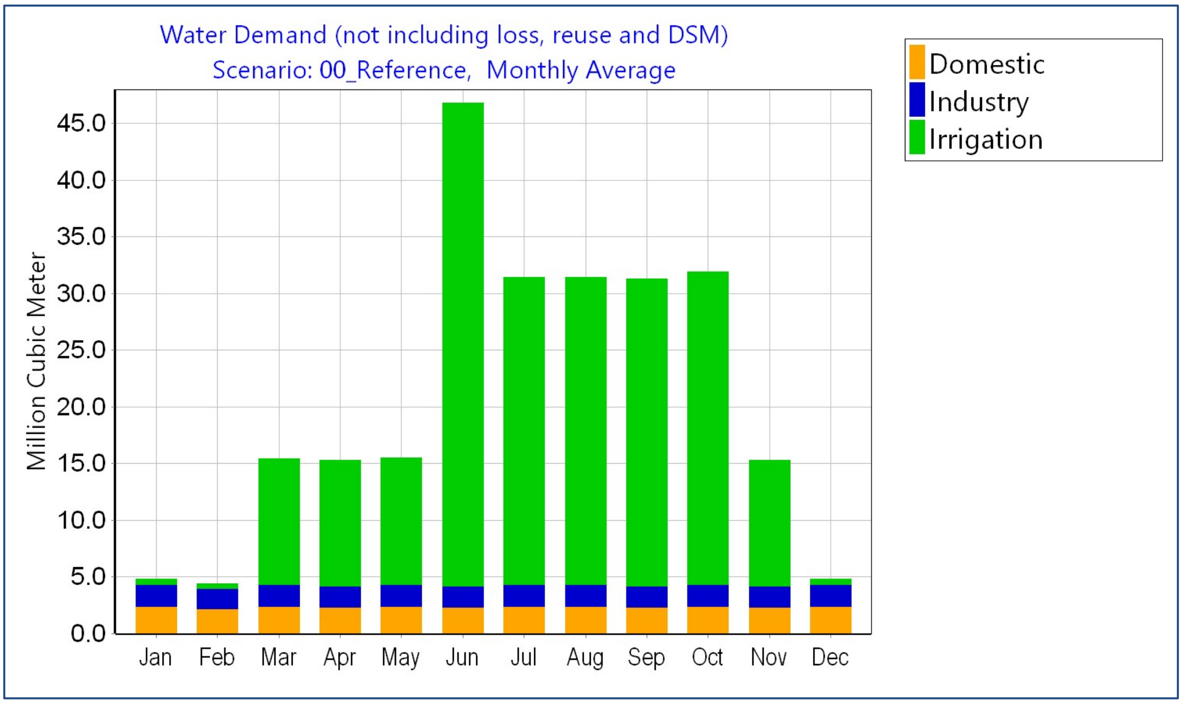


Figure 18. Monthly water demand in the Bhagirathi Basin for the three main sectors for 2001-2020.

[1] See the Box on page 39 for the use of terminology

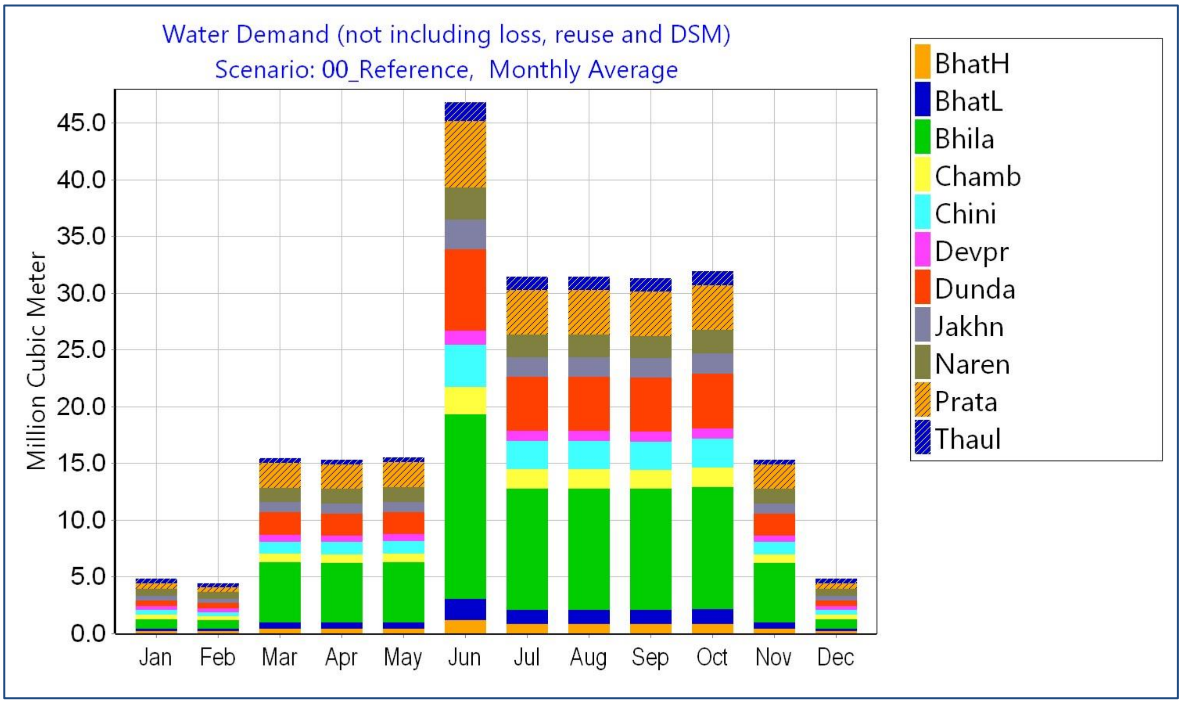


Figure 19. Monthly water demand in the Bhagirathi Basin for the eleven Community Development Blocks for 2001-2020.

For the abbreviation of the Community Development Blocks see Table 3

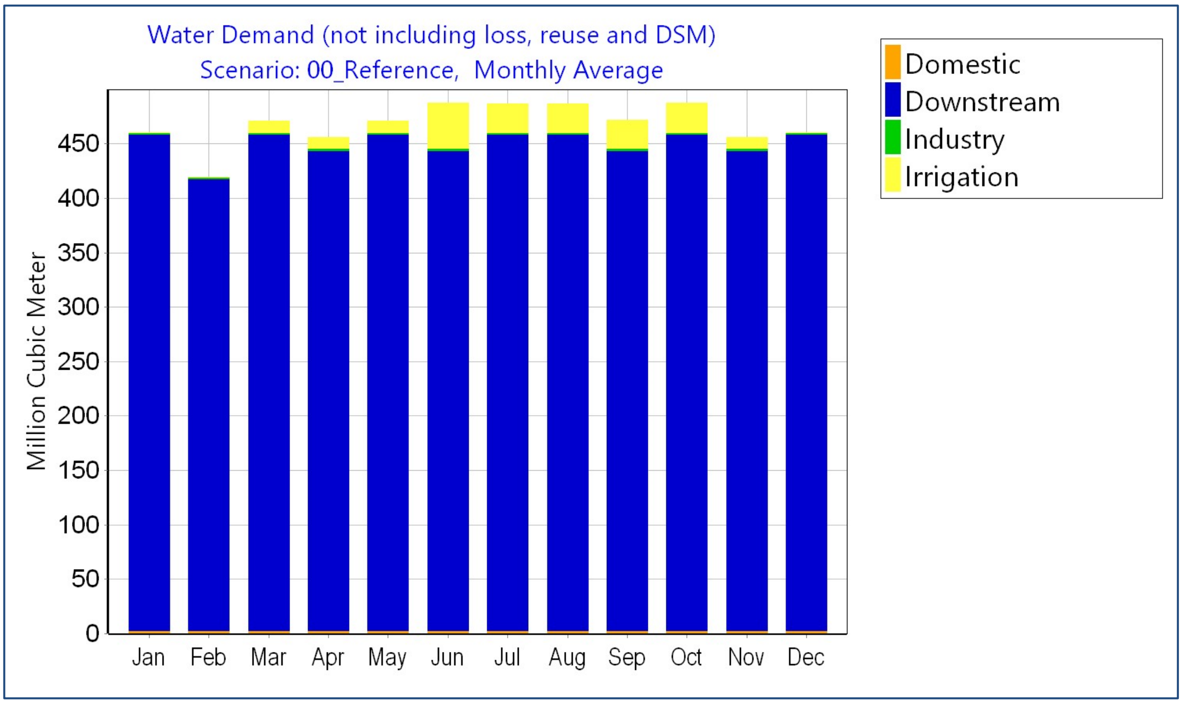


Figure 20. Monthly water demand in the Bhagirathi Basin for the three main sectors as well as downstream water requirements for 2001-2020.

Note: Downstream water requirements are described in detail in Chapter 2.2.1. In summary: irrigation of 270,000 hectares, irrigation stabilization of 600,000 hectares, and a supply of

1.2×106 m³ of drinking water per day to the industrialized areas of Delhi, Uttar Pradesh and Uttarakhand.

Box: Terminology: Projections, Storylines, Adaptation Options, Interventions

Terminology is ambiguous in the field of climate change and scenarios. A clear distinction can be made between:

- Changes that cannot be influenced by the group concerned (in this case water decision makers)
    - Terms used: **storylines**, **projections**, **pathways**
- Changes that can be influenced by the group concerned.
    - Terms used: **interventions**, (**adaptation) options**

The term Scenario is a more general one reflecting to a future (whether with or without interventions).

4.1.2 Water Shortage

The Bhagirathi basin is located in the Himalayan region, often termed the "Water Tower of Asia," and is home to vast glacial and snow reserves, feeding large perennial river systems such as the Ganges. Consequently, the region is not inherently water-scarce, given these extensive freshwater resources. However, water shortage in the Bhagirathi often arises from the challenge of accessibility rather than availability. The rugged terrain and the remoteness of water sources necessitate robust infrastructure to ensure reliable water delivery. As explained before, this accessibility has been included in the current WEAP model.

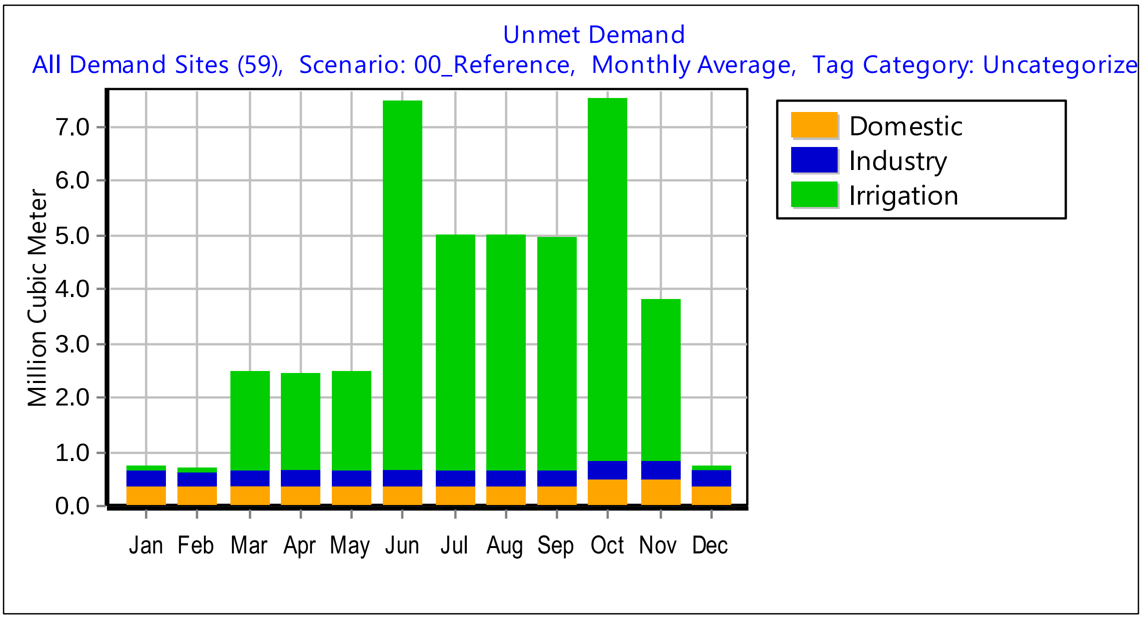


Figure 21. Monthly water shortage in the Bhagirathi Basin for the three main sectors for 2001-2020.

