HYDROLOGY OF THE UPPER GANGA RIVER

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Introduction

The Ganga River Basin covers 981,371 km^2 shared by India, Nepal, China (Tibet) and Bangladesh. The River originates in Uttar Pradesh, India from the Gangrotri glacier, and has many tributaries including the Mahakali, Gandak, Kosi and Karnali which originate in Nepal and Tibet. The focus of the present study is on the Upper Ganga - the main upper main branch of the River. The UpperGanga Basin (UGB) was delineated by using the 90m SRTM digital elevation map with Kanpur barrage as the outlet point (Figure 1). The total area of the UGB is 87,787 km^2. The elevation in the UGB ranges from 7500 m at upper mountain region to 100 m in the lower plains. Some mountain peaks in the headwater reaches are permanently covered with snow. Annual average rainfall in the UGB is in the range of 550-2500mm. A major part of the rains is due to the south-western monsoon from July to October.

The main river channel is highly regulated with dams, barrages and corresponding canal systems (Figure 1). The two main dams are Tehri and Ramganga. There are three main canal systems. The Upper Ganga G Canal takes off from the right flank of the Bhimgoda barrage with a head discharge of 190 m^3/s, and presently, the gross command area is about 2 mill ha. The Madhya Ganga canal takes off from the Ganga at Raoli barrage near Bijnor and provides annual irrigation to 178,000 ha. The Lower Ganga canal comprises a weir across the Ganga at Naraura and irrigates 0.5 million ha.

To provide the background hydrological information for the assessment of environmental flow requirements at four selected 'Environmental Flow' (EF) sites, a hydrological model was set up to simulate the catchment in the present state (with water regulation infrastructure) and to generate the natural flows (without water regulation infrastructure). The report further summarizes the hydrological information at these sites using a series of graphs which illustrate annual runoff variability, seasonal flow distribution, 1-day flow duration curves and daily flow hydrographs for one wet and one dry year. The document also contains a table, which lists some typical flow characteristics at EF sites on a month-by-month basis: range of expected baseflow discharges, number, magnitude and duration of flood events.

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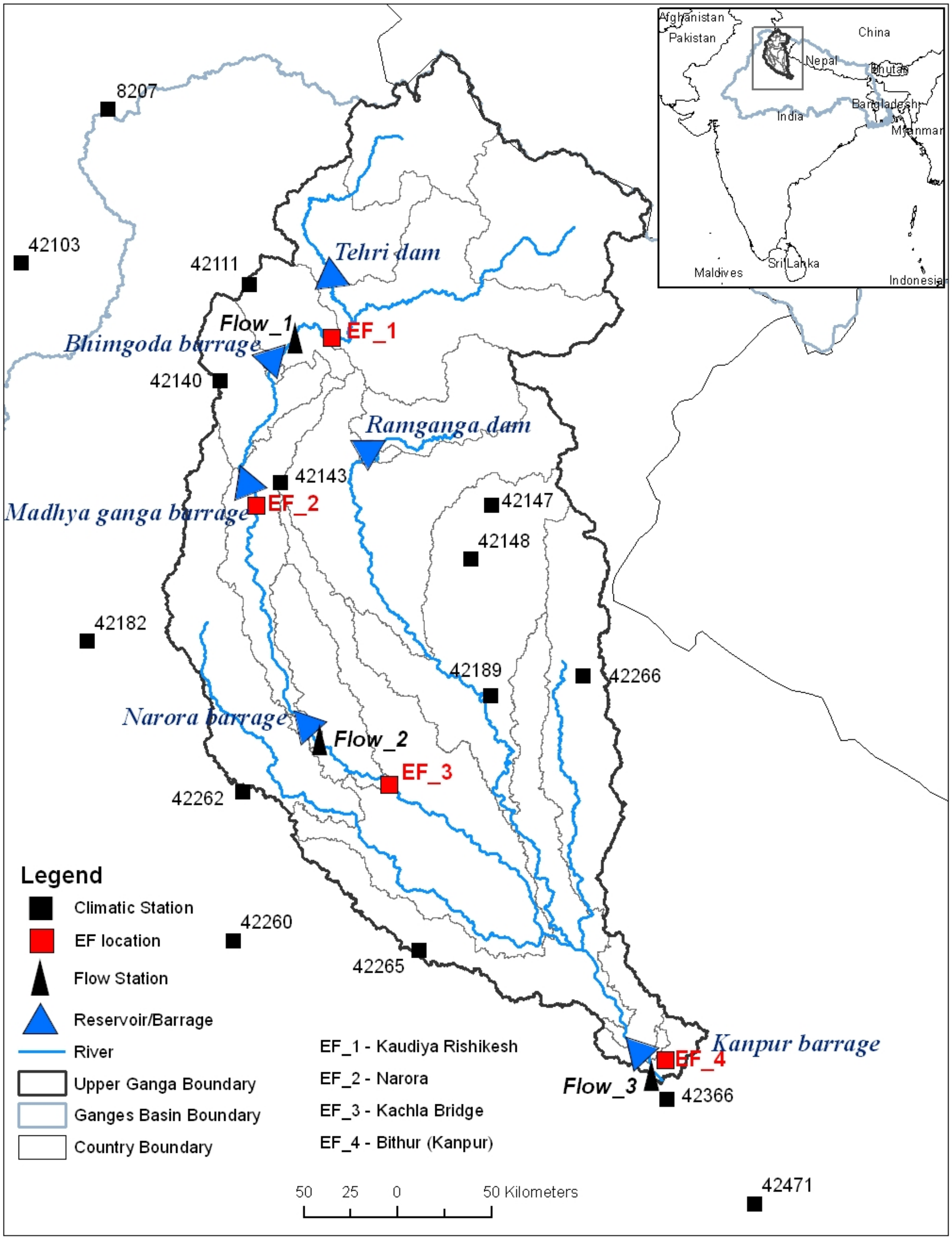


Figure 1: A map of the Upper Ganga River catchment showing the boundaries of the UGB, location of the barrages, reservoirs, EF sites and observed data points used in the study

Description of the Soil and Water Assessment tool (SWAT)

SWAT is a process-based continuous hydrological model that predicts the impact of land management practices on water, sediment and agricultural chemical yields in complex basins with varying soils, land use and management conditions (Arnold et al., 1998; Srinivasan et al., 1998). The main components of the model include: climate, hydrology, erosion, soil temperature, plant growth, nutrients, pesticides, land management, channel and reservoir routing.

Conceptually SWAT divides a basin into sub-basins. . Each sub-basin is connected through a stream channel and further divided in to Hydrologic Response Unit (HRU). HRU is a unique combination of a soil and a vegetation type in a sub watershed, and SWAT simulates hydrology, vegetation growth, and management practices at the HRU level. Following paragraphs describe the model functionality with respect to individual component of the hydrological cycle.

The hydrologic cycle as simulated by SWAT is based on the water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{n} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad (1)$$

Where,

SW_t	:	Final soil water content (mm)
SW_o	:	Initial soil water content (mm)
t	:	Time in days
R_{day}	:	Amount of precipitation on day i(mm)
Q_{surf}	:	Amount of surface runoff on day i (mm)
E_a	:	Amount of evapotranspiration on day i (mm)
w_{seep}	:	Amount of percolation on day i (mm)
Q_{gw}	:	Amount of return flow on day i (mm)

Since the model maintains a continuous water balance, the subdivision of the basin enables the model to reflect differences in evapotranspiration for various crops and soils. Thus runoff is predicted separately for each sub-basin and routed to obtain the total runoff for the basin. This increases the accuracy and gives a much better physical description of the water balance. More detailed descriptions of the model can be found in Arnold et al. (1998) and Srinivasan et al. (1998).

Model Setup

SWAT requires three basic files for delineating the basin into o sub-basins and HRUs: Digital Elevation Model (DEM), Soil map and Land Use/Land Cover (LULC) map. Figure 2 shows the DEM for the basin using 90m Shuttle Radar Topography Mission (SRTM) data. Figure 3 shows the land use map which was developed using the LandSat TM image from 2003. Around 65% of the basin is occupied by agriculture. The main crop types are wheat, maize, rice, sugarcane, bajra and potato. Around 25% of the land is covered by forests and mostly appears in the upper mountains. Figure 4 shows the soil map for the basin. There are eight soil types; Lithosols dominate the upper, steep mountainous areas and are very shallow and erodible soils. Cambisols and Luvisols are found in the lower areas. Cambisols are developed in medium and fine textured material derived from alluvial, colluvial and aeolian deposits. Most of these soils make good agricultural land. Luvisols are tropical soils most used by farmers because of its ease of cultivation but they are greatly affected by water erosion and loss in fertility.

