Hydrological Modelling of the Ramganga River Basin

INRM Consultants, New Delhi

Hydrological Modelling of the Ramganga River Basin

Starter Document - March, 2015

Hydrological Modelling of the Ramganga River Basin

CONTRACT NO.

Submitted to: World Wide Fund for Nature (WWF-India)

Lodhi Estate, New Delhi

Prepared by: INRM Consultants Pvt. Ltd.

Project: WWF/2013/2

February, 2015

INRM Consultants, New Delhi

Table of Contents

List of Figures

Abbreviations

cms/cumecs	: Cubic meter per second
d/s	: downstream
DD	: Degree Decimal
DEM	: Digital elevation model
E-flow/ EF	: Environmental flow
FAO	: Food and Agriculture Organization
FDC	: Flow Duration curves
GOI	: Government of India
HRU	: Hydrological response unit
IMD	: India Meteorological Department
JF	: January-February
JJAS	: June-Jul-Aug-Sept
m	: Meter
MAM	: March-April-May
MCM	: Million Cubic Meter
NRCS	: Natural Resources Conservation Service
NRSC	: National Remote Sensing Center
OND	: Oct-Nov-Dec
PPU	: Percent Prediction Uncertainty
sq km	: Square Kilometers
SWAT	: Soil and Water Assessment Tool
SWAT-CUP	: SWAT Calibration and Uncertainty Procedures

Introduction

Hydrology is an important component while assessing the environmental flow assessment of a river system. Objective of this study is to assess the spatial and temporal stream flow on the Ramganga River using hydrological modeling. This will help in evaluating seasonal/monthly the E-flow requirement at different stretch of the river and recommended possible modifications to E-Flows.

Total of eight cross section sites were shortlisted for E-flow assessment over entire stretch of Ramganga River.

For this purpose SWAT hydrological modelling has been used.

Scope and Objectives

Scope of study

The main scope of this segment is to perform hydrological modeling for Ramganga river basin and assess and analyze the flow regime at various cross section sites.

Objectives

The Main objectives of the study are:

- Hydrological modelling of Ramganga River basin.
- Assessment of Monthly and seasonal flow regime.
- Flow dependability assessment for Low flows and high flow seasons.
- Flow health assessment at all environmental flow (EF) sites.

Methodology

SWAT Overview

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.

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.

Hydrological Model Setup

SWAT hydrological model has been setup using basic spatial data (land use, DEM, Soil layer) and time series observed weather data. Subsequent paragraphs will elaborate on model setup and basic input data used.

Input Data

Data from the public domain has been collected and processed to comply with the hydrological modeling requirement.

Following data required for the hydrological modelling has been pre-processed in the model required format. The data include:

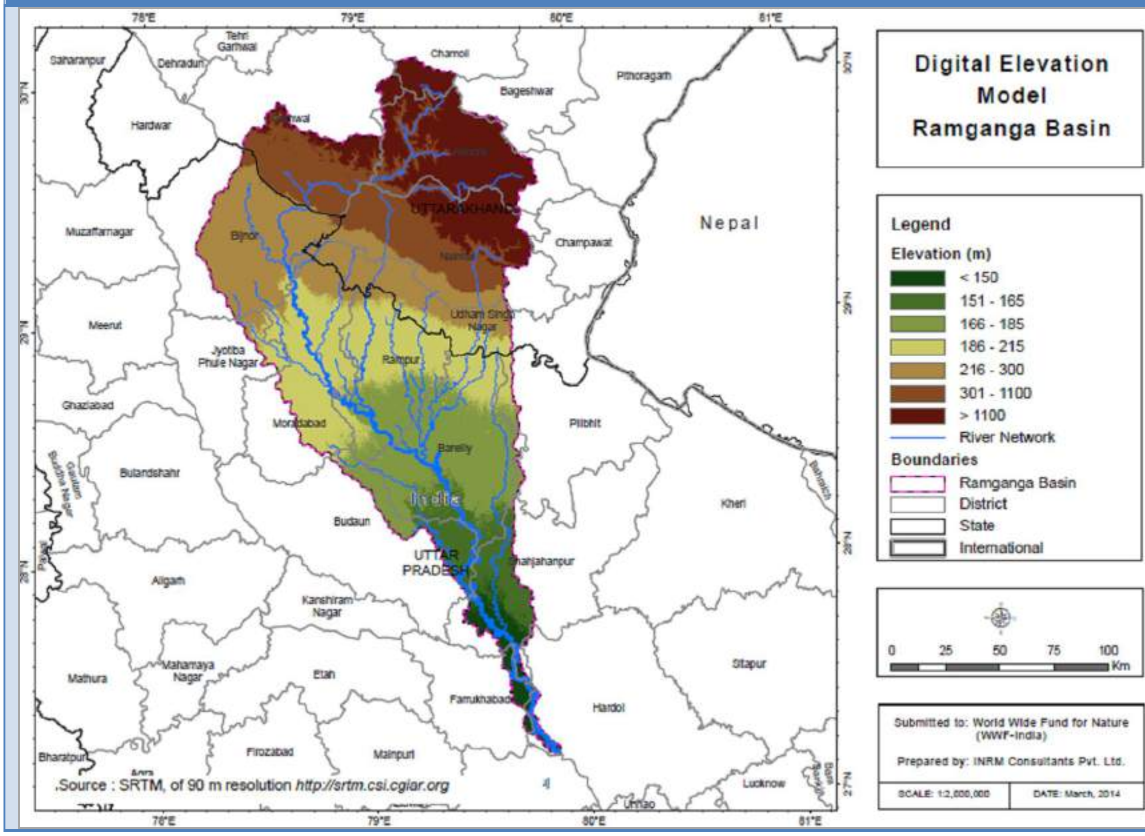
- DEM (source: SRTM) - 90 m resolution – Raster.
- Land use map: NRSC landuse map, 2007 merged with IWMI irrigation source map – Raster.
- Soil maps and associated soil characteristics – NBSSLUP data soil merged with FAO soil.
- Reservoirs - Point locations.
- Rain gauge and temperature stations (Latitude, Longitude) – IMD and Tehsil level daily data, (WWF India procurement).
- Time series data of rainfall and temperature has been reformatted in the model required format.
- Additional information on general groundwater level and characteristics are collated using available literature (CGWB District brochures), cropping pattern from Agriculture statistics.
- Crop Management (Agricultural statistics and contingency plans, GOI).

Digital Elevation Model

The ArcSWAT interface has been used to pre-process the spatial data for the river system. A digital elevation model (90m horizontal resolution DEM) from the SRTM[1] was used for basin delineation and is shown Figure 1.