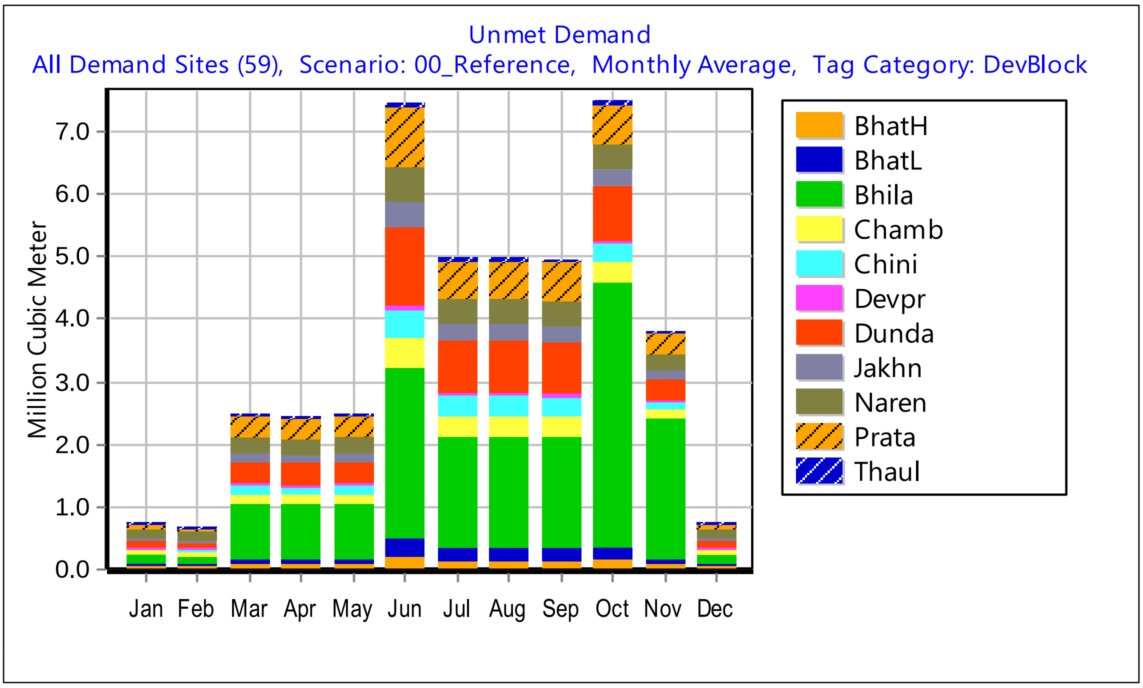


Figure 22. Monthly water demand in the Bhagirathi Basin for the eleven Community Development Blocks for 2001-2020.

For the abbreviation of the Community Development Blocks see Table 3

4.1.3 Water Supply

The amount of water available for use within the basin and as water source for downstream areas has been split between the three main sources: rainfall runoff (surface and base flow), snowmelt and glacial melt. The source of water has been assessed using the virtual tracer approach as described in Chapter 3.1.2.

For the Community Development Blocks located in higher regions snowmelt and glacial melt are important sources of water. For example, in the northern Bhatwari 12% of the water flowing into Bhagirathi River originated from glacial melt and over 61% from snow melt. And 27% entered the river from rainfall runoff. Those numbers are averages in the years 2001 to 2021.

Monthly variation between the source of water is huge. For example in May and June the contribution of snow is 87% and 91% respectively. Glacial melt contributes for 38% in August. Details can be seen from Figure 23 to Figure 25.

Numbers above are only for the upstream part of the Bhagirathi. Concentrating on the entire Bhagirathi Basin glacial melt contributed for 5%, snowmelt for 27% and the remainder, 67%, originates from rainfall runoff. Monthly variation between those three sources of water is again very high (Figure 25).

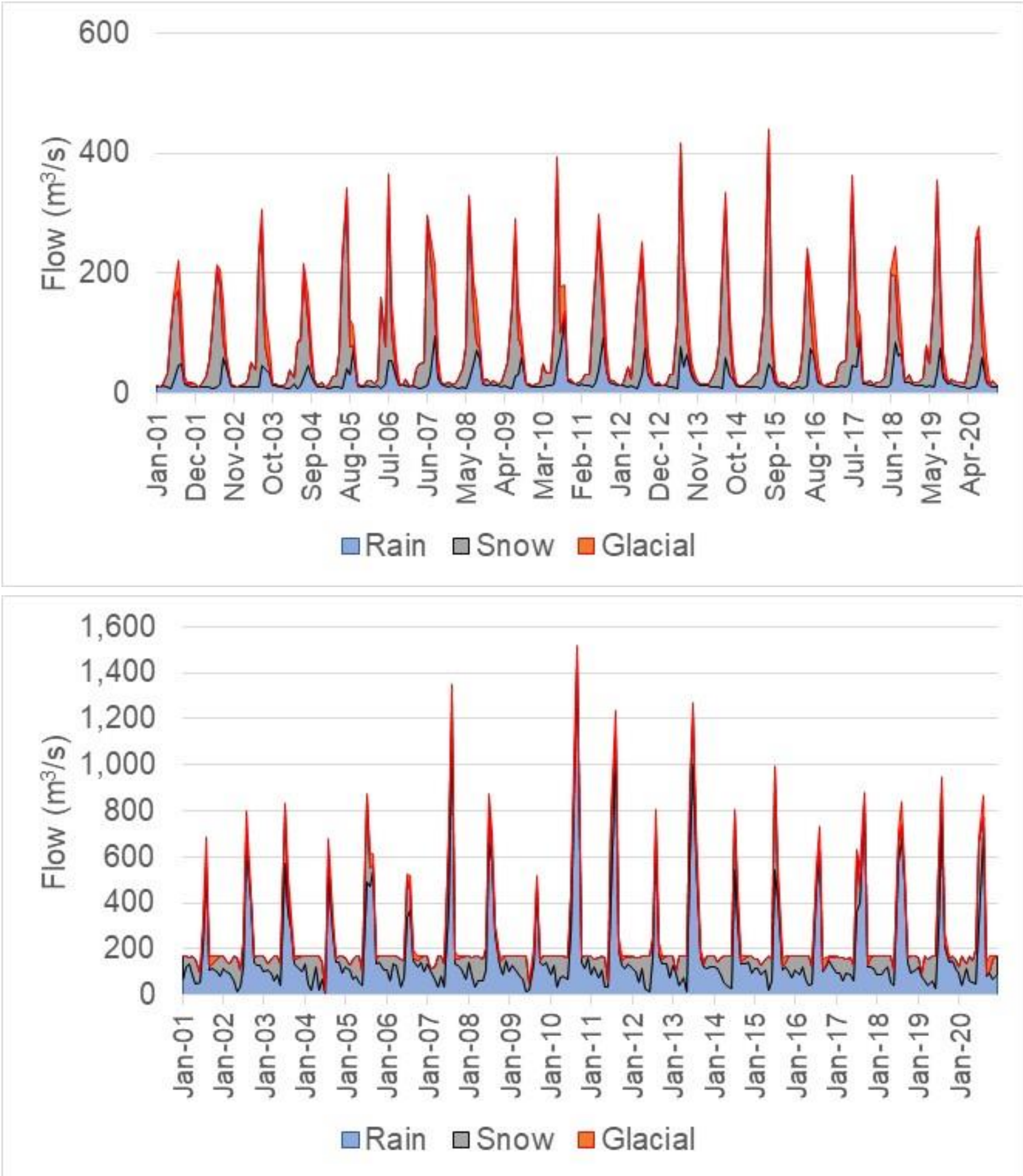


Figure 23. Origin of water. Monthly 2001-2020. Top: upstream Bhatwari_H; bottom inflow Tehri Reservoir.

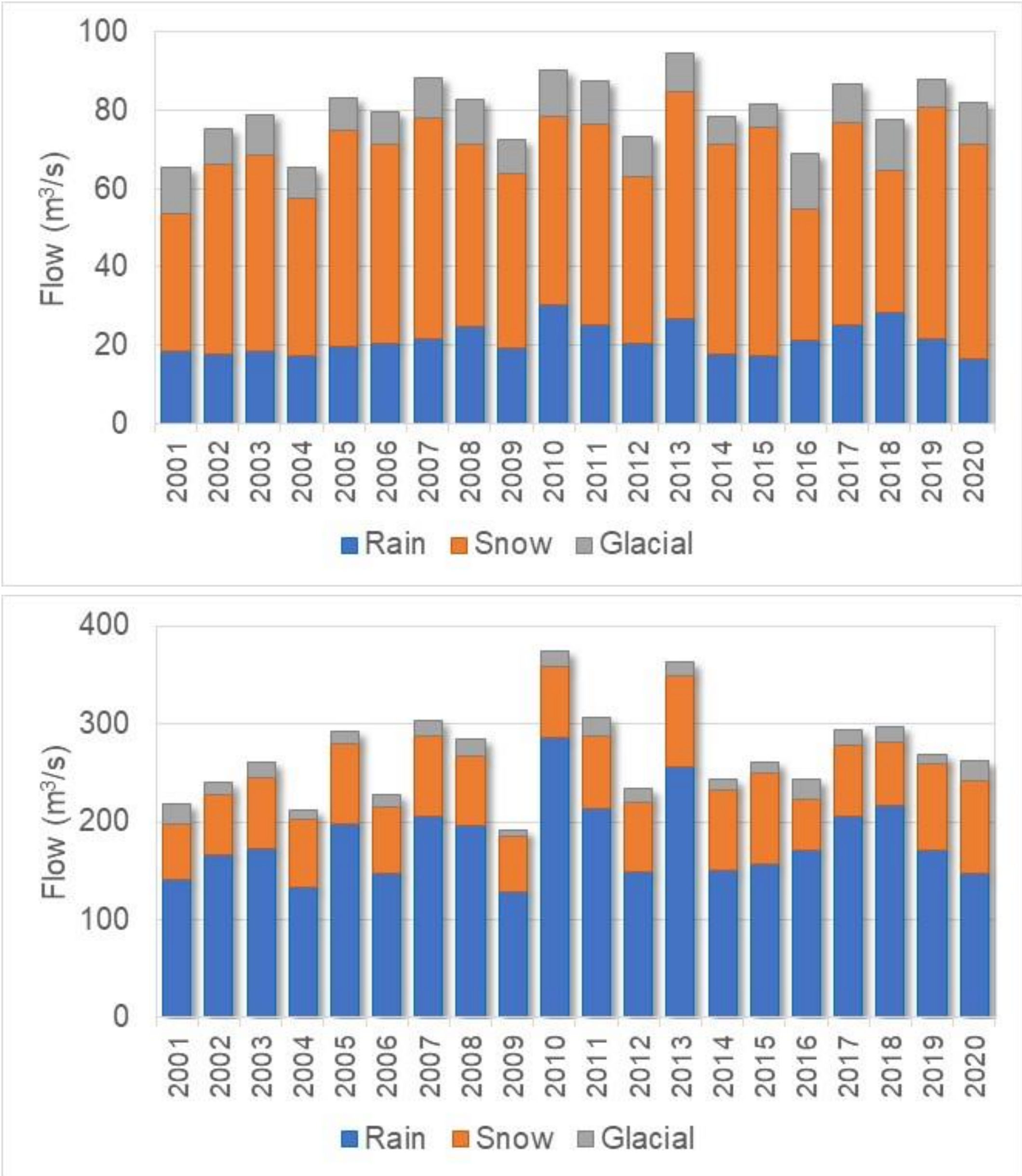


Figure 24. Origin of water. Annual average 2001-2020. Top: upstream Bhatwari_H; bottom inflow Tehri Reservoir.