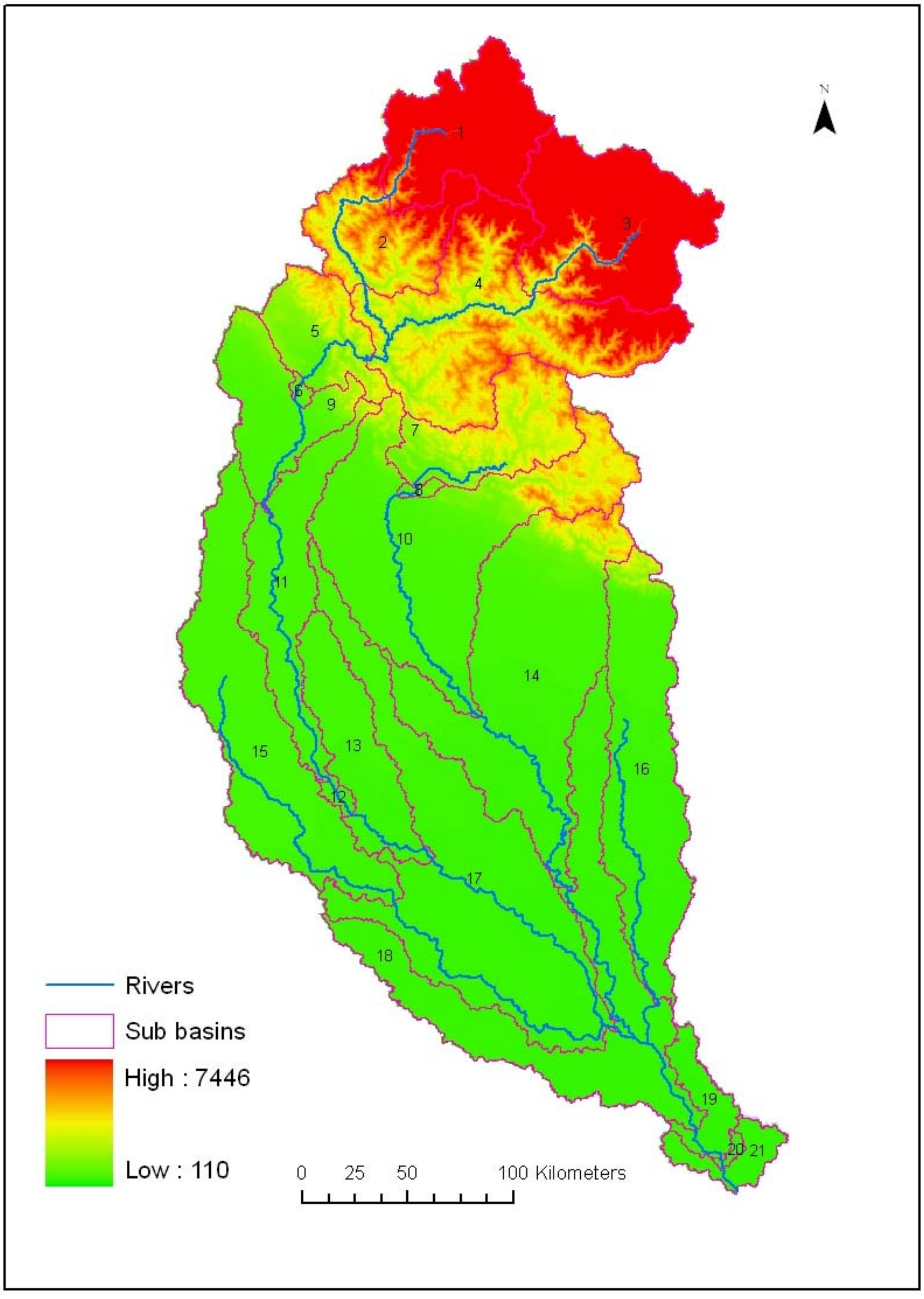


Figure 2: Digital Elevation model of the UGB with numbers and boundaries of sub-catchments used in hydrological simulations

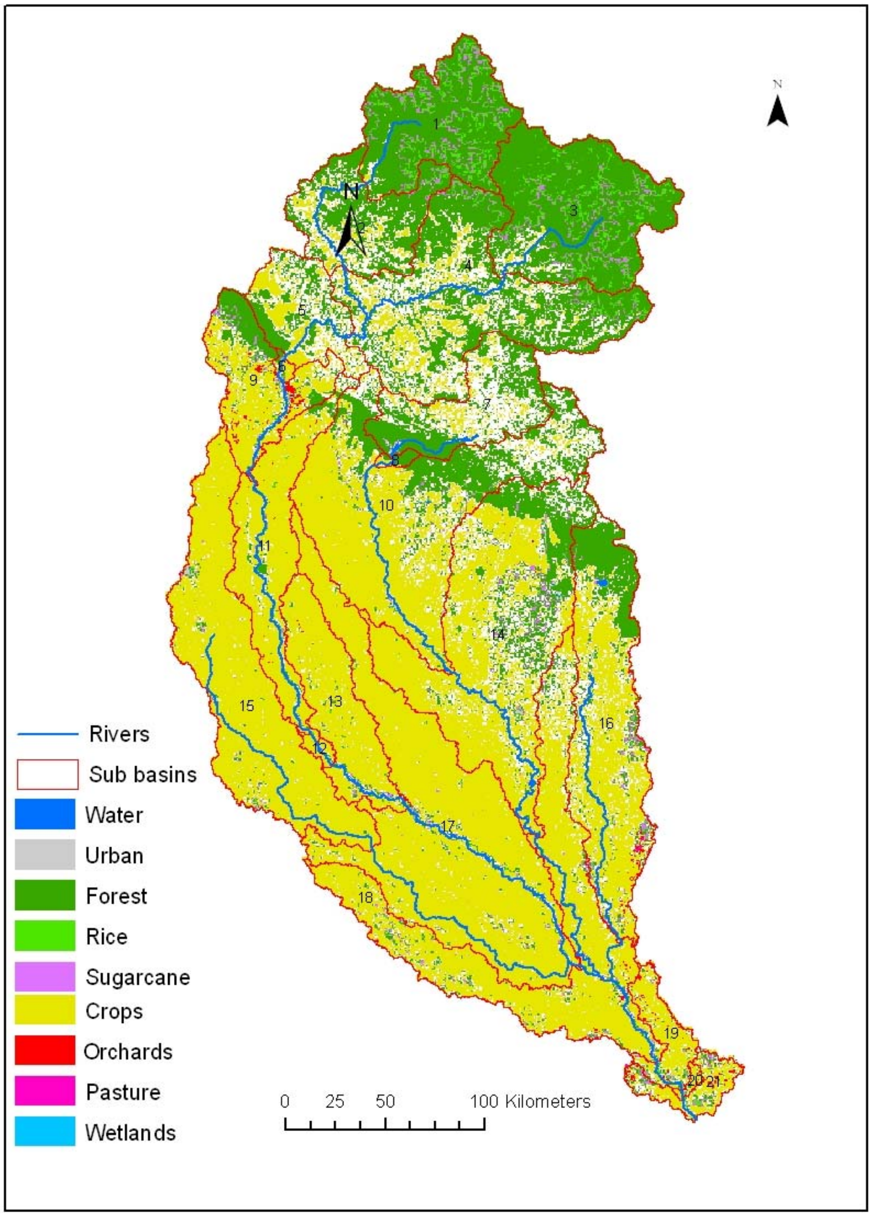


Figure 3: Land use map (2003) of UGB

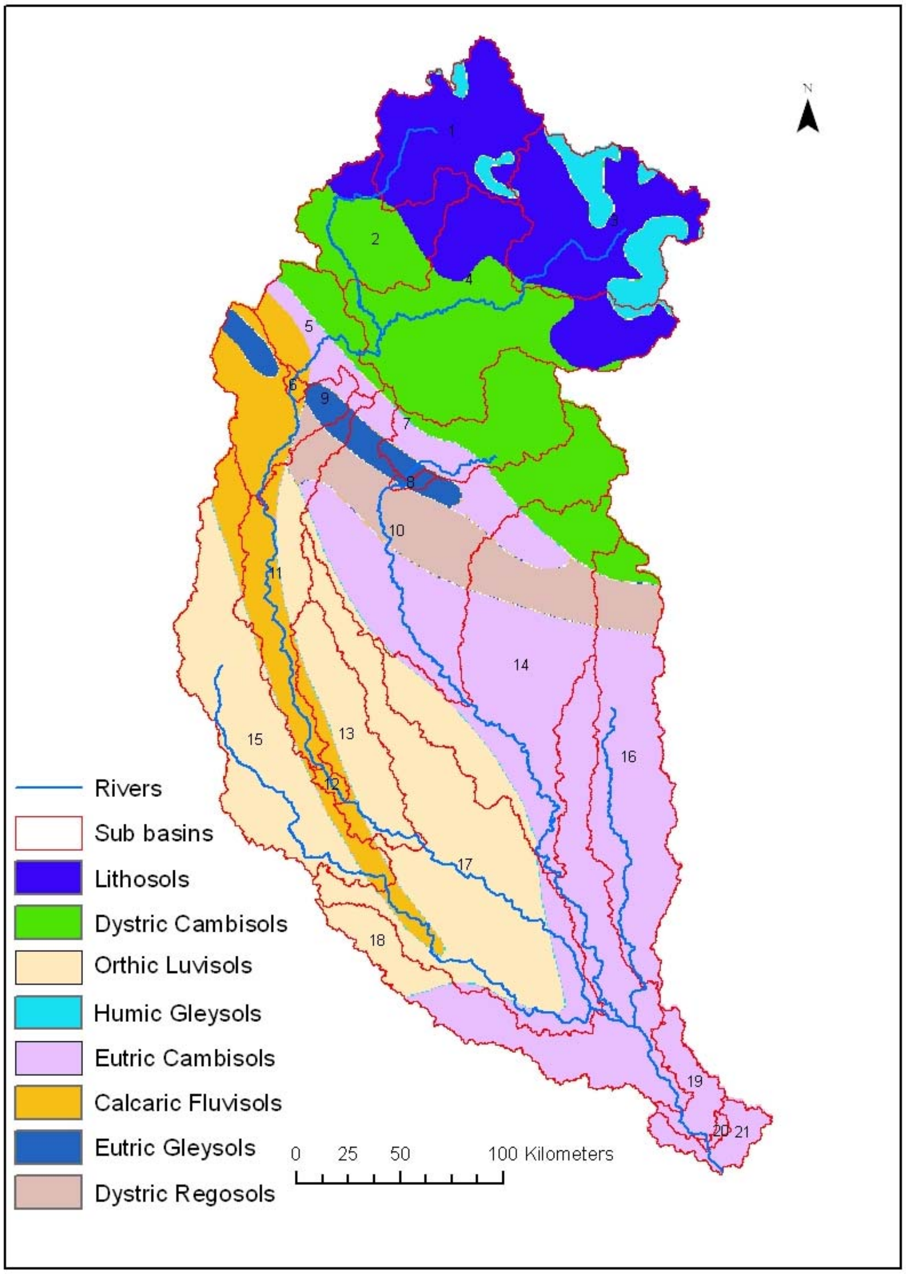


Figure 4: Soil map of the UGB based on FAO data

Available observed time series data

SWAT requires time series of observed climate data i.e. rainfall, minimum and maximum temperature, sunshine duration, wind speed and relative humidity. Table 1 lists the climate stations used for simulations and the location of stations can be seen in Figure 1. Data from the climate stations are spatially interpolated by the model to produce a gridded map of climate input. The upper parts of the basin are mountainous with peaks and valleys therefore, the interpolated climate data may not be able to capture micro-climate variability, typical of mountainous regions. Furthermore, there are no climate stations in the Northwest part of the basin where there are high mountains. Therefore, the rainfall may be overestimated due to interpolation from stations in lower elevations with higher rainfall values. Contribution of glacier melt was not considered in the modeling due to a lack of glacier melt data.