[1] http://glcf.umiacs.umd.edu/data/srtm/

Figure 1: Digital Elevation Model of Ramganga River Basin

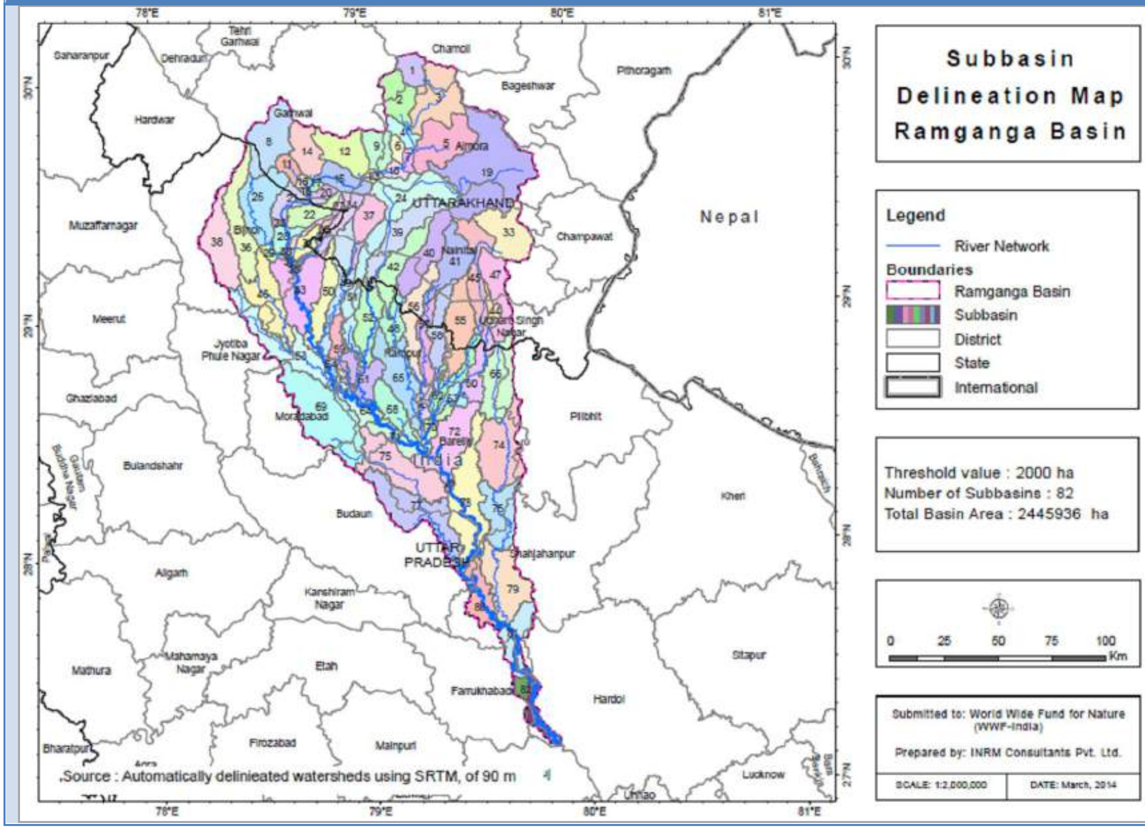


Basin Demarcation and Watersheds delineation

shows the automatically delineated Ramganga catchment with the generated drainage network using the DEM. The course of drainage network was corrected (before delineation and using latest available satellite images/Google earth) so that actual basin boundary could be delineated. A "Burn In" stream dataset is used to force the SWAT sub-basin reaches to follow known stream locations.