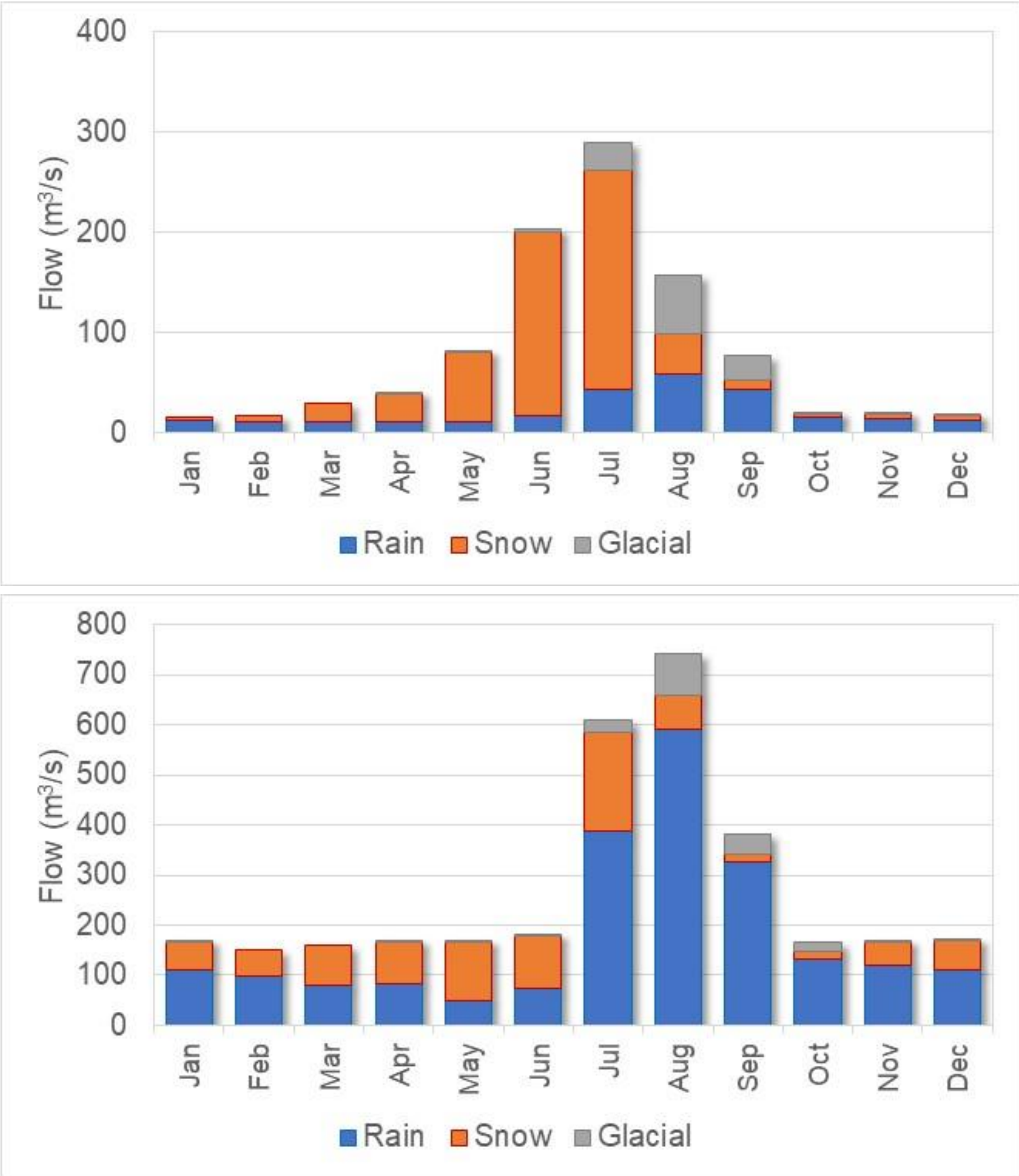


Figure 25. Origin of water. Mean monthly 2001-2020. Top: upstream users Bhatwari_H; bottom inflow Tehri Reservoir.

4.1.4 Return flows

The rate of dependency on return flows has been assessed using the virtual tracer approach as described in the previous chapter. Obviously, upstream users depend less on return flows compared to the more downstream users. The overall rate of return flow water in the Bhagirathi River is relatively low. Only when natural flows are low and irrigation is still producing return flow the dependency on return flows can be substantially. This happens particular during October.

Figure 26 to Figure 28 provide inside on those return flows dependency. The Figures presented the percentage of return flows that passes a certain point in the river. The three locations used for this are:

- Upstream: outflow from Bhatwari_Lower
- Middle: inflow into Tehri Reservoir
- Downstream: outflow from the entire study area

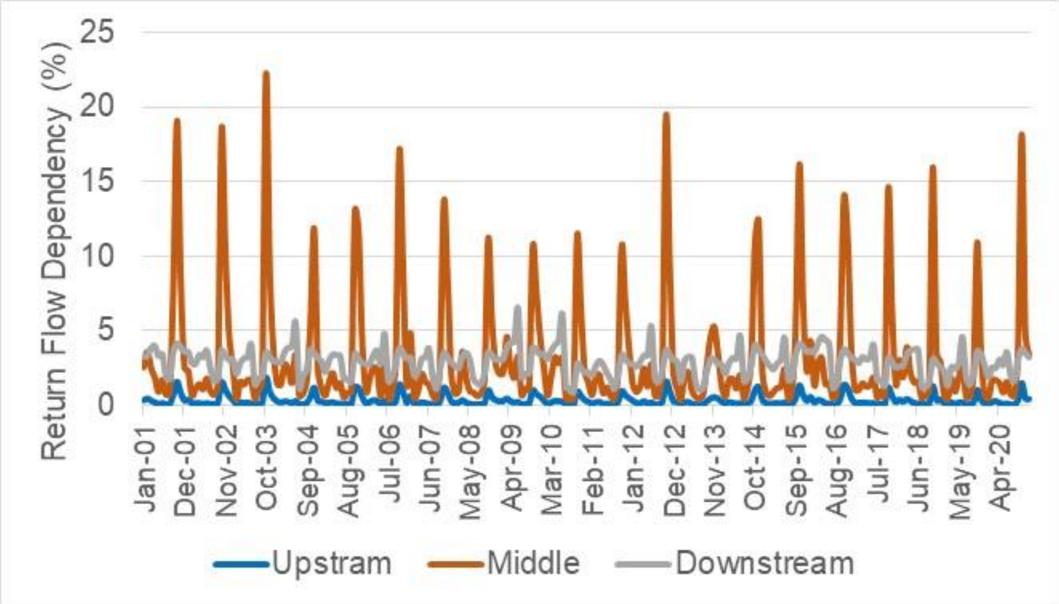


Figure 26. Dependency of users on return flow from upstream users at three locations in the basin. Monthly 2001-2020

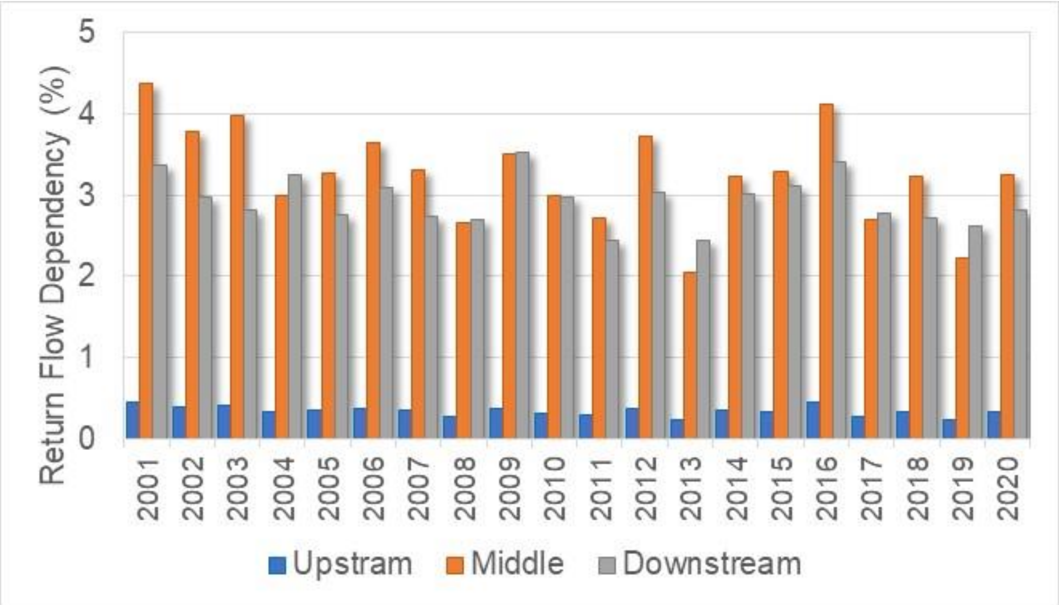


Figure 27. Dependency of users on return flow from upstream users at three locations in the basin. Annual 2001-2020

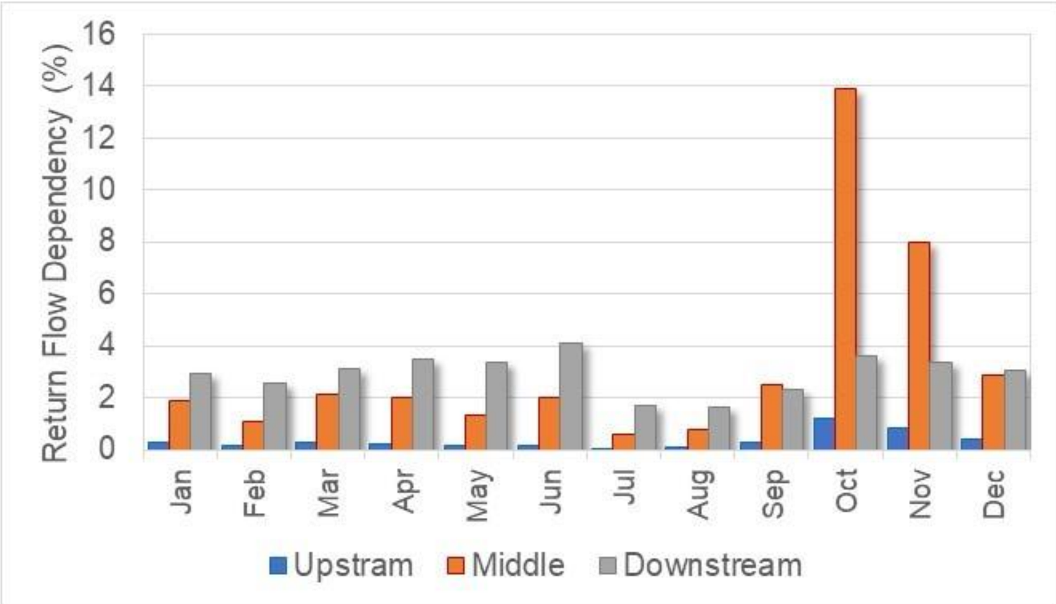


Figure 28. Dependency of users on return flow from upstream users at three locations in the basin. Monthly average 2001-2020

4.2 Sensitivity Analysis

A sensitivity analysis was undertaken to explore to what extent the Bhagirathi Basin is sensitive for changes in: (i) climate, (ii) population, and (iii) irrigated area. For climate it was assumed that the total annual inflow would change (decrease or increase) by a certain factor. Similar. for population and irrigated area a decrease and increase were assumed. For those three categories 10% and 5% decreases as well as 5% and 10% increases were explored.