Table 1: Details of the data at meteorological stations in the UGB

Station Code	Location	Available Record	Available Data Type
42111	Dehradun*	1970-2005	Rainfall, Minimum and Maximum temperature, Sunshine duration, Wind Speed, Relative Humidity
42103	Ambala*	1970-2004	Rainfall, Minimum and Maximum temperature, Sunshine duration, Wind Speed, Relative Humidity
8207	Simla*	1989-2005	Rainfall, Minimum and Maximum temperature, Sunshine duration, Wind Speed, Relative Humidity
42140	Roorkee*	1970-1994; 2002-2005	Rainfall, Minimum and Maximum temperature, Sunshine duration, Wind Speed, Relative Humidity
42182	Delhi*	1970-2005	Rainfall, Minimum and Maximum temperature, Sunshine duration, Wind Speed, Relative Humidity
42366	Kanpur	1970-1974, 1986-1995	Rainfall and Temperature only
42471	Fatehpur	1970-2005	Rainfall and Temperature only
42189	Bareilly*	1970-2005	Rainfall, Minimum and Maximum temperature, Sunshine duration, Wind Speed, Relative Humidity
42260	Agra	1970-2005	Rainfall and Temperature only
42262	Aligarh	1970-2005	Rainfall and Temperature only
42143	Najibad*	1970-2005	Rainfall, Minimum and Maximum temperature, Sunshine duration, Wind Speed, Relative Humidity
42147	Mukteshwar*	1970-2005	Rainfall, Minimum and Maximum temperature, Sunshine duration, Wind Speed, Relative Humidity
42148	Pant Nagar*	1970-2005	Rainfall, Minimum and Maximum temperature, Sunshine duration, Wind Speed, Relative Humidity
42265	Mainpuri	1970-2005	Rainfall, Temperature and Wind Speed only
42665	Shajapur	1970-2005	Rainfall, Temperature and Wind Speed only

**Significant missing values*

Table 2 presents details of the flow stations used for calibration and validation of the model. Their locations are shown in Figure 1. Due to the restrictions on Ganga data from the Central Water Commission (CWC), only a very short time series of data at some barrages were available. The observed flow data except for one site (Narora) are monthly time series, while the model works with daily time step. Simulated daily flow values therefore, have to be accumulated into monthly for comparison. This created additional uncertainty. Also, the quality of the observed data could not be ascertained. Therefore the model was set up and calibrated in the conditions of extreme lack of reliable observations. The use of data from additional flow gauging stations would have greatly increased the reliability of the model simulations. The existing dams, barrages and irrigation deliveries were incorporated in the model.

Table 2: Details of the flow stations and data available for calibration of the model

Station code	Location	Catchment Area, km2	Available Record	Type of data	Gauged MAR as % of natural
Flow_1	Bhimgoda	23,080	2002April-2005 December	Monthly inflow to the Barrage	59
Flow_2	Narora	29,840	2000 Jan -2005 June	Monthly spill release from the dam	57
Flow_3	Kanpur	87,790	2002 June – 2005 December	Monthly Spill release from the dam excluding dry season flows	77

SWAT Model Calibration and Validation

Table 3 presents the calibration and validation period considered for the model simulation according to available observed flow data at the three flow sites. The period from 1st Jan 1970 to beginning of calibration period is considered as a warn-up period for simulation. Model parameters were calibrated simultaneous for the all three flow stations. The model was calibrated in present water use condition of the basin.

Table 3: Calibration and validation period at flow sites for model simulation

Station code	Location	Calibration Period	Validation Period
Flow_1	Bhimgoda	1st Apr 2002 – 31st Dec 2003	1st Jan 2004 – 31 Dec 2005
Flow_2	Narora	1st Jan 2000 – 31st Dec 2002	1st Jan 2003 – 30 Jun 2005
Flow_3	Kanpur	1st Jun 2003 – 31st Oct 2003 1st Jun 2004 – 31st Oct 2004	1st Jun 2005 – 31 Dec 2005

The model performance was determined by calculating coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE). The calculated statistics R^2 are NSE in each simulation are presented in the Table 4. The model performance was within an acceptable range according to model performance statistics (*Liu et al., 2004*) in both the calibration and validation periods.

Table 4: Model performance statistics at flow sites for the simulation

Station code	Model Efficiencies	Calibration Period		Validation Period	
		Statistic	Performance Result	Statistic	Performance Result
Flow_1	R^2	0.84	(0.65 – 0.85) Very Good	0.89	(> 0.85) Excellent
	NSE	0.61	(0.50 – 0.65) Good	0.81	(0.65 – 0.85) Very Good
Flow_2	R^2	0.83	(0.65 – 0.85) Very Good	0.83	(0.65 – 0.85) Very Good
	NSE	0.82	(0.65 – 0.85) Very Good	0.80	(0.65 – 0.85) Very Good
Flow_3	R^2	0.67	(0.65 – 0.85) Very Good	0.90	(> 0.85) Excellent
	NSE	0.69	(0.65 – 0.85) Very Good	0.95	(> 0.85) Excellent

In addition, annual water flow volume balance was also checked to get perfectness in calibration and the results were presented in Table 5. The flow volume balance shows higher flow difference between observed and simulated results in flow site at Bhomgoda than the other downstream flow sites. The flow site at Kanpur is the outlet of this study basin and where water flow difference is below than 10%. This also shows that the model was performing quite well in terms of water flow volume.

Table 5: Annual water flow volume at flow sites for the simulation

Station code	Calibration Period			Validation Period		
	Observed	Simulated	Difference	Observed	Simulated	Difference
Flow_1	1152 mm	1524 mm	32.3%	1017 mm	1269 mm	24.8%
Flow_2	905 mm	1086 mm	20.0%	697 mm	790 mm	13.4%
Flow_3	756 mm	826 mm	9.3%	622 mm	624 mm	0.3%

In average, the results of both evaluations; performance statics and water flow volume balance; show that the model was performed better in validation periods than in calibration in all flow sites. In overall, the model result was little bit overestimation than the observation.

Figure 5, Figure 7 and Figure 9 show observed and simulated discharges for the inflow into the Bhimgoda barrage, the outflow from Narora barrage and outflow from Kanpur barrage. Figure 6, Figure 8 and Figure 10 show observed and simulated cumulative water volume plot for the inflow into the Bhimgoda barrage, the outflow from Narora barrage and outflow from Kanpur barrage.