Automatic delineation of watersheds was done by using the DEM as input. The target outflow point was interactively selected. The Ramganga basin has been delineated using 2,000 hectare as minimum stream threshold and has resulted in 82 sub-basins which were further divided into 576 HRU's (Hydrological response units)as shown in . Basin area of the Ramganga up to the basin outflow point is 24,459.36 sq km. Care was also taken to incorporate the locations of major dams, reservoirs/ barrages , major tributary confluences, cross- section locations while undertaking the delineation process.

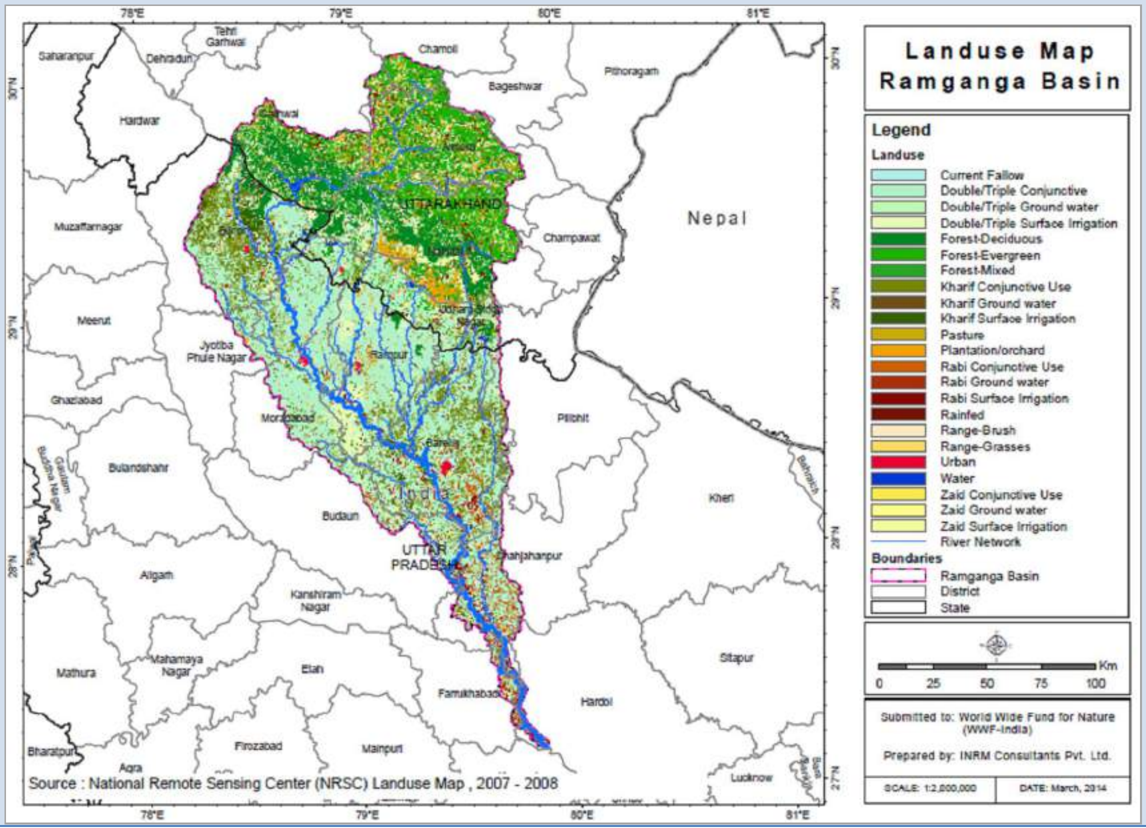
Figure 2: Delineated Basin boundary and sub-catchments