The WEAP model was run for all those combinations and average annual results for the years 2001 to 2020 were averaged. Results are presented in Table 6. Based on those results it is clear that all three factors, inflow, population and change in irrigation area, are important factors in terms of projected changes in water demand and water shortages. Population change has the lowest impact, while an expansion of irrigation can results in substantial increase in water shortages. The combined effect, reduction in inflow, increase in population growth and an expansion of irrigated area, will results in a substantial increase in water shortage. It should be however emphasized that water shortage compared to water demand is in all cases relatively small.

Two additional and more extreme analysis were included as well. For the most extreme one it was considered that climate change would result in a reduction in inflow of 10%, population growth of 10% and an expansion of irrigated area of 10%. A less extreme analysis was considered by implying for those three factors a percentage of 5%.

Table 6. Sensitivity analysis on changes in climate (inflow), population and irrigated area. Results are average annual over period 2001-2020. Percentage change in demand and unmet demand (last two columns) are all compared to the baseline.

Inflow	Population	Irrigation	Water Demand	Unmet Demand	**Water Demand Change**	**Unmet Demand Change**
(fraction)	(fraction)	(fraction)	(MCM/y)	(MCM/y)	**(%)**	**(%)**
-10%	0%	0%	248.4	5.9	**0.0%**	**9%**
-5%	0%	0%	248.4	5.7	**0.0%**	**5%**
0%	0%	0%	248.4	5.5	**0.0%**	**0%**
+5%	0%	0%	248.4	5.2	**0.0%**	**-4%**
+10%	0%	0%	248.4	5.0	**0.0%**	**-9%**
0%	-10%	0%	243.3	5.3	**-2.0%**	**-2%**
0%	-5%	0%	245.8	5.4	**-1.0%**	**-1%**
0%	0%	0%	248.4	5.5	**0.0%**	**0%**
0%	+5%	0%	250.9	5.5	**1.0%**	**1%**
0%	+10%	0%	253.4	5.6	**2.0%**	**2%**
0%	0%	-10%	228.6	4.5	**-8.0%**	**-17%**
0%	0%	-5%	238.5	5.0	**-4.0%**	**-9%**
0%	0%	0%	248.4	5.5	**0.0%**	**0%**
0%	0%	+5%	258.3	5.9	**4.0%**	**9%**
0%	0%	+10%	268.2	6.4	**8.0%**	**17%**
-10%	+10%	+10%	273.2	7.1	**10.0%**	**30%**
-5%	+5%	+5%	260.8	6.2	**5.0%**	**14%**

4.3 Projections

Based on the sensitivity analysis and projections on population growth and climate change models 2 projections have been defined to explore further.

The data from the United Nations World Population Prospects[1] for the entire country can be summarized[2] as:

	2010	2050 LOW	2050 MEDIUM	2050 HIGH
Population (millions)	1,241	1,527	1,670	1,816
Increase (millions)		287	430	576
Increase (%)		23%	28%	34%

[1] https://reliefweb.int/report/world/world-population-prospects-2022-summary-results#:~:text=Attachments&text=The%20world's%20population%20is%20projected,and%2010.4%20billion%20in%202100.

[2] https://ourworldindata.org/

Changes in runoff and inflow are presented in the SPHY report. Multiple climate projections were analyzed and the overall conclusion is that quite some variation exists. Most likely around 2050 somewhat more water can be expected, although some projections and during some years a decrease can be expected.

Increase in irrigation water demand is hard to assess as this depends on many factors. In general an increase in temperature of 2°C will results in an increase in crop water requirements of 5%. The expansion of irrigated area is difficult to assess, and it was therefore assumed that the irrigated area expansion will be same as the population increase.

The following assumptions for those projections have been used:

- Proj_01 (most likely)
  - No changes in runoff
  - Population growth
    - +23% by 2050 (medium projection)
  - Increase in irrigation water demand
    - +5% by higher temperatures
    - +23% by expansion of areal

- Proj_02 (extreme)
  - Runoff and inflow
    - reduction of 5% by 2050
  - Population growth
    - +34% by 2050
  - Increase in irrigation water demand
    - +10% by higher temperatures
    - +34% by expansion of areal

All those projections were included in the WEAP model assuming a linear change between 2020 and 2050. Main results are presented in the Figures and Tables below. Detailed results can be found in the WEAP model itself (attached to report).

In summary the main results:

- <u>Water demand</u> *within* Bhagirathi
  - Increase by 23% (Proj_01) up to 35% (Proj_02)
  - **Substantial increase in demand**
- <u>Unmet demand</u> (water shortage) *within* Bhagirathi
  - Increase from 43 MCM/y (current) to 54 (Proj_01) and 60 (Proj_02) MCM/y
  - Coverage reduction from 83% (current) to 82% (Proj_01) and 82% (Proj_02)
  - **Coverage within the basin projected not to change very much.**

- <u>Water demand</u> *within* Bhagirathi and *downstream* requirements
  - Increase by 47% (Proj_01) up to 75% (Proj_02)
  - **Very high increase in demand**
- <u>Unmet demand</u> (water shortage) *within* Bhagirathi and *downstream* requirements

- Increase from 43 MCM/y (current) to 244 (Proj_01) and 998 (Proj_02) MCM/y
    - Coverage reduction (=supply over demand) from 99% (current) to 97% (Proj_01) and 90% (Proj_02)
    - **Unmet demand within the basin and for downstream at critical level. Proj_01 good coverage; Proj_02 severe problems.**

  - Reservoir storage
    - **Critical low under both future projections**

  - Origin of water
    - **Most water originates from rainfall runoff. In future snowmelt contribution can be expected to peak one month earlier (from June to May).**

- Reuse of water
  - **Reuse of return flows will double from about 2% current to 4% in future (Proj_02) as more water will be used so more return flow will be generated.**

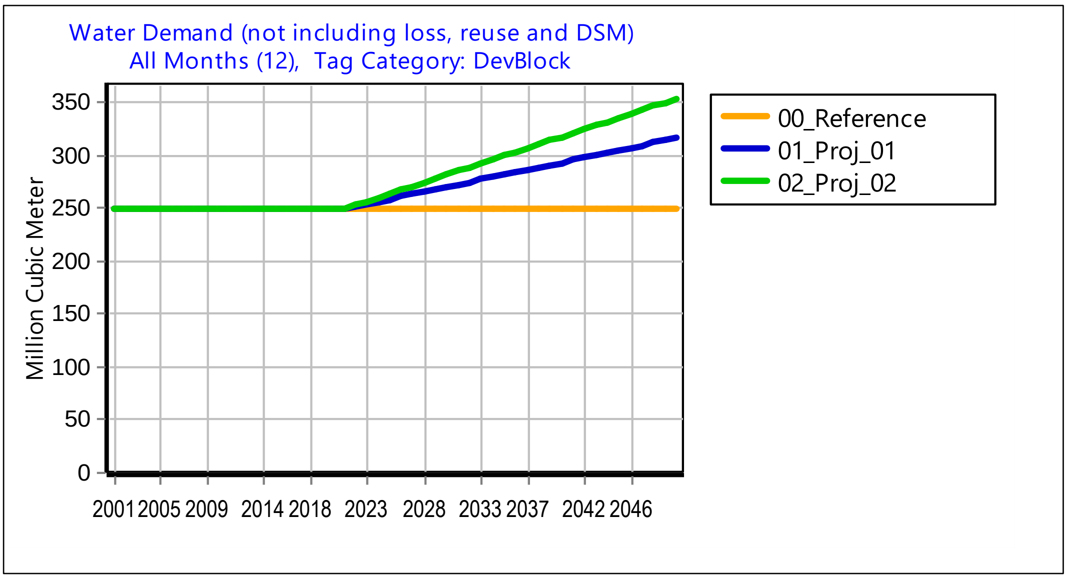


Figure 29. Annual water demand in the Bhagirathi Basin for the reference (2001-2020) and the two projections for the future (2021-2050). Only water demand within the Bhagirathi Basin are considered.

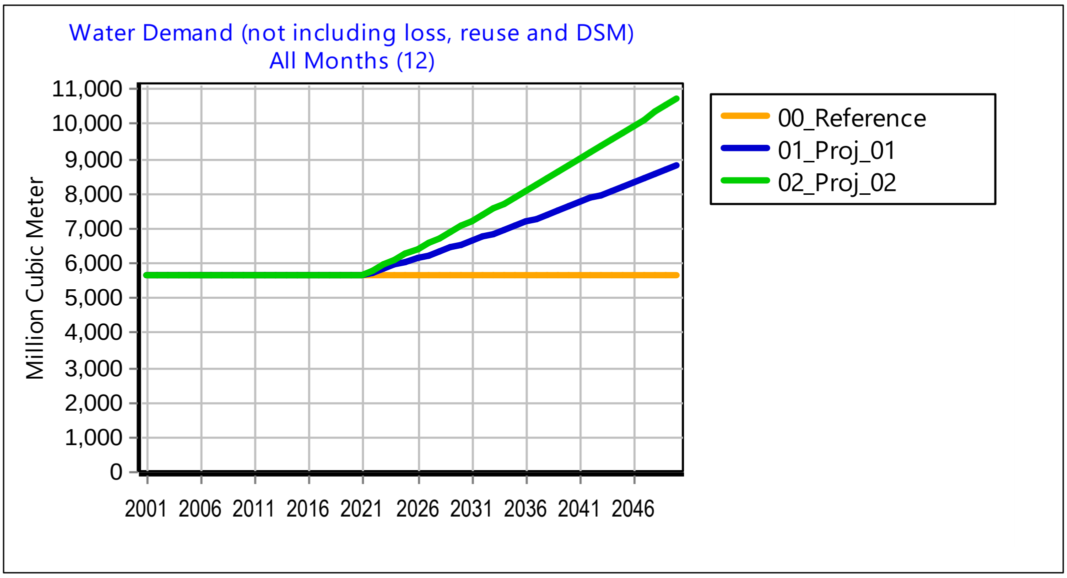


Figure 30. Annual water demand in the Bhagirathi Basin for the reference (2001-2020) and the two projections for the future (2021-2050). Water demand within the Bhagirathi Basin and the additional demand expected to be delivered for downstream use are considered.