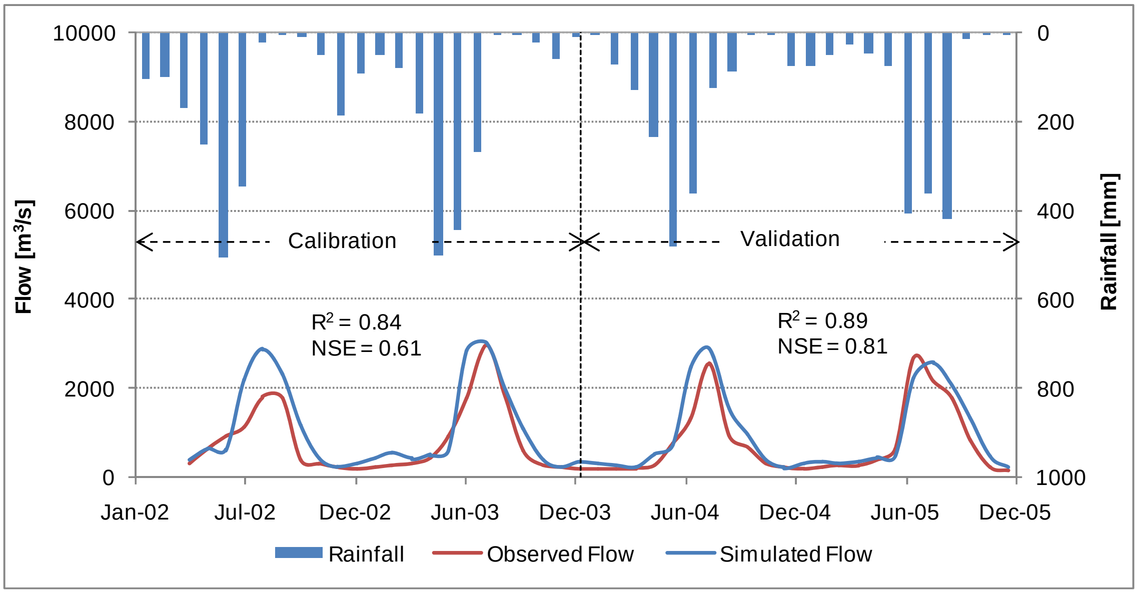


Figure 5: Observed and simulated flows at the Bhimgoda barrage

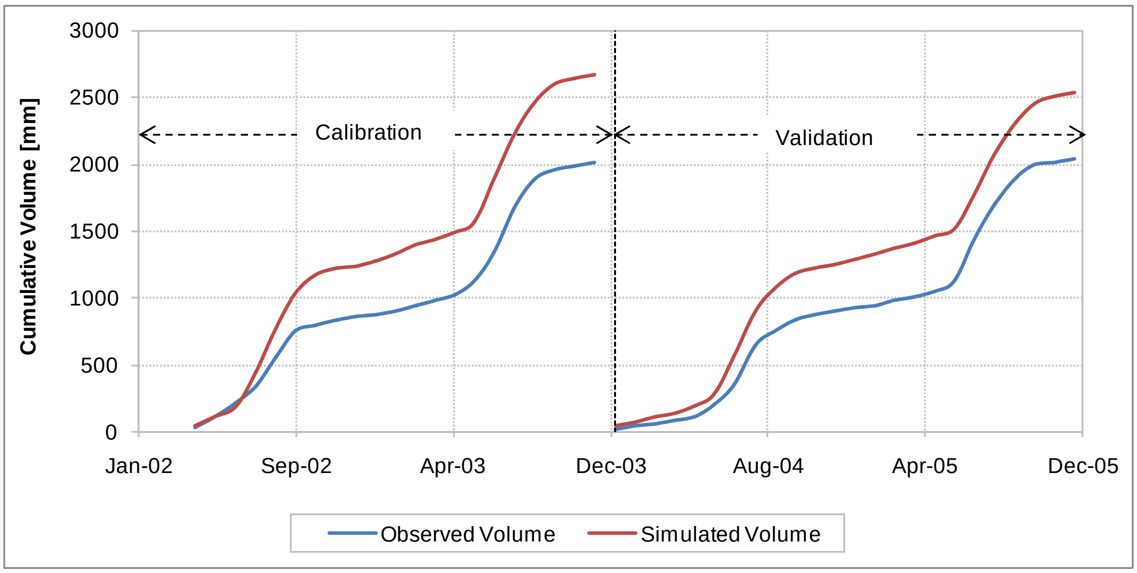


Figure 6: Observed and simulated cumulative flow volume at the Bhimgoda barrage

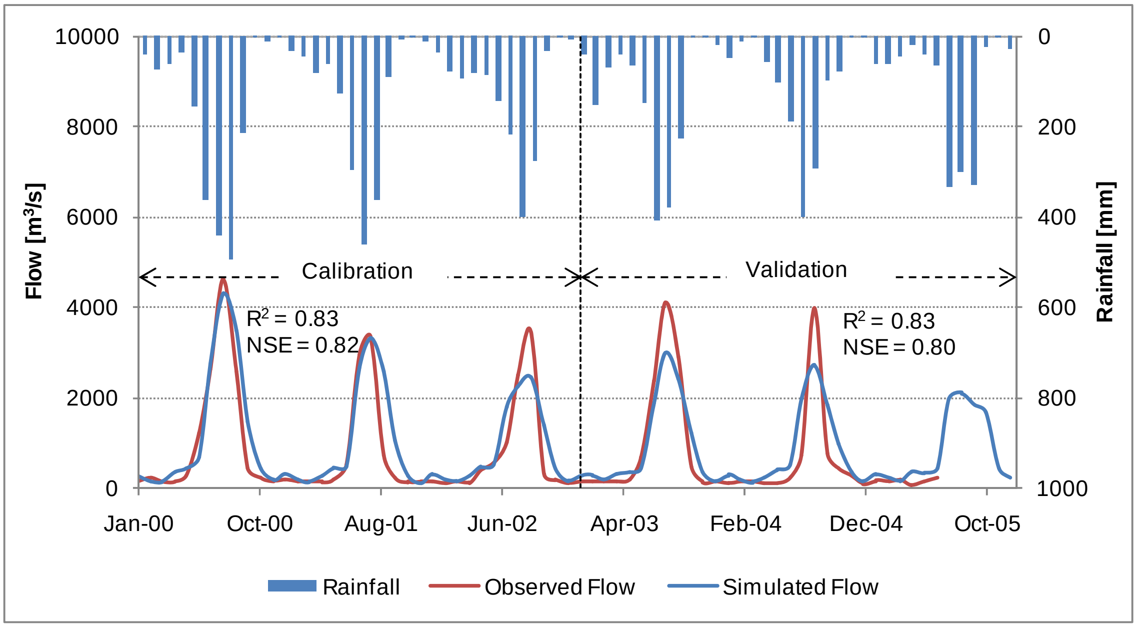


Figure 7: Observed and simulated flows at the Narora barrage

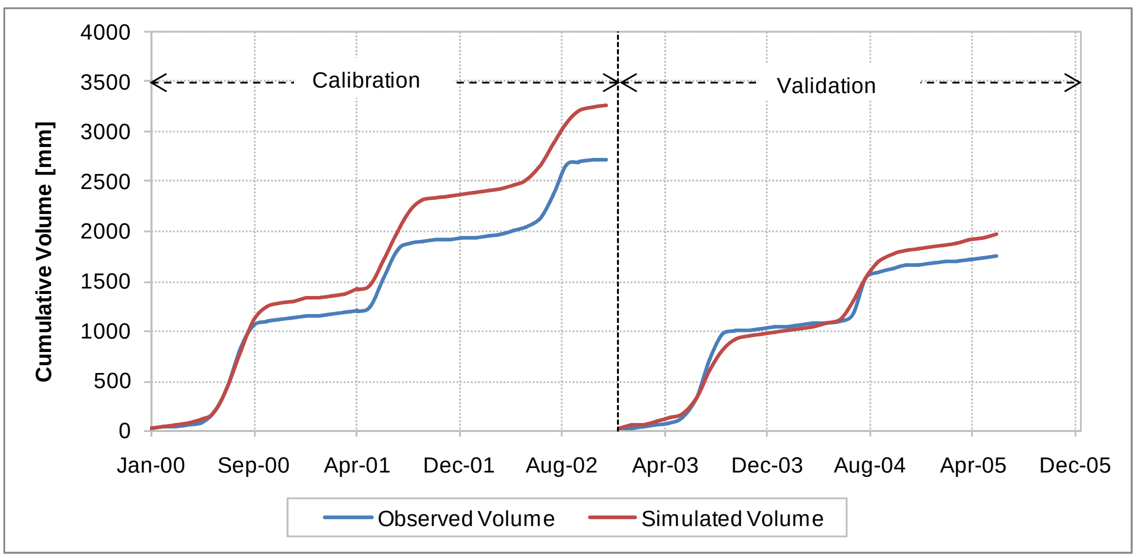


Figure 8: Observed and simulated cumulative flow volume at the Narora barrage

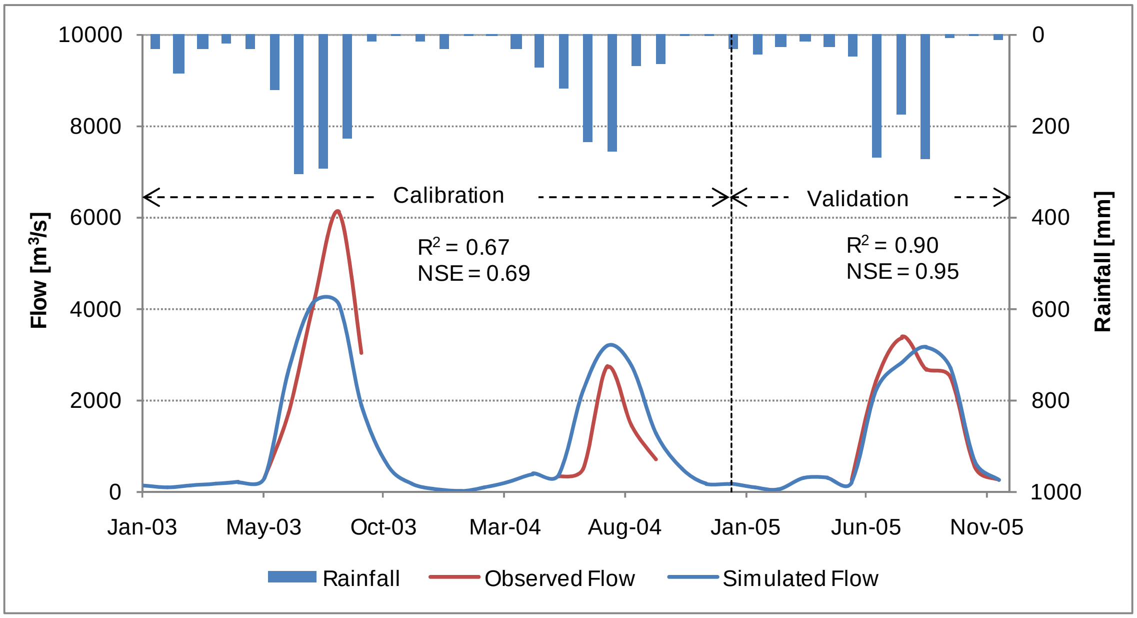


Figure 9: Observed and simulated flows at the Kanpur barrage

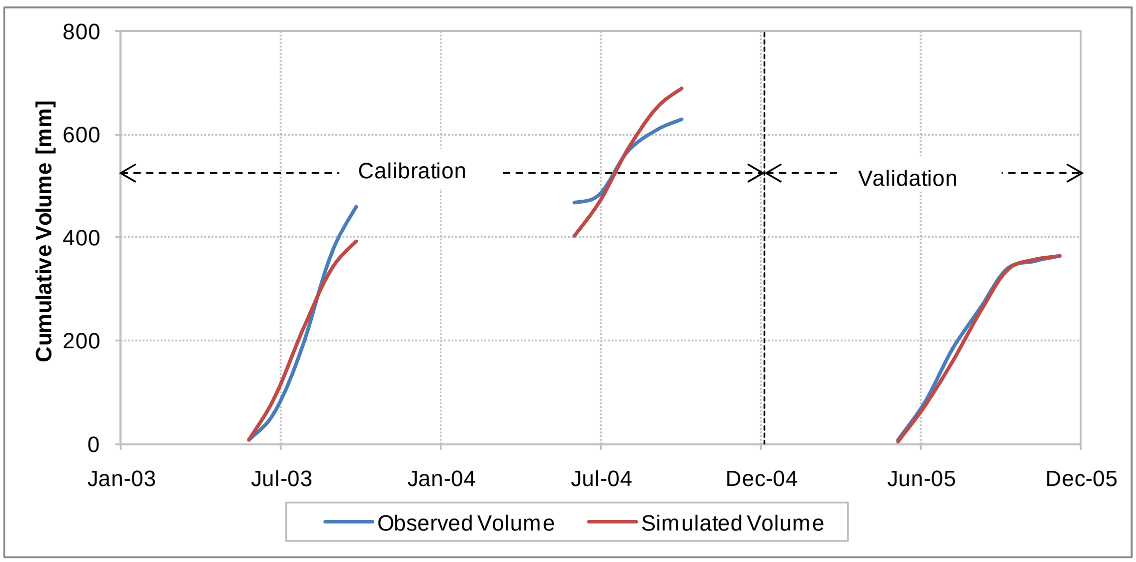


Figure 10: Observed and simulated cumulative flow volume at the Kanpur barrage

Simulation of natural flow conditions for the four EF sites

The names and locations of the EF sites that are used in this study are listed in Table 6 and shown in Figure 1, with Google Earth images of their environments – in Figure 11. The selected EFR sites are representative of the different agro-ecological zones in the study river stretch.