Landuse Data

NRSC[2] landuse data was merged with irrigation source map (IWMI's Global Map of Irrigated Areas (GMIA)[3]) and used as an basic input layer for SWAT model. The general landuse pattern is shown in .

Figure 3: Landuse/ Landcover map of Ramganga basin

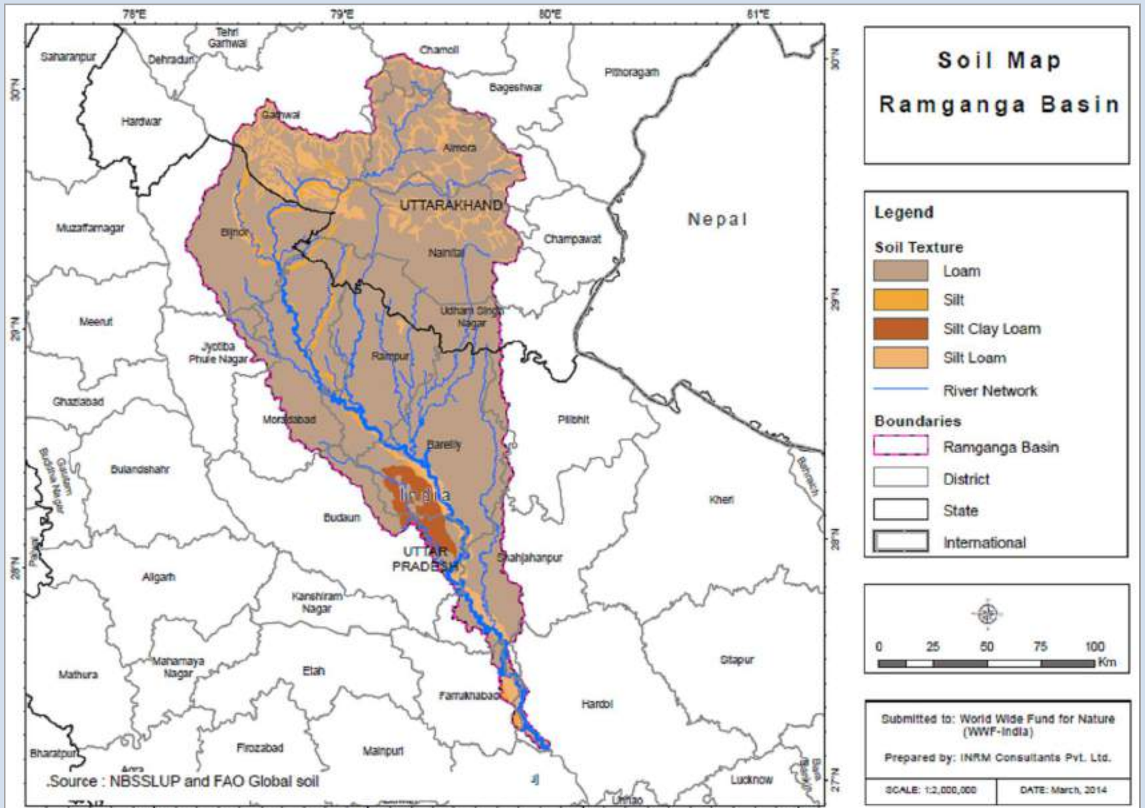


[2] http://applications.nrsc.gov.in/products.asp
[3] http://www.iwmigiam.org/info/main/index.asp

Soil layer data

NBSSLUP[4] data was merged with FAO[5] global soil data and used as an input layer for SWAT modeling (Figure 4). Major soil type in the basin is loam followed by silt which is concentrated on upper reaches.

Figure 4: Soil Map of Ramganga river basin



[4] http://www.nbsslup.in/

[5] http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/

Weather Data

Daily rainfall and temperature data is used for hydrological modeling. Other weather data such as wind speed, relative humidity and sunshine hours were generated using SWAT weather generator.

- IMD gridded daily and tehsil level daily rainfall data of Ramganga River Basin stations is used for the time period 1971-2011 (41 years). Tehsil level daily data is used for 28 stations (out of 38 stations data available) while IMD gridded data is used for 7 stations. IMD gridded rainfall resolution is at 0.5°.
- IMD gridded daily maximum and minimum temperature at 5 stations of Ramganga River Basin is used for the time period 1969-2011 (43 years). IMD gridded temperature resolution is at 1°.

The details of rainfall and temperature stations are presented in Table 1.

Table 1 Rainfall and Temperature data stations

S.No	Station code/Name	Agency	District	Longitude	Latitude	Elevation (m)
			Rainfall Stations			
1	785300	IMD	Garhwal	78.50	30.00	1156.65
2	790300	IMD	Garhwal	79.00	30.00	1813.84
3	795295	IMD	Almora	79.50	29.50	1007.90
4	795300	IMD	Bageshwar	79.50	30.00	1963.40
5	800295	IMD	Almora	80.00	29.50	709.17
6	790295	IMD	Nainital	79.00	29.50	629.55
7	Bijnor	Revenue Deptt.	Bijnor	78.15	29.39	241.00
8	Bilari	Revenue Deptt.	Moradabad	78.76	28.66	198.00
9	Chandpur	Revenue Deptt.	Bijnor	78.28	29.14	227.00
10	Dhampur	Revenue Deptt.	Bijnor	78.59	29.29	223.00
11	Moradabad	Revenue Deptt.	Moradabad	78.84	28.89	196.00
12	Nagina	Revenue Deptt.	Bijnor	78.50	29.48	254.00
13	Nazibabad	Revenue Deptt.	Bijnor	78.29	29.60	260.00
14	Sambhal	Revenue Deptt.	Moradabad	78.55	28.64	202.00
15	Swar	Revenue Deptt.	Rampur	79.08	29.03	207.00
16	Thkurdwara	Revenue Deptt.	Moradabad	78.78	29.13	216.00
17	795290	IMD	Udham Singh Nagar	79.50	29.00	221.96
18	Aunla	Revenue Deptt.	Bareilly	79.21	28.31	169.00
19	Baheri	Revenue Deptt.	Bareilly	79.49	28.72	190.00
20	Bareilly	Revenue Deptt.	Bareilly	79.43	28.42	182.00
21	Bisalpur_P	Revenue Deptt.	Pilibhit	79.84	28.34	170.00
22	Bisalpur_R	Revenue Deptt.	Rampur	79.27	28.86	190.00
23	Bisauli	Revenue Deptt.	Badaun	78.94	28.30	182.00
24	Faridpur	Revenue Deptt.	Bareilly	79.55	28.22	170.00
25	Milak	Revenue Deptt.	Rampur	79.16	28.66	180.00
26	Mirganj	Revenue Deptt.	Bareilly	79.27	28.52	173.00
27	Pilibhit	Revenue Deptt.	Pilibhit	79.79	28.68	187.00