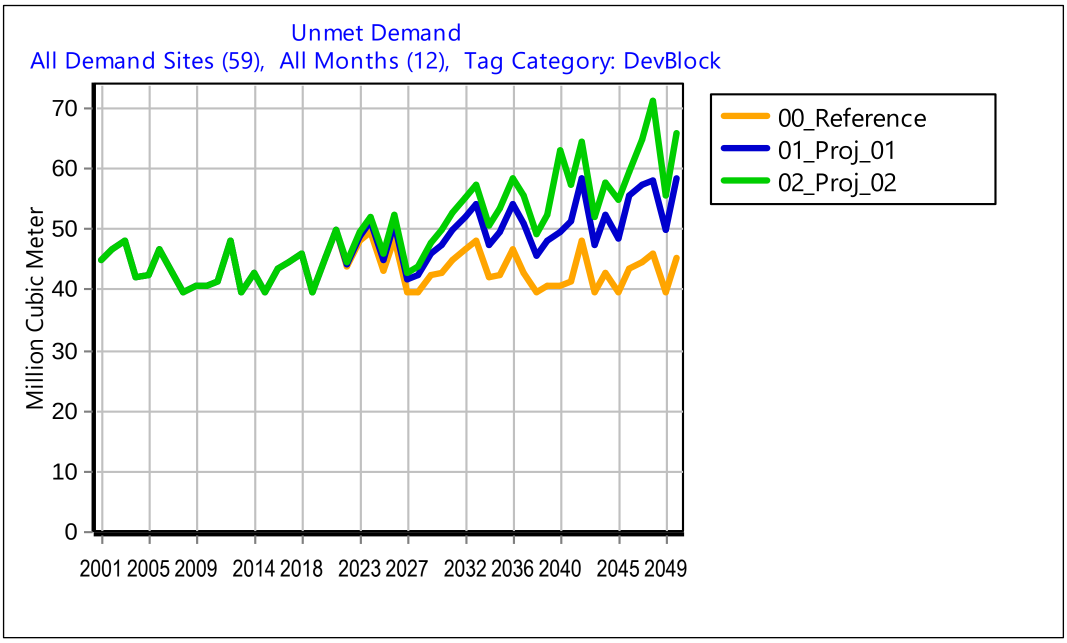


Figure 31. Annual unmet water demand (water shortage) in the Bhagirathi Basin for the reference (2001-2020) and the two projections for the future (2021-2050). Only water demands within the Bhagirathi Basin are considered.

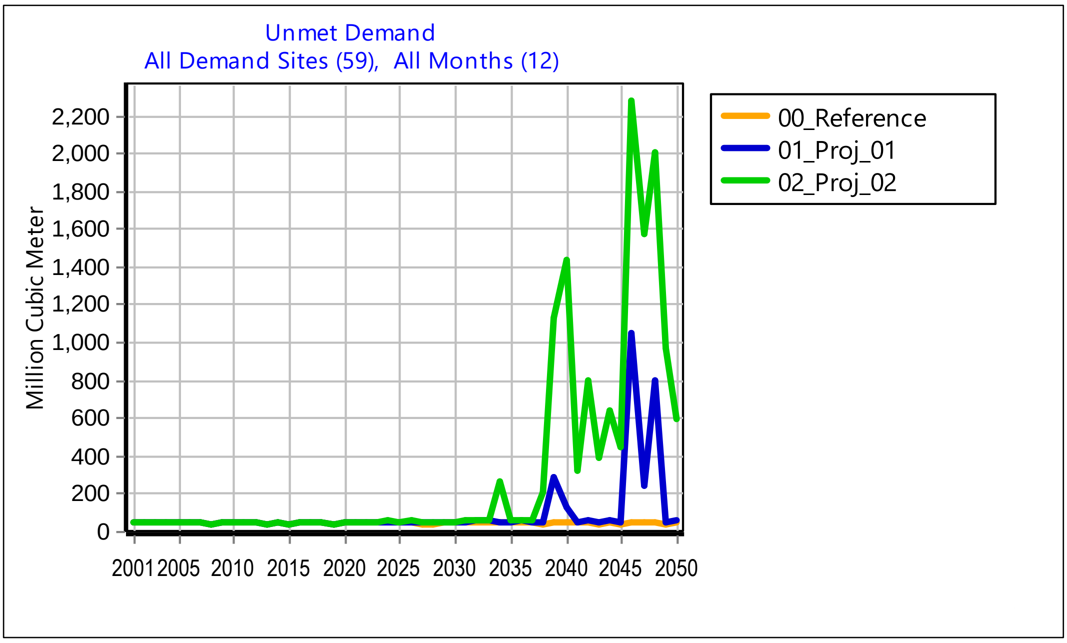


Figure 32. Annual unmet water demand (water shortage) in the Bhagirathi Basin for the reference (2001-2020) and the two projections for the future (2021-2050). Water demand within the Bhagirathi Basin and the additional demand expected to be delivered for downstream use are considered.

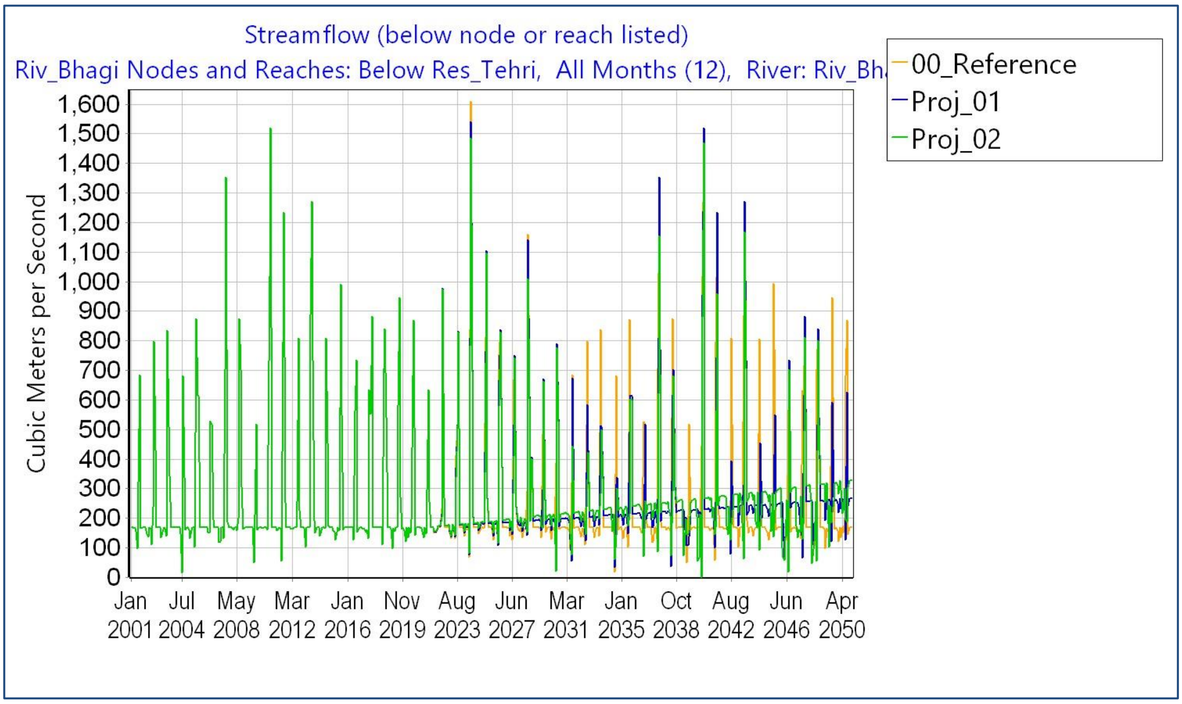


Figure 33. Monthly outflow from Tehri dam under the reference and the two projections.

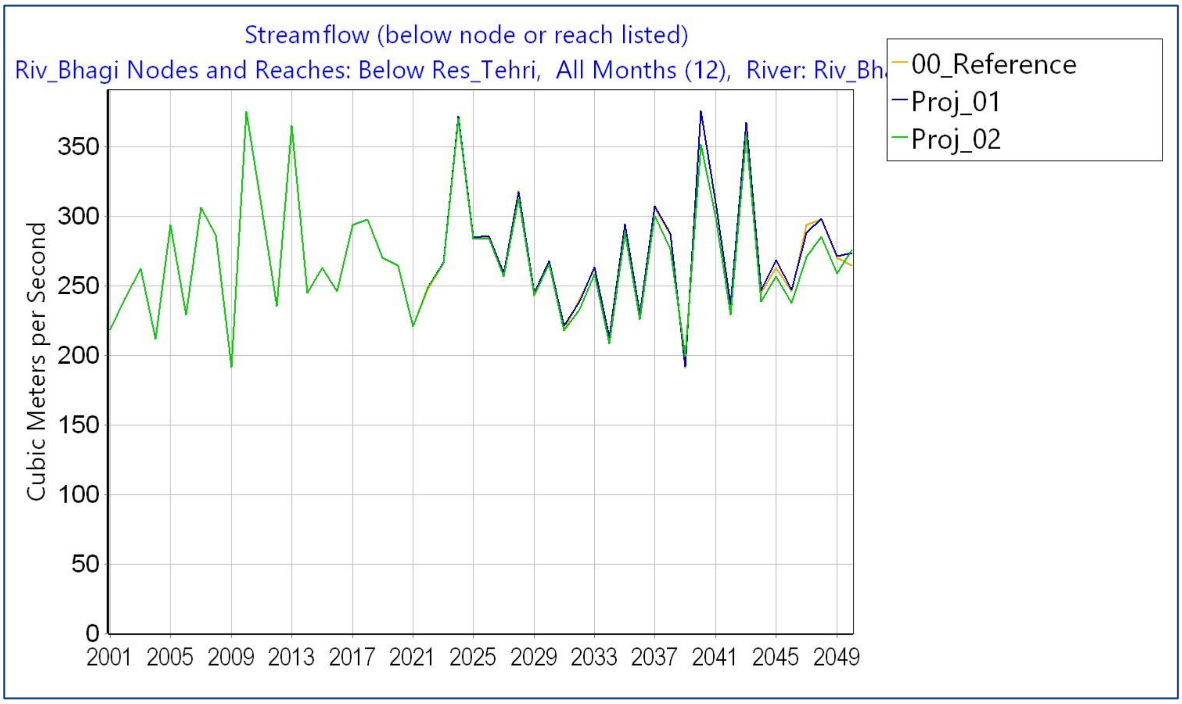
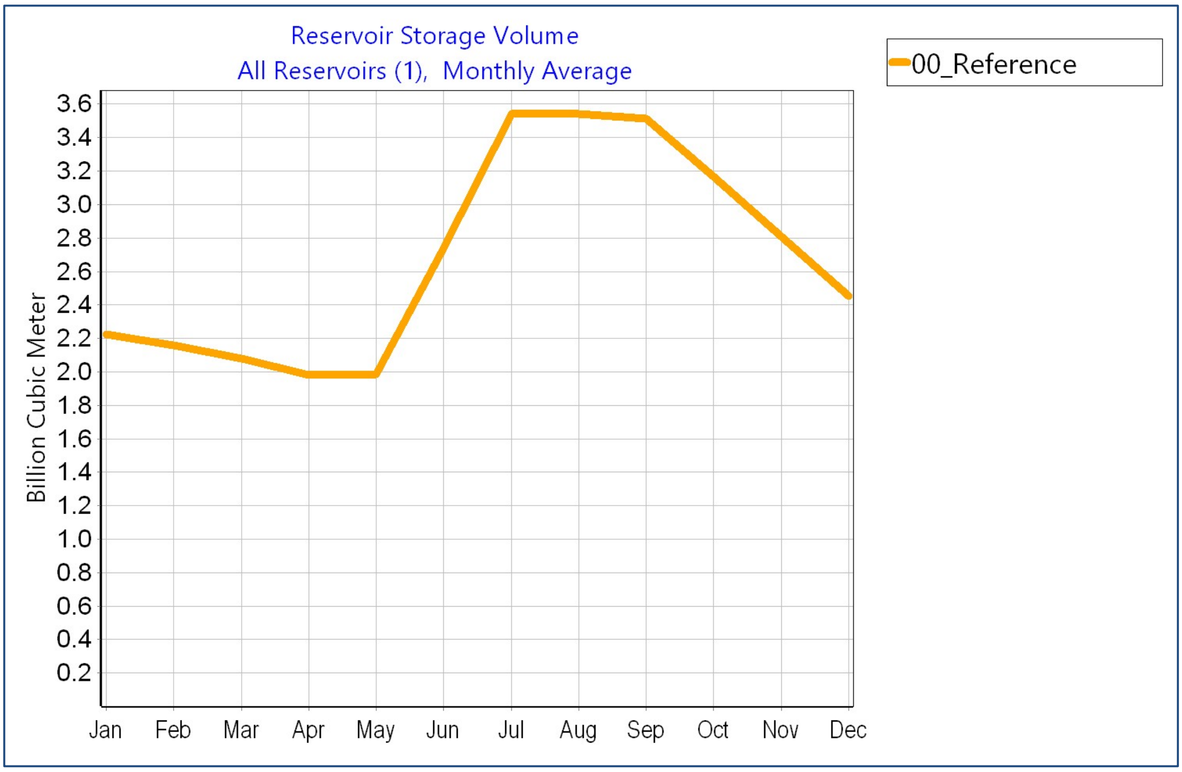


Figure 34. Mean annual outflow from Tehri dam under the reference and the two projections.