Table 6: Location and names of EF sites in the UGB

Site code	Site Name	Latitude	Longitude
EF1	Kaudiyala (Rishikesh)	30°04’29” N	78°30’09” E

EF2	Narora	29°22'22” N	78°2'20” E
EF3	Kachla Bridge	27°55’59” N	78°51’42” E
EF4	Bithur (Kanpur)	26°36'59” N	80°16'29” E

Figure 11: EF site locations - Google Earth images

The calibrated model was run for the period of 1970 to 2005 (36 years) and two scenarios were considered:

- Present-day scenario- representing the most recent condition of the basin (as if these conditions existed during the entire simulation period of 36 years and
- Natural conditions scenario which represent minimal human intervention in the basin i.e. without dams and irrigation infrastructure.

In addition to presence/ absence of the water infrastructure, land use also varied between the present day and natural conditions. Irrigated crops such as rice, wheat, corn, bajra, sugarcane, potato represent the major crops types during present conditions. Natural conditions' scenario is characterized by rainfed crops such as mung bean and wheat, as well as a larger area covered in natural forest. Parameters of the model were changed accordingly to reflect the difference between scenarios in the model.

Simulated daily flow data were then summed up at monthly and annual time steps and are presented in the tables and figures below. The simulated data are also used to illustrate the characteristic features of each EF site's flow regime. The following characteristics of the flow regime are presented in graphic form in Figures below:

- plots of annual streamflow volumes as a time series for available period
- averaged seasonal distribution of monthly flow volumes;
- annual 1-day flow duration curves;
- daily hydrographs for one wet and one dry year

Plots of annual streamflow totals allow wet, dry and intermediate years to be quickly identified. Averaged seasonal flow distributions illustrate the mean flows, which may be expected in each calendar month and help to identify the wettest, driest and intermediate months. Flow duration curve is an aggregated way to illustrate the variability of daily flows and the range of flows experienced (in this case – in natural flow conditions). Daily hydrographs illustrate the variability of flows in specific years of different wetness.

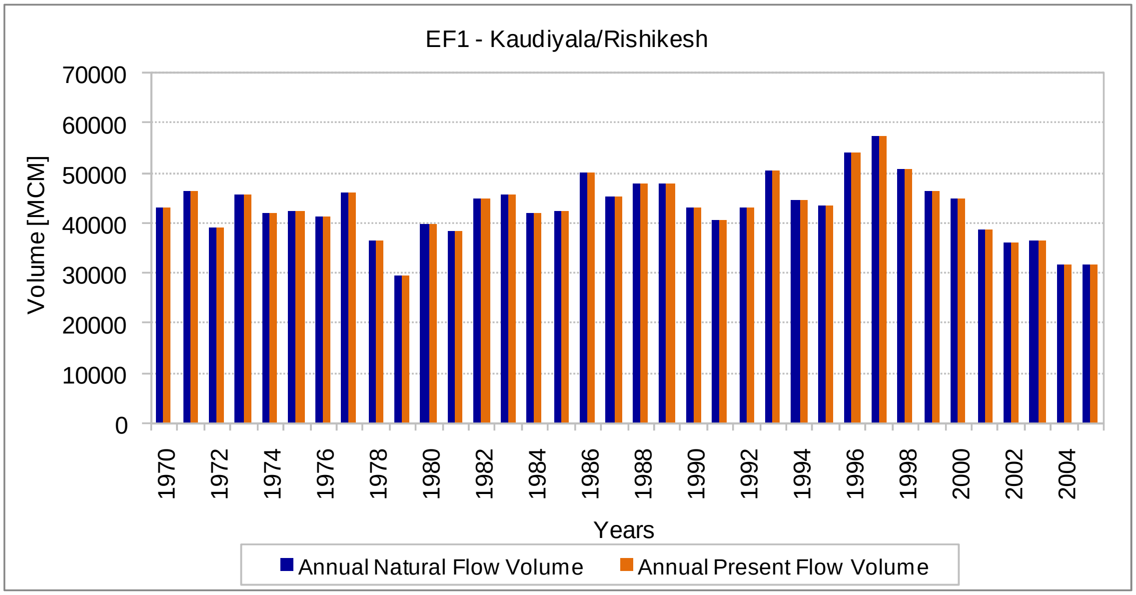
Table 7 contains the details of some typical flow sequences at the EFR sites for each calendar month including the range of baseflows, magnitude, number and duration of floods. This information was obtained from visual inspection of the simulated time series for each EF site. The 'baseflow range' was estimated as the range of the density of low-flow parts of the hydrograph in each month. When the number of floods in the table is specified as << 1 it implies that in 36 years of record only a few (less than 10) events have been identified in this month. In cases when this value is "< 1 ", the floods in this month occur more frequently, but their total count is less than 30 (e.g. 20-30) in 36 years. If the number of floods is specified as "0", it implies that none or only a few insignificant events in this month were simulated. In monsoonal months it is difficult to separate events from each other and the approach was – to rather identify these events over the entire wet period. Such cases are at two downstream sites (Table 7). In such case, the range of event numbers is given, which is normally 1-2, implying that there is 1 or 2 large events often spanning through the wet months.

Table 7: Typical flow characteristics for EF sites (natural conditions), where flows are in m^3/s and durations are in days.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
EF1- Kaudiyala /Rishikesh – area : 20,800 km^2 MAR (nat)**= 43,112 MCM												
Range of Base Flow	238-436	440-579	577-598	429-530	433-670	681-1593	1616-3033	3063-3805	2118-3497	1002-2030	360-925	239-353
No. of Events	*0*	*0*	*0*	*0*	*0*	*<<1*	*1*	*1*	*0*	*0*	*0*	*0*
Range of Peaks	401-609	533-1288	523-1190	444-710	569-1230	1279-11520	2395-8320	2588-12110	1938-6650	1123-3266	517-1222	220-478
Average of Peaks	492	647	660	532	804	2338	4050	5547	3765	2085	943	358
Main Duration	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*6*	*6-7*	*6*	*N/A*	*N/A*	*N/A*	*N/A*
EF2- Narora- area : 26,090 km^2 MAR (nat)= 45,974 MCM												
Range of Base Flow	250-426	430-573	556-586	392-542	396-643	650-1614	1645-3129	3171-4135	2385-4083	1141-2321	367-1107	254-359
No. of Events	*0*	*0*	*0*	*0*	*0*	*<<1*	*<1*	*1*	*0*	*0*	*0*	*0*
Range of Peaks	448-687	578-1154	569-1178	464-804	591-1088	1295-6697	2589-7550	2880-10800	2379-7154	1253-5509	682-1468	240-1040
Average of Peaks	554	663	672	591	744	2133	4047	5620	4483	2487	1122	448
Main Duration	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*8*	*8*	*8-9*	*N/A*	*N/A*	*N/A*	*N/A*
EF3 - Kachla Bridge-area : 30,030 km^2 MAR (nat)= 46,326 MCM												
Range of Base Flow	272-417	429-592	567-590	389-568	386-601	607-1406	1434-2865	2923-4271	2648-4289	1386-2609	440-1344	280-425
No. of Events	*0*	*0*	*0*	*0*	*0*	*1-2**			*0*	*0*	*0*	*0*
Range of Peaks	477-667	522-1057	529-1141	487-947	549-976	1253-2991	2438-6613	2672-8549	2588-7633	1297-3621	714-1885	263-707
Average of Peaks	531	646	674	604	693	1763	3647	5175	4683	2690	1344	455
Main Duration	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*14-30**			*N/A*	*N/A*	*N/A*	*N/A*
EF4 – Bithur/Kanpur – area :86,950 km^2 MAR (nat)= 57,323 MCM												
Range of Base Flow	308-448	452-632	573-690	436-602	428-587	591-1413	1434-3499	3559-5170	3547-5107	1700-3473	554-1655	323-539
No. of Events	*0*	*0*	*0*	*0*	*0*	*1-2**			*0*	*0*	*0*	*0*
Range of Peaks	391-1936	504-6690	555-11550	465-3578	463-1629	1232-2684	2553-7865	3995-11110	3027-14420	1788-5835	925-4231	329-800
Average of Peaks	635	866	1036	719	722	1960	4744	7045	6591	3710	1976	547
Main Duration	*N/A*	*N/A*	*N/A*	*N/A*	*N/A*	*15-30**			*N/A*	*N/A*	*N/A*	*N/A*