S.No	Station code/Name	Agency	District	Longitude	Latitude	Elevation (m)
			Rainfall Stations			
28	Rampur	Revenue Deptt.	Rampur	79.04	28.79	192.00
29	Sahabad	Revenue Deptt.	Rampur	78.98	28.57	188.00
30	Badaun	Revenue Deptt.	Badaun	79.11	28.00	172.00
31	Data Ganj	Revenue Deptt.	Badaun	79.34	27.92	153.00
32	Sahjahanpur	Revenue Deptt.	Sahjahanpur	79.85	27.81	146.00
33	Tilhar	Revenue Deptt.	Sahjahanpur	79.69	28.03	161.00
34	Zalalabad	Revenue Deptt.	Sahjahanpur	79.54	27.71	147.00
35	Farrukhabad	Revenue Deptt.	Farrukhabad	79.49	27.30	150.00
			Temperature stations			
1	795295	IMD	Almora	79.5	29.5	1007.90
2	785285	IMD	Moradabad	78.5	28.5	195.27
3	785295	IMD	Bijnor	78.5	29.5	254.50
4	795285	IMD	Bareily	79.5	28.5	176.97
5	795275	IMD	Farrukabad	79.5	27.5	151.17

The base map showing weather data stations and other point locations is shown in Figure 5.

Interventions and EF site locations

One reservoir Kalagarh dam and 4 barrages (Afzalgarh, Hareolli, Kho and Kosi) were implemented in the model. Kalagarh is located in Garhwal district of Uttarakhand. Water from Kalagarh is diverted from Afzalgarh barrage to Hareolli barrage located on main Ramganga River. Water from Hareolli barrage is then diverted to Kho barrage (located on right bank of Ramganga river on its tributary Kho) through network of canals. Water from Kho barrage is then transferred inter basin and dumped near Garhmukteshwar in Ganga river. A small amount of water is used for irrigation diverted through Afzalgarh barrage.

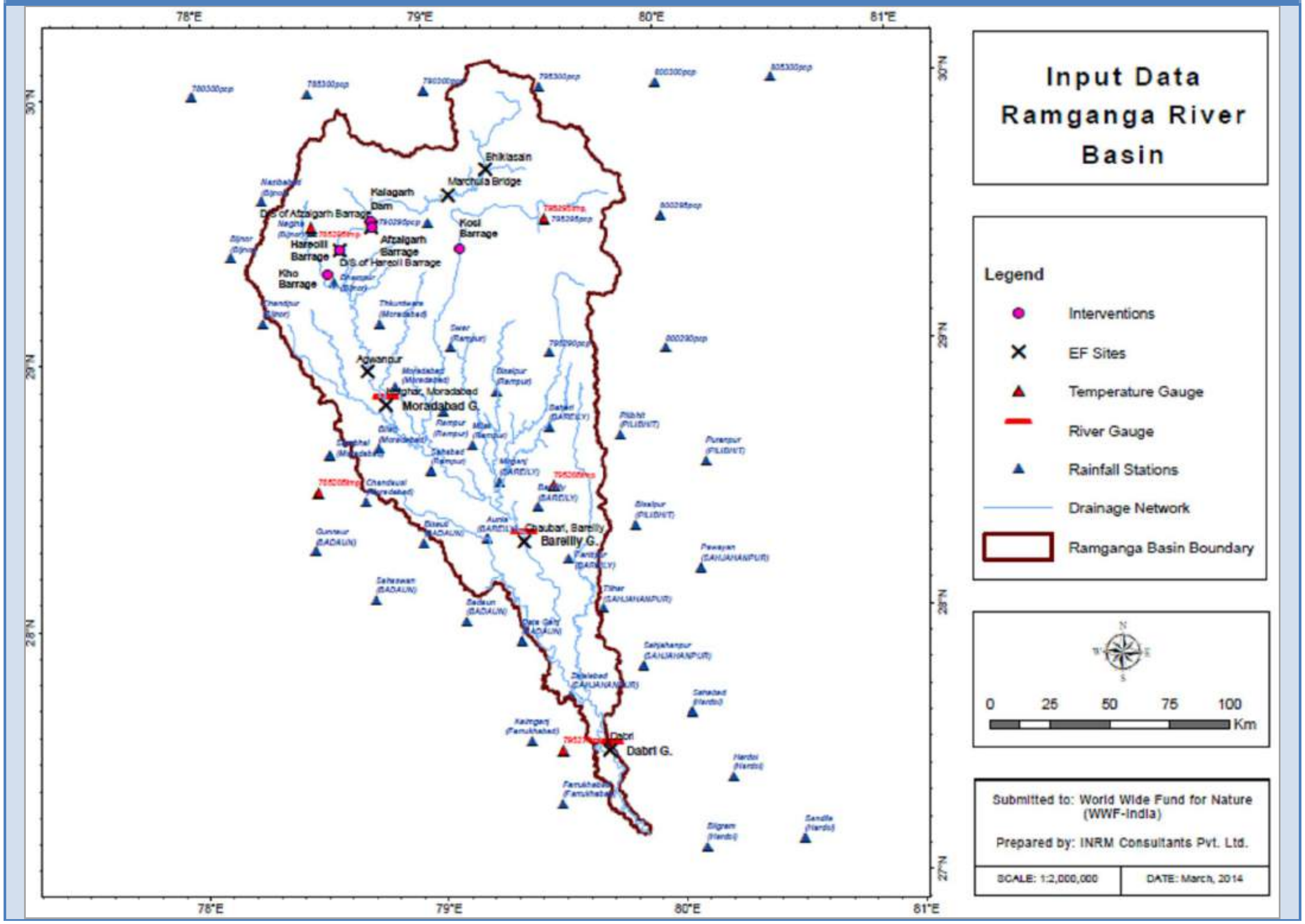
Eight EF (Environmental Flow) locations were selected for EF assessment, details of which are presented in Table 2.