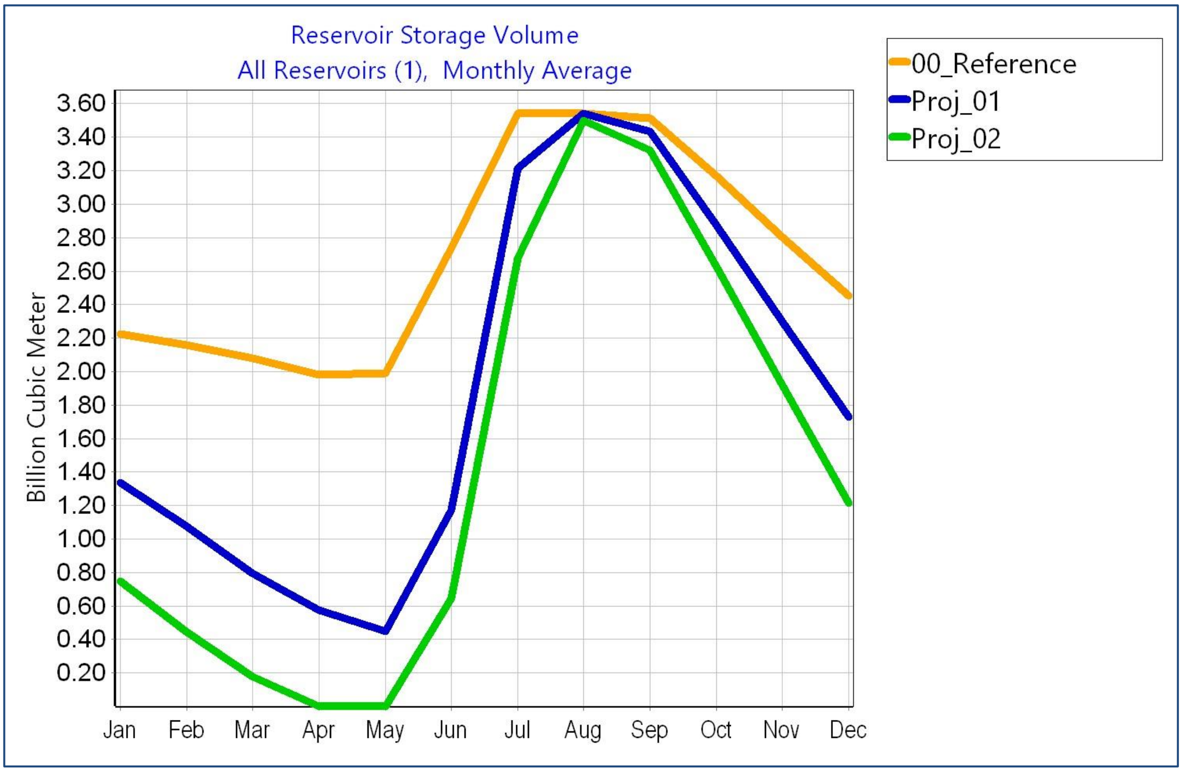
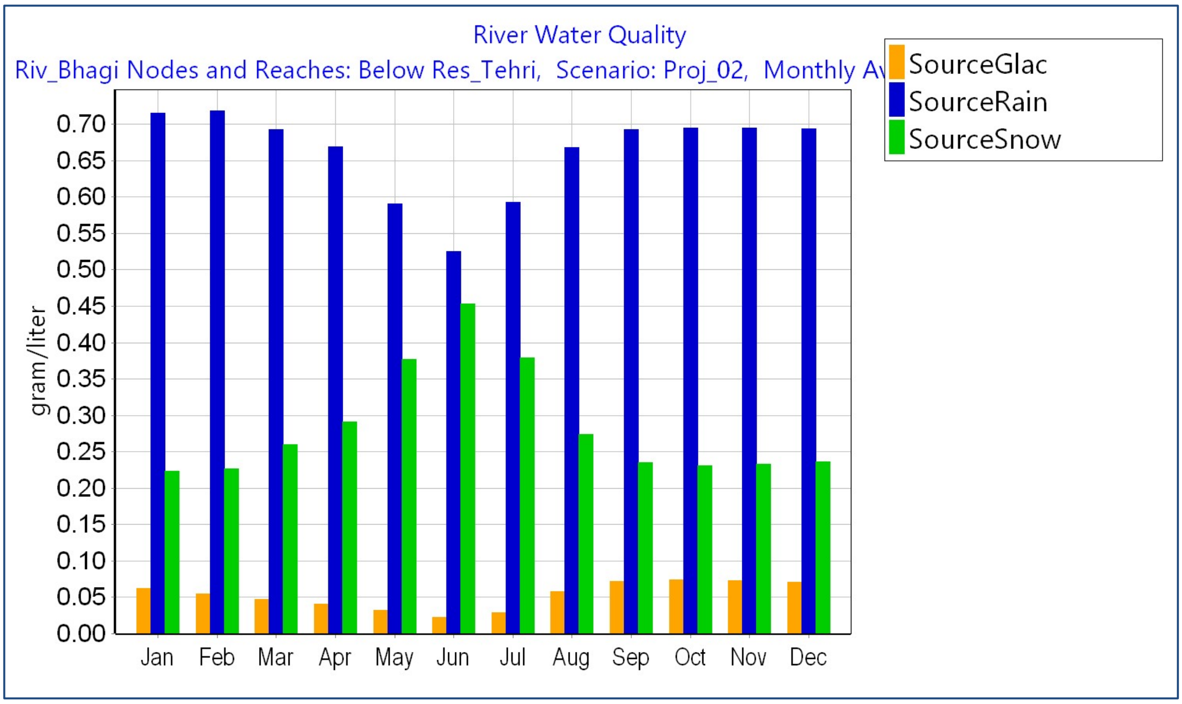


Figure 35. Mean monthly storage of Tehri dam under the reference and the two projections. Top: 2011-2020; bottom 2041-2050.



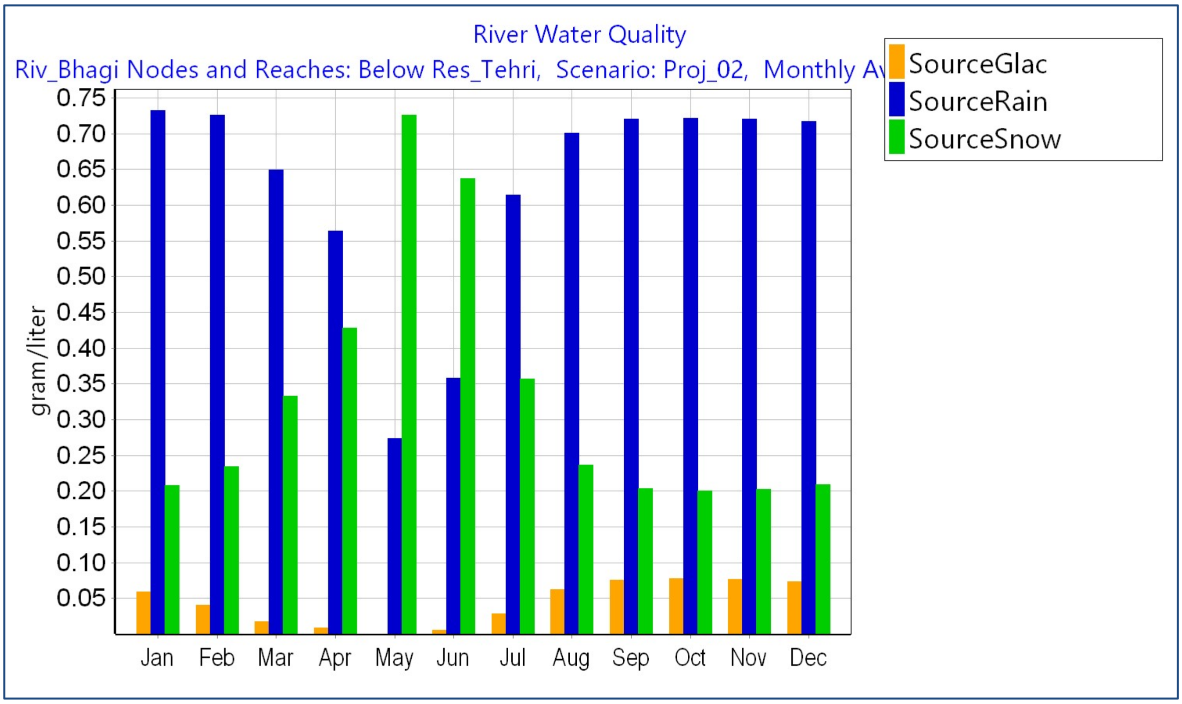
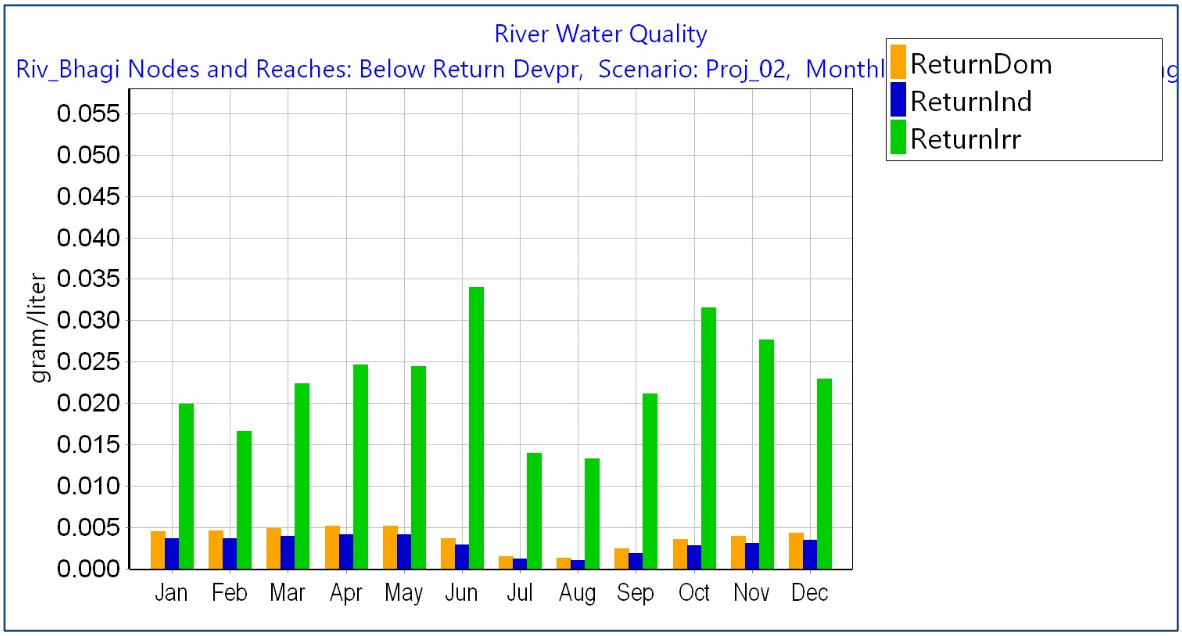


Figure 36. Mean monthly origin of water source flowing out of Tehri dam under the reference (top) projections Proj_02 (extreme). Top: 2011-2020; bottom 2041-2050.
Note: Y-axis values are concentrations of the virtual tracers and can be interpreted as fractions of the source. Total for each month is 1 (=100%).