**June, July and August are combined together for the sites EF3 and EF4 as it is difficult to estimate some parameters*

*** Mean Natural Annual Runoff*



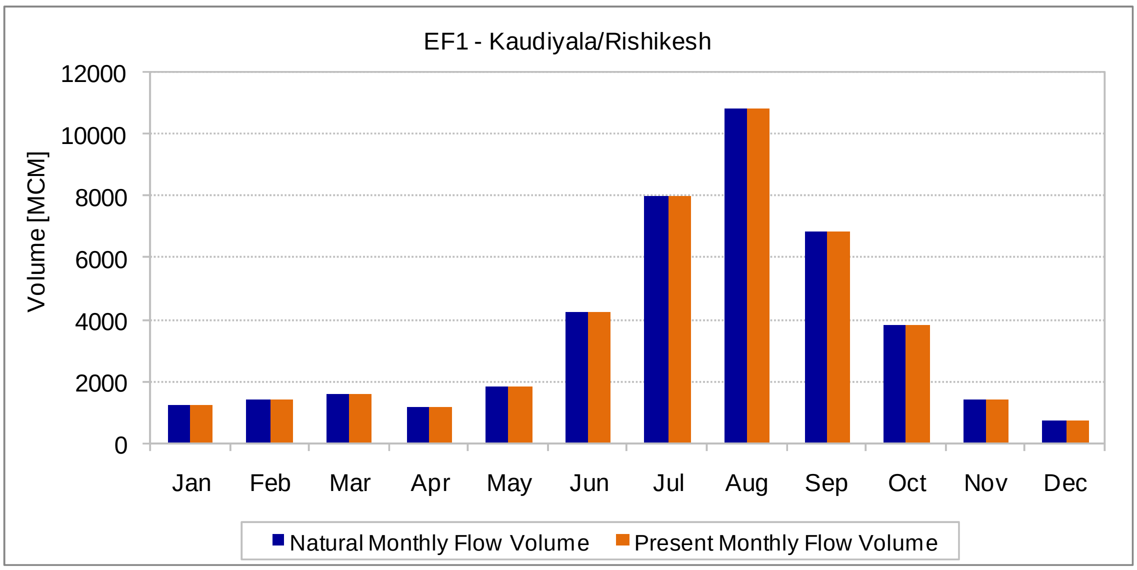
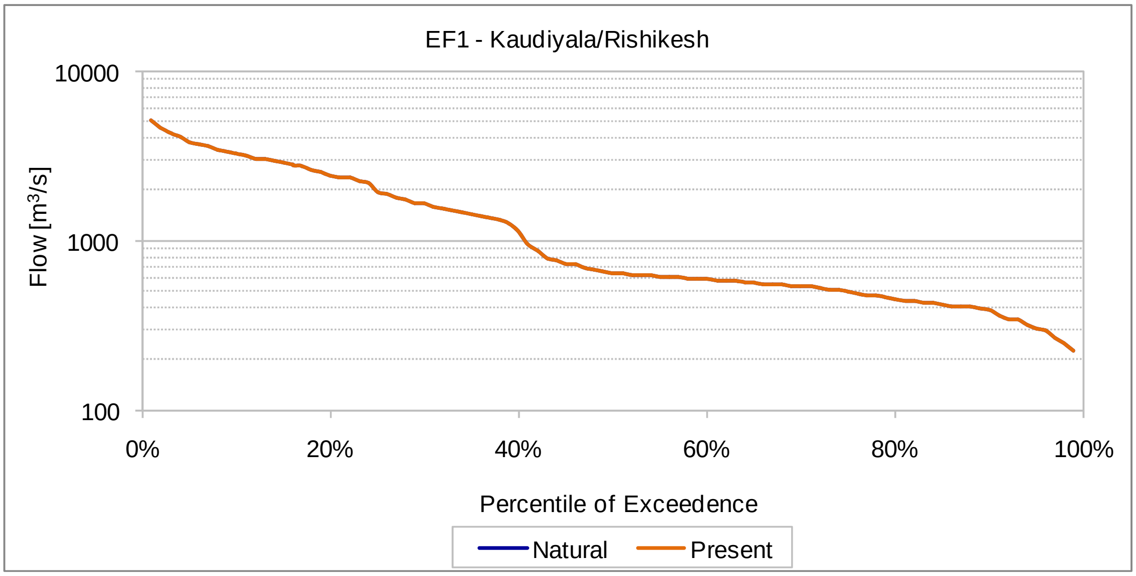


Figure 12: Annual flow totals (top) and average monthly flow distribution (bottom) for Kaudiyala/Rishikesh site



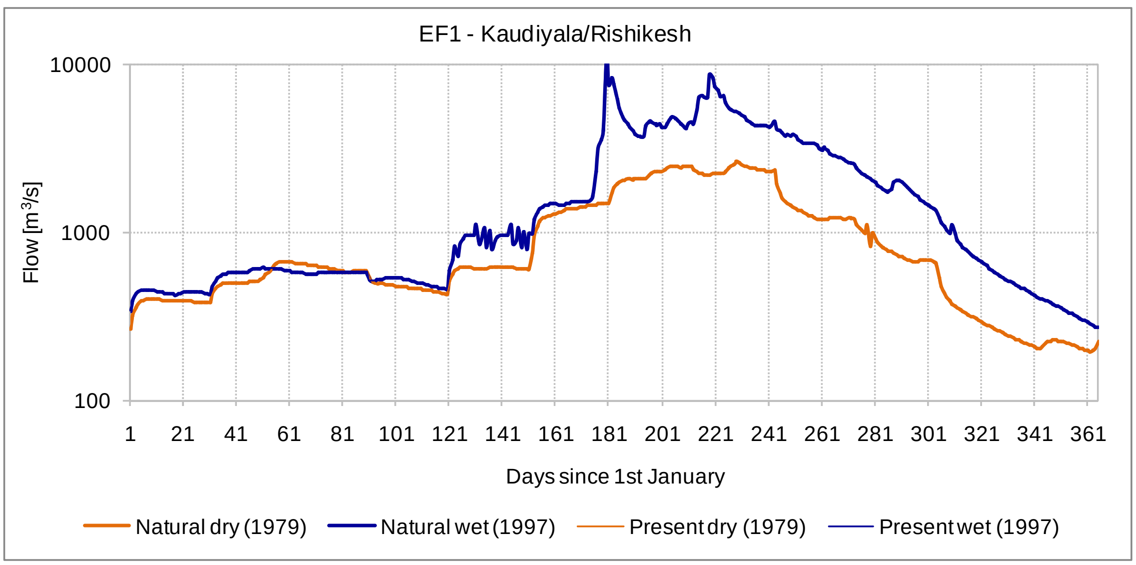
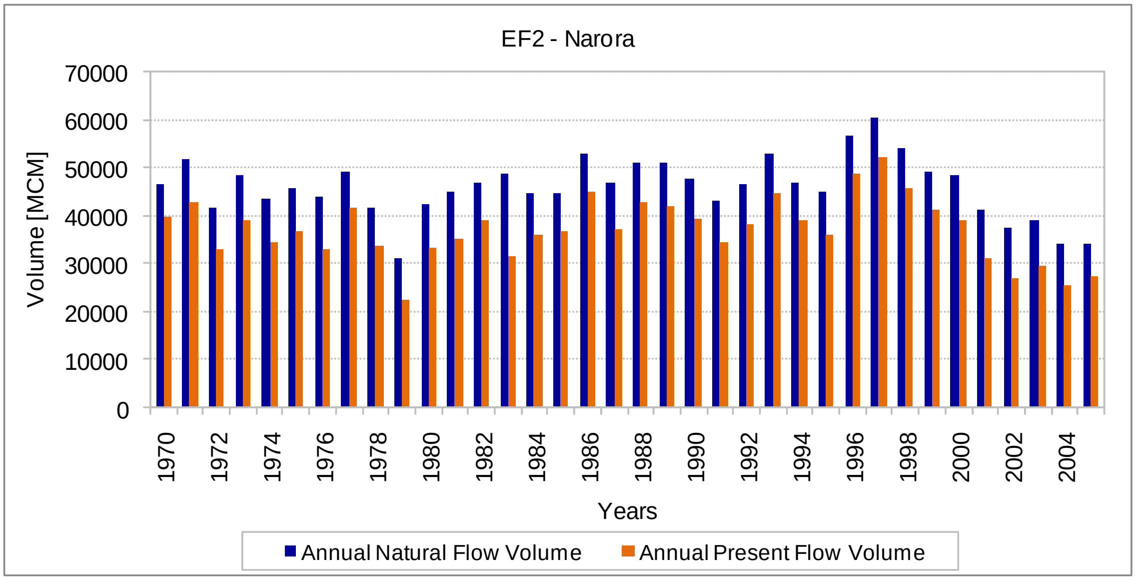


Figure 13: Flow Duration curves (top) and example daily hydrographs (bottom) for Kaudiyala/Rishikesh site



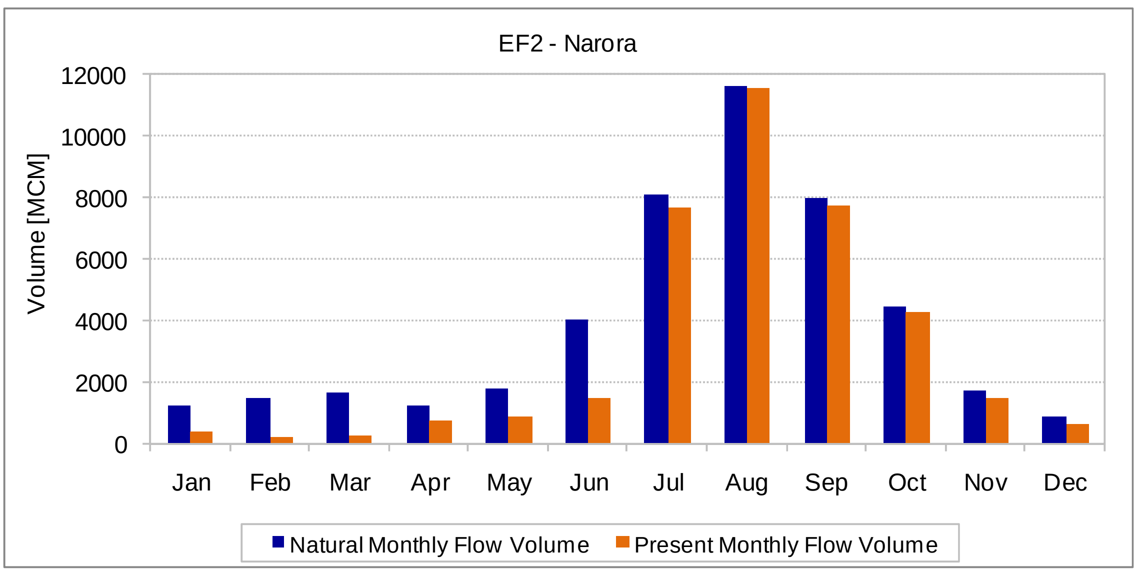
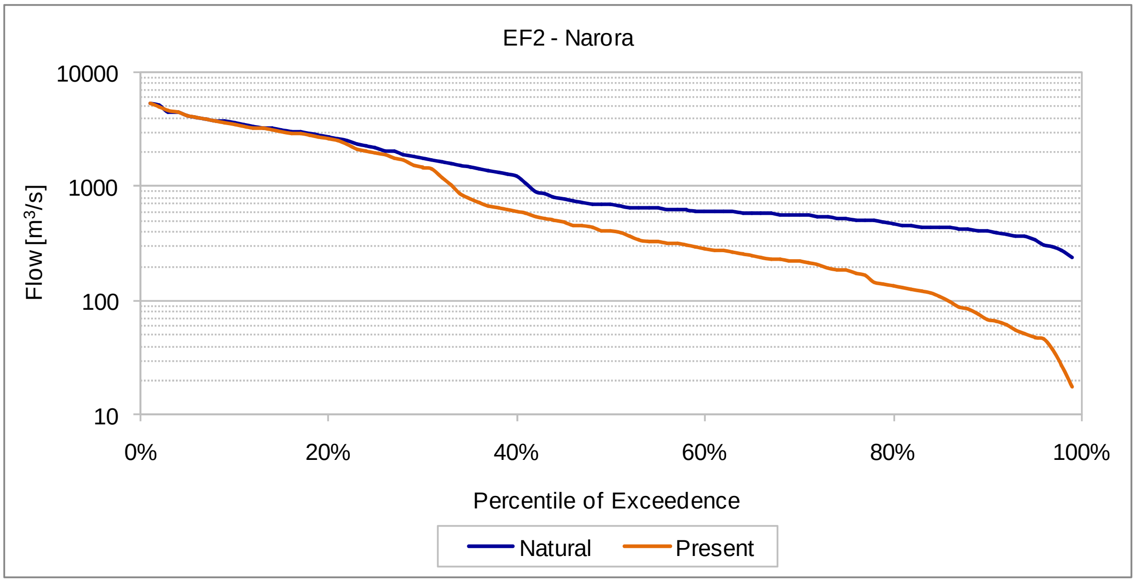


Figure 14: Annual flow totals (top) and average monthly flow distribution (bottom) for Narora



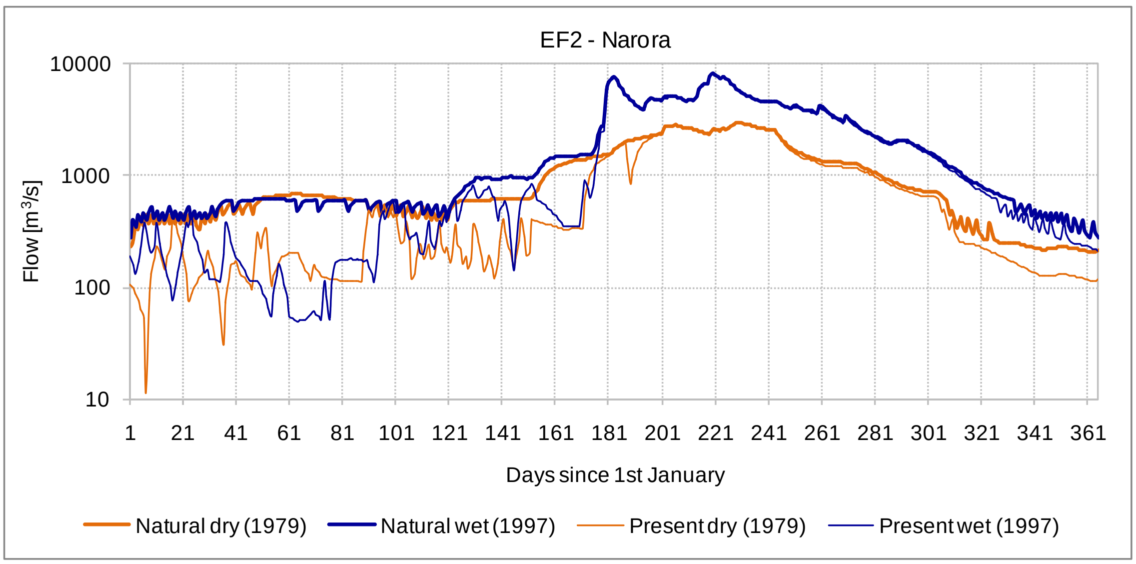
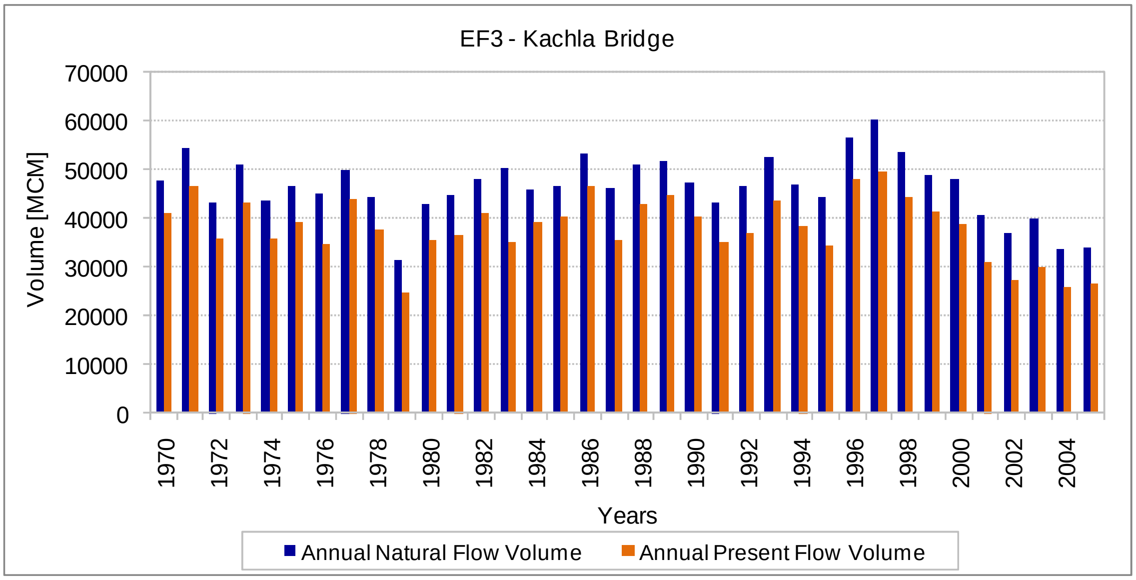


Figure 15: Flow Duration curves (top) and example daily hydrographs (bottom) for Narora



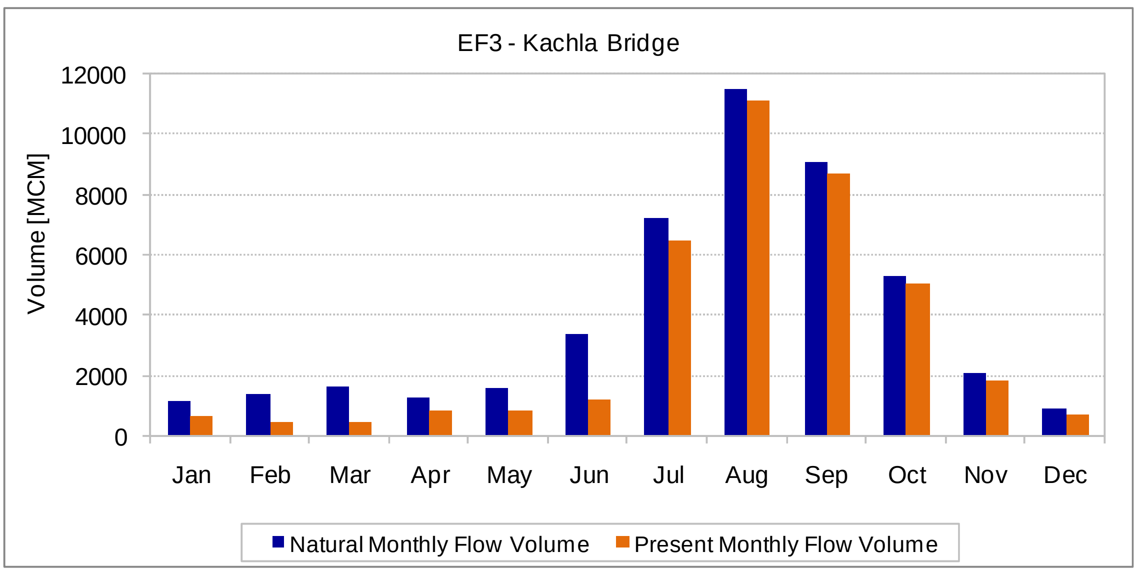
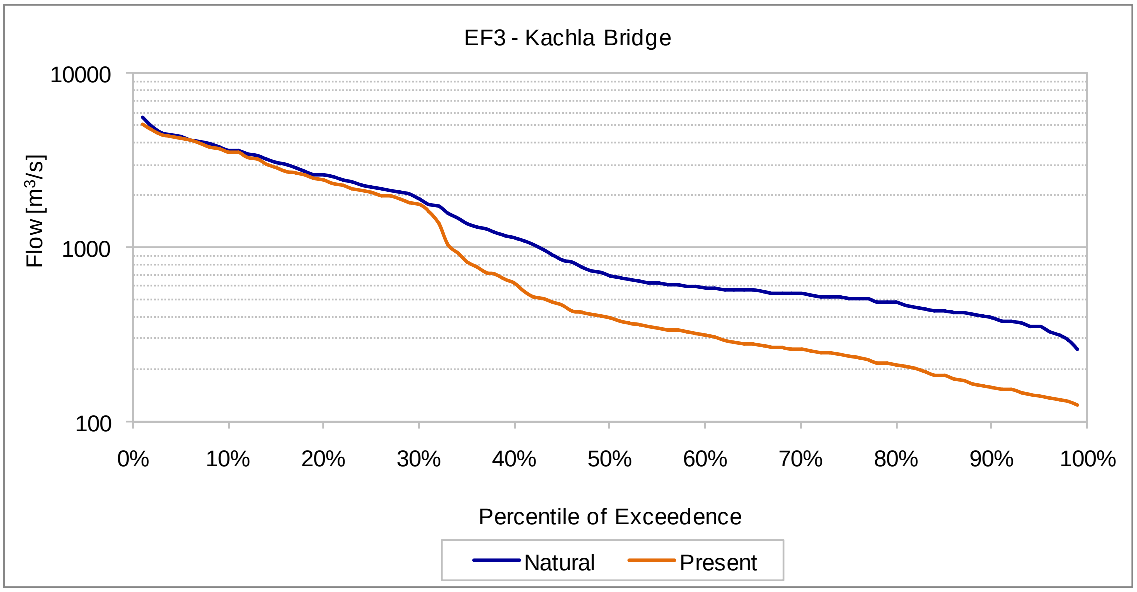


Figure 16: Annual flow totals (top) and average monthly flow distribution (bottom) for Kachla Bridge