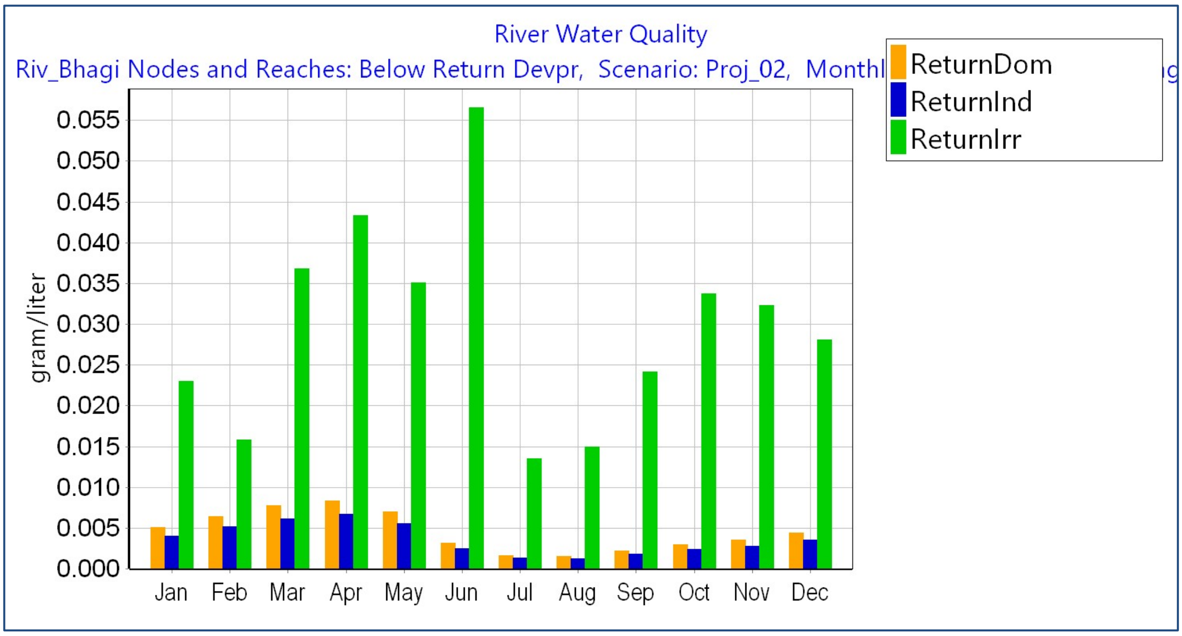


Figure 37. Mean monthly dependency on return flows flowing out of the basin under the reference (top) projections Proj_02 (extreme). Top: 2011-2020 (Reference); bottom 2041-2050 (Proj_02).
Note: Y-axis values are concentrations of the virtual tracers. And are identical as fractions. Total for each month is not necessary 1 (=100%) as only reuse of water is presented.

4.4 Adaptation Options

The main topics of concern as concluded from the previous sections based on the two future projections are:

- Low reservoir levels
- Slightly lower outflow around 2040-2050 and increasing demand downstream
- Local water shortage in the Bhilangana Development Block

In order to overcome those issues, the following interventions (adaptation options) are implemented in the WEAP model to evaluate their potentials on improving water allocations. As reference the Projection 02 (extreme) will be used. Three intervention types will be explored, each with some sub-interventions. So in total seven scenarios will be tested in WEAP:

- **Int_01: Adaptation measures focused on land use**
  - Overcoming local water shortage, especially in the Bhilangana Development Block, will be investigated by the following measures:
    - **Int_01_a**: increasing rainwater harvesting
      - WEAP: assume that 10% more water will be available by various rainwater harvesting techniques
      - `Int_01_a > Key > IrrOtherYY: *90%`
      - `Int_01_a > Key > IrrRiceYY: *90%`
      - `Int_01_a > Key > IrrWheatYY: *90%`
      - `Key\Projections\InflowFactor *99%`
    - **Int_01_b**: converting rice to wheat[1]
      - WEAP: changes in cropped area for those two crops
      - `Int_01_b > Irr_BathH > Annual Activity Level > ha`
      - `for all 11 development blocks`
    - **Int_01_c**: stop growing rice at all (so an overall decrease in irrigated area) [2]
      - WEAP: set rice area to nil
      - `Int_01_b > Irr_BathH > Annual Activity Level > ha`
      - `for all 11 development blocks`

- **Int_02: Adaptation measures focused on reducing demands**
  - Although the water that is released from Tehri Dam is sufficient to supply the planned additional demand, more water downstream is desirable given downstream economic development. Also at the extreme projection (Proj_02) water shortage can be expected towards 2050. The following measures will be explored.
    - **Int_02_a**: Deficit irrigation by 5% in the entire basin
      - WEAP: reduce irrigation applications by 5%
      - `Int_02_a > Key > IrrOtherYY: *0.95`
      - `Int_02_a > Key > IrrRiceYY: *0.95`

[1] Note that those interventions are mainly provided to show the dominant water use in the basin. In realty reducing rice areal would be difficult to justify.
[2] Note that those interventions are mainly provided to show the dominant water use in the basin. In realty reducing rice areal would be difficult to justify.

        - `Int_02_a > Key > IrrWheatYY: *0.95`
    - **Int_02_b**: Deficit irrigation by 10% in the entire basin
        - WEAP: reduce irrigation applications by 10%
        - `Int_02_b > Key > IrrOtherYY: *0.90`
        - `Int_02_b > Key > IrrRiceYY: *0.90`
        - `Int_02_b > Key > IrrWheatYY: *0.90`

- **Int_03: Adaptation measures focused on enhancing storage capacity**
  - Same Int_02, trying to overcome water shortage, but now by a more technological solution
    - **Int_03_a**: Increased water retention by grey and/or green infrastructure[1]
        - WEAP: Increase in retention by 1770 MCM (comparable with 50% of Tehri). This can be implemented by improved catchment management and/or by reservoirs.
    - **Int_03_b**: Extensive increased water retention by grey and/or green infrastructure
        - WEAP: Increase in retention by 3540 MCM (comparable with doubling Tehri). This can be implemented by improved catchment management and/or by reservoirs.
    - **Int_03_c:** Improve access to water by developing pumping and/or canal capacity.
        - WEAP: In Section 3.3.5 the method of water access is explained. Under this intervention it is assumed that access is no limiting factor and only total water shortage in a development block can cause unmet demand.

The amount of output WEAP generates is enormous. For the sake of clarity, the effectiveness of the Interventions will be compared using the following key indicators (all using conditions for 2041-2050)[2]:

- Irrigation demand
  - average over the period 2041-2050
- Irrigation unmet demand
  - average over the period 2041-2050
- Agricultural yield
  - The agricultural yield is estimated by using the water productivity assuming a value of 0.5 kg m^3 for all crops
- Outflow from the basin to downstream
- Occurrence of low Teri Reservoir levels
  - Low levels were set at 0.1 MCM

[1] The WEAP model for the reference includes only Tehri Reservoir
[2] Detailed output can be obtained from the WEAP model attached to this Report

Table 7. Effectiveness of the Interventions as analysed using the WEAP water allocation model. Al results are based on the period 2041-2050.

	Irrigation Demand	Irrigation Unmet	Yield	Outflow	Reservoir low
	(MCM/y)	(MCM/y)	(ton/y)	(MCM/y)	(months in 10 years)
No adaptation	271.6	49.9	66,516	10,004	16
Int_01_a	244.4	44.4	66,000	9,905	17
Int_01_b	138.0	34.3	31,112	10,005	21
Int_01_c	65.2	12.7	15,740	10,005	17
Int_02_a	258.0	47.0	63,319	10,004	16
Int_02_b	244.4	44.3	60,054	10,004	15
Int_03_a	271.6	49.4	66,646	10,067	2
Int_03_b	271.6	49.4	66,645	10,049	0
Int_03_c	271.6	9.2	78,709	10,004	0

Table 8. Same as Table 7 but now as difference in percentage compared to the non-intervention projection Proj_02.

	Irrigation Demand	Irrigation Unmet	Yield	Outflow	Reservoir low
	(MCM/y)	(MCM/y)	(ton/y)	(MCM/y)	(months in 10 years)
Int_01_a	-10%	-11%	-1%	-1%	+6%
Int_01_b	-49%	-31%	-53%	+0%	+31%
Int_01_c	-76%	-75%	-76%	+0%	+6%
Int_02_a	-5%	-6%	-5%	+0%	0%
Int_02_b	-10%	-11%	-10%	+0%	-6%
Int_03_a	0%	-1%	+0%	+1%	-88%
Int_03_b	0%	-1%	+0%	+0%	-100%
Int_03_c	0%	-81%	+18%	-0%	-100%

The most relevant conclusions from those interventions:

- The amount of water used within the Bhagirathi Basin itself is a very small fraction of the fresh water available in the streams[1].
- Whatever intervention is considered, changes in the amount of outflow are minor. Obviously, every additional cubic meter that can flow downstream is beneficial.
- The three categories of intervention show a distinct difference:
  - Int_01 land-use-focused measures: will have quite some effect on crop production, outflow is hardly influenced.
  - Int_02 demand-management measures: will have some impact on water use and minor impact on downstream water supply.
  - Int_03 Infrastructure: some positive impact on reducing water shortage in the basin, small positive impact on outflow and very positive on Tehri reservoir levels.

[1] Total runoff entering into streams and rivers is about 10,000 MCM/y; total withdrawal for urban, industry and irrigation is about 300 MCM/y. So about 3%. Note that those number reflect 2041-2050 and ET from natural vegetation is not included.

Overall it can be concluded that loss of natural storage by glaciers and snow might be compensated by additional storage by reservoirs. Other interventions to increase storage by for example groundwater recharge might be explored using hydrological models. Small scale local water shortages might be overcome by roof top water collection, local village ponds and similar interventions.