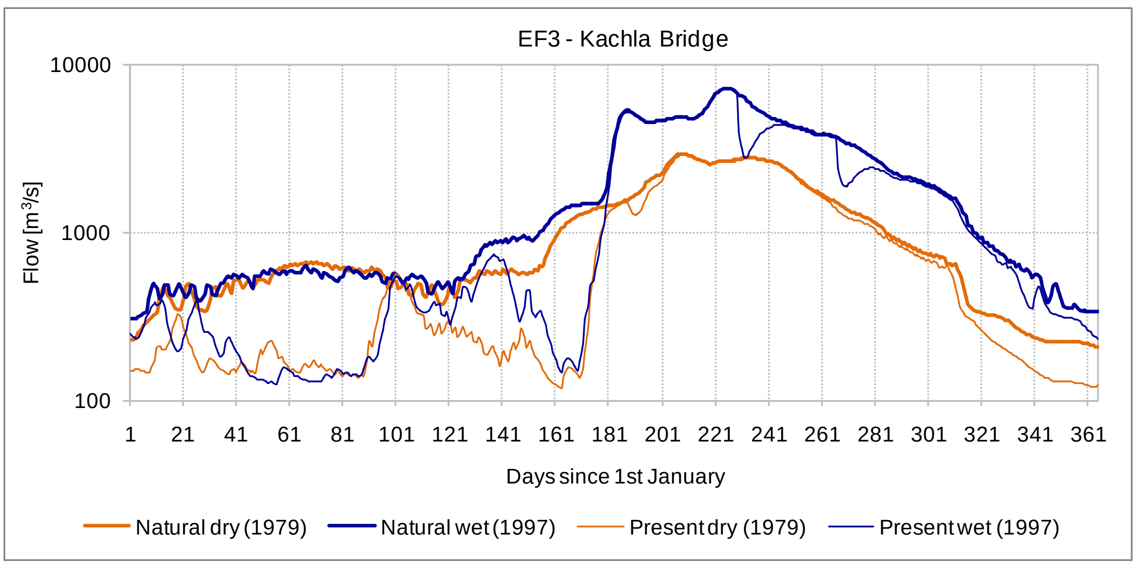
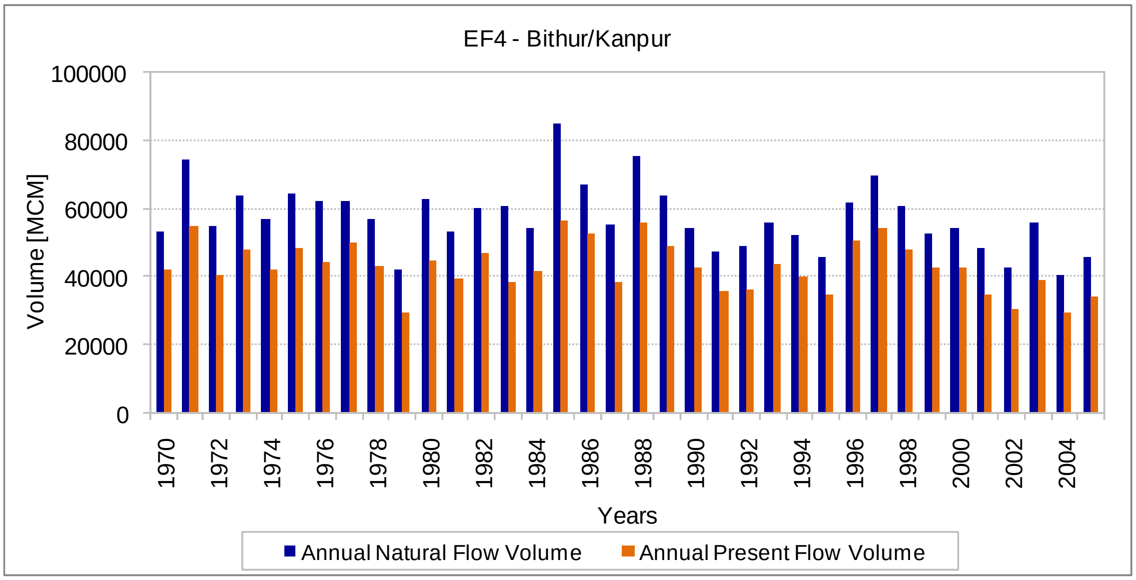


Figure 17: Flow Duration curves (top) and example daily hydrographs (bottom) for Kachla Bridge



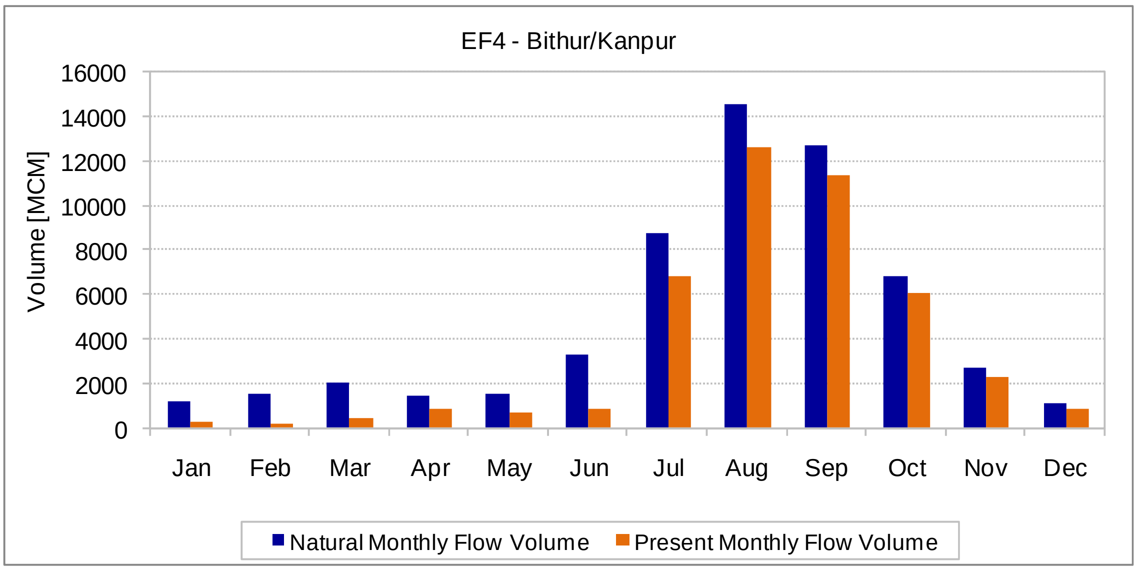
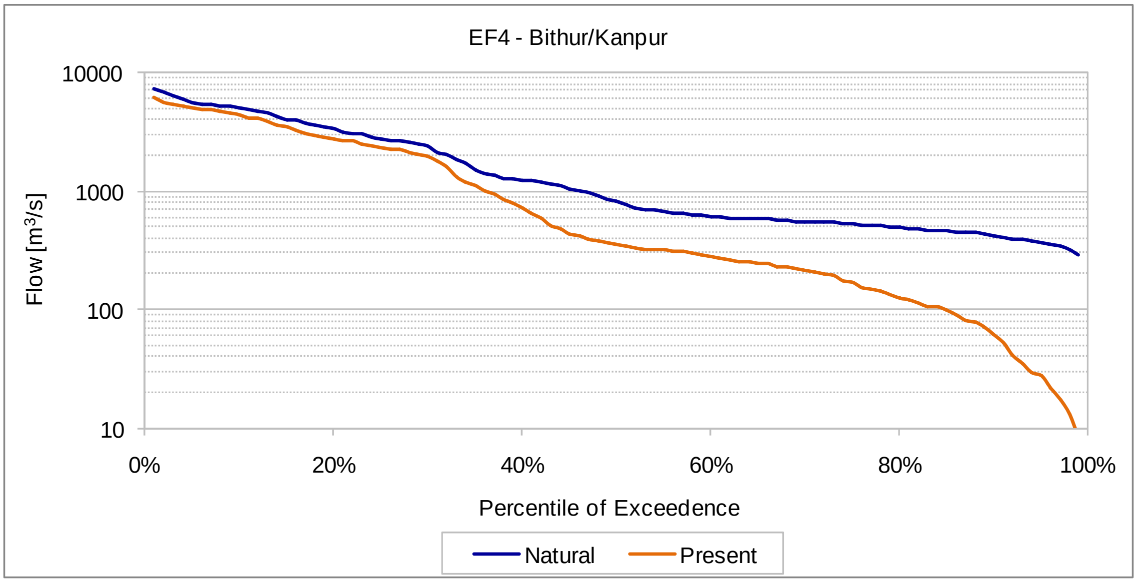


Figure 18: Annual flow totals (top) and average monthly flow distribution (bottom) for Bithur/Kanpur



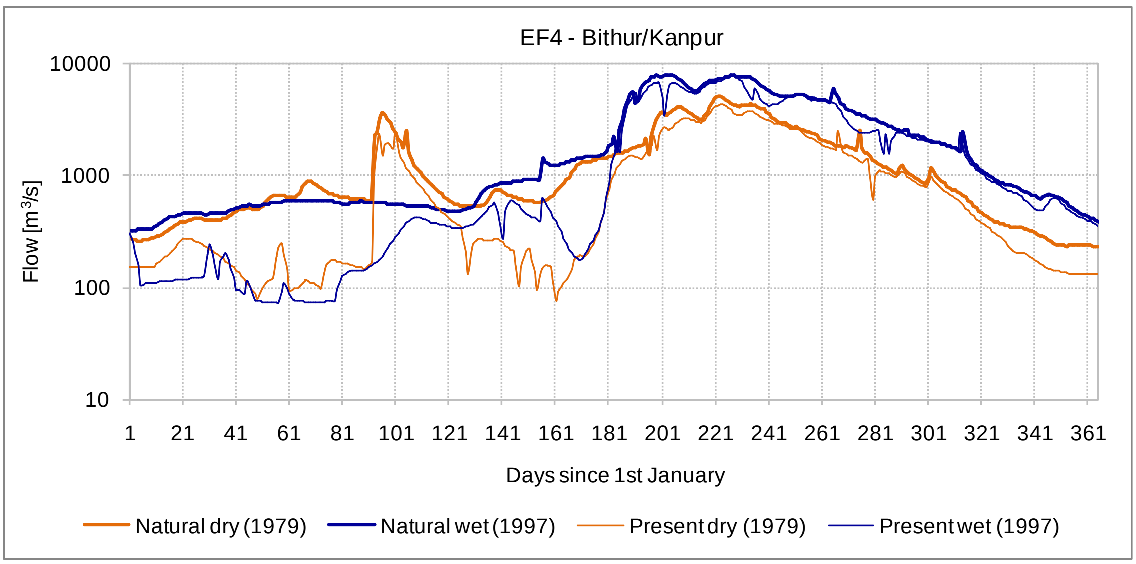


Figure 19: Flow Duration curves (top) and example daily hydrographs (bottom) for Bithur/Kanpur

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