Some examples of more detailed figures to better understanding the dynamics of the water allocation interventions:

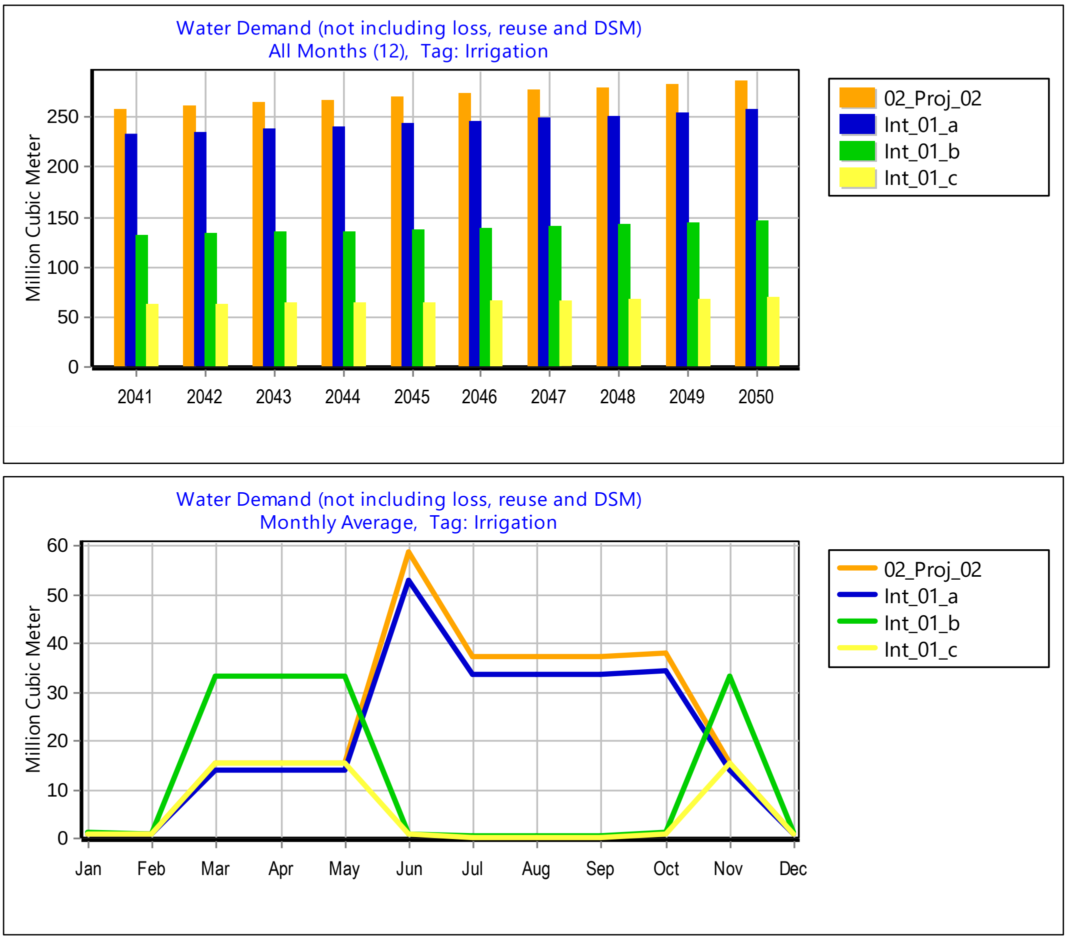
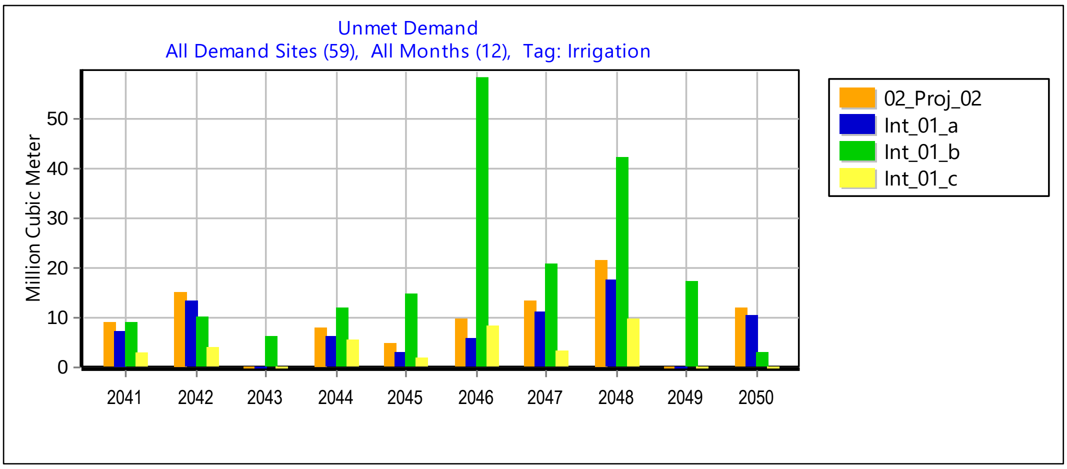


Figure 38. Water demand for the irrigation sector for the non-intervention (Proj_02) and the three local interventions (Int_01). Top: annual totals; bottom monthly averages over 2041-2050.



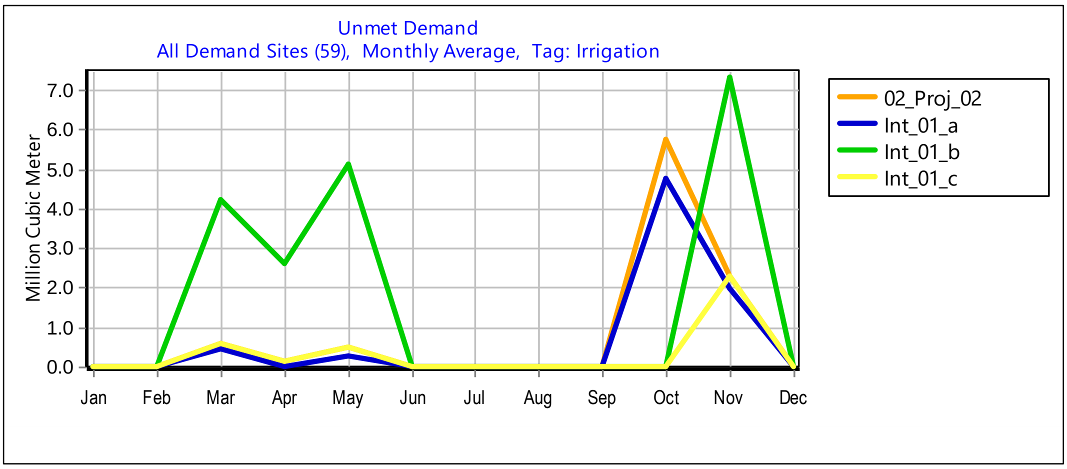
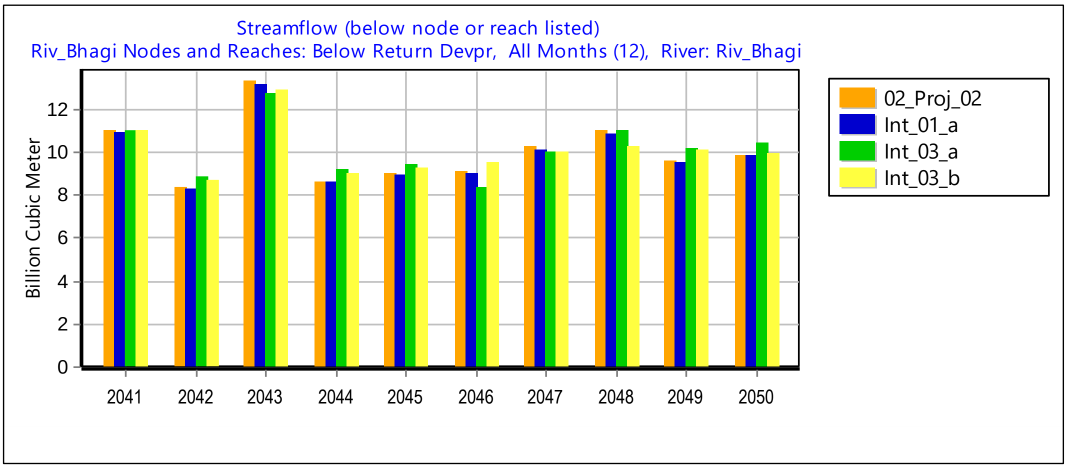


Figure 39. Unmet water demand for the irrigation sector for the non-intervention (Proj_02) and the three local interventions (Int_01). Top: annual totals; bottom monthly averages over 2041-2050.



5 Conclusions

The study described in this report is developed in the context of the “Strengthening State Strategies for Climate Action” project which is a collaboration between Institutions across the Indian Himalayan Region (IHR) and Swiss Agency for Development and Cooperation’s (SDC). This specific report is one of the outputs of the components of the modeling efforts: development, application and scenario analysis of a water allocation model. The goal for this specific component can therefore be defined as: “Application of a water allocation model to evaluate climate actions: case study Bhagirathi”.

Using all available data, information, resources and expertise a water allocation model using the WEAP framework was developed. WEAP was selected as it stands out on water allocation and scenario analysis. Scalability of the WEAP model is also a very relevant aspect of the current project. Since the complexity of the WEAP model, given its nice interface, is also relatively low, the model can also be used for training. The WEAP model as used in this study has been expanded by adding “virtual tracers”. This is a quite innovative approach to track different sources and reuse of water.

The model was setup to run at a monthly basis from 1991-2020 (reference period) and expanded from 2021-2050 using projections. The spatial resolution was set at the Development Block level (in total 11).

The results show that water demand for the reference period within the basin for domestic use, industry and irrigation is about 250 MCM per year, where irrigation is responsible for about 80% of this demand. However, Tehri reservoir was constructed to allocated water for downstream users with a total demand of over 5,000 MCM. Total supply to rivers from glacial and snow melt and rainfall runoff are about 10,000 MCM per year. Water shortage within the Bhagirathi Basin is therefore quite limited, at the given time resolution (monthly) and spatial resolution (development block). Obviously at smaller time-scales (e.g. days) and/or spatial scales (e.g. villages) water shortage might occur.

Projections for the future show that demand will increase substantially. The climate projections indicate that more rainfall can be expected, so based on those projections no severe water shortage can be expected. Given uncertainty in climate projection also a stress-test analysis was done, assuming a 5% reduction in rainfall. Under this assumptions water shortage might become an issues, especially for the delivery to downstream areas.

Three adaptation options (interventions) have been explored (local, cooperation and techno). Results of those adaptation options indicate that: (i) local, will have quite some effect on crop production, outflow is hardly influenced; (ii) cooperation, will have some impact on water use and hardly any positive impact on downstream water supply; (iii) techno, will have some positive impact on reducing water shortage in the basin, small positive impact on outflow and very positive on Tehri reservoir levels.

Results find can be fine-tuned and additional scenarios can be evaluated with the framework developed.

6 Annex: WEAP

In this section some specifics of the WEAP model as developed are presented. Standard WEAP input will not be discussed, only specific tailor-made and non-standard input features are presented here.

6.1 Inflow data from SPHY using Cycle

The WEAP water allocation model uses flow data as generated by the SPHY model. The reference period is 1991-2020. In order to use those data for the future an adjustment factor on those baseline data is used.

The WEAP ReadFromFile function with Cycle is used in combination with an Inflow Adjustement Factor that can be set by the used in the \Key Assumptions.

Without "Cycle"

```
ReadFromFile(Data\Supply.csv, "G_BhatH") * Key\Climate\InflowFactor
```

With "Cycle" where the two years reflect the starting and end year to be used for the future. So in this case a period of 30 years (1991-2020) will be used for each year after 2020. E.g. 2021 will use same climate as 1991.

```
ReadFromFile(Data\Supply.csv, "G_BhatH" , , , , , , 1991, 2020, Cycle) *
Key\Climate\InflowFactor
```

6.2 Projections on Inflow

The projections after 2020 are given using the Interp (Interpolation) function of WEAP. For the Inflow changes (rain) the following \Key Assumption\Projections\InflowFactos is used:

```
Interp(1991, 1, 2021, 1, 2050, 0.7)
```

The value 0.7 can be adjusted by the user, based on the expected changes in Inflow.

Projections are that by 2050 India will have a population of 1.64 billion, while in 2020 this is 1.38 billion. So an increase of 19% by 2050. The Interp (Interpolation) function of WEAP has been used. As discussed earlier the years 1991-2020 are assumed to be constant in terms of population.

```
Interp(1991, 1, 2021, 1, 2050, 1.19)
```

6.3 Reservoirs

Tehri:
Capacity: 3540 MCM

Koteshwar
Capacity: 35 MCM (live storage)

6.4 Potential Improvements

Reservoirs:

- Better assessment of reservoir rainfall and ET
- Operational Rules

Interventions

- Priorities