Table 2: EF site location details

EF site name	Location (Lat,Long) DD	District
Bhikiasain	79.26121, 29.6968	Almora
Marchula bridge	79.09277, 29.60585	Almora
Afzalgarh Barrage	78.7614, 29.49589	Garhwal
Hareolli barrage	78.61933, 29.41264	Bijnor
Aghwanpur	78.72453, 28.94921	Moradabad
Katghar Rly. Bridge, Moradabad	78.79818, 28.82544	Moradabad
Chaubari, Bareilly	79.3676, 28.29492	Bareilly
Dabri	79.69642, 27.49838	Shahjahapur

Basic layout showing interventions and other point features are shown in .

Figure 5: Basic input data layout of Ramganga basin



Crop Management

Agriculture details like types of crops and cropping calendar were taken from district wise "Agricultural statistics and contingency plans, GOI". Major crops in this area were rice, wheat and sugarcane, where rice is mainly grown in kharif season, wheat in rabi season while sugarcane implemented as annual crop.

Effort was also made identify and implement the irrigation practices followed in the area in terms of source of irrigation and irrigation schedules. Agriculture statistics and contingency plans, GOI and Irrigation Source map, IWMI were used as source of information.

Model Calibration

Model was calibrated after implementing appropriate crop management operations, adjusting various groundwater parameters, releases and consumptive use from dams and barrages and other factors governing the water yield. The parameters were adjusted repeatedly and simulated stream flow outputs compared with observed stream flow data until a fair calibration is not achieved.

Model calibration requires time series observed stream flow data which is described in subsequent paragraphs.

Crop Management

- Main crops : Wheat, Rice, Sugarcane.
- Cropping calendar : Kharif (Rice), Rabi(Wheat), Perennial crop (Sugarcane).

Reservoir and Barrages

One reservoir and 4 barrages were implemented with total water holding capacity of 2796 MCM (among which Kalagarh dam being the largest with capacity of 2448 MCM).

Irrigation Source

Major source of irrigation in Ramganga basin is groundwater followed by surface water through canals in small portion of basin. In upper reaches in hilly areas of Uttarakhand, the main source of irrigation is surface water while in plain areas the main source of irrigation is groundwater.

The irrigation scheduling is incorporated as per actual ground conditions taking reference from various secondary sources like Agriculture Statistics and Contingency Plans, GOI.

Auto Calibration

Apart from manually adjusting some of numerous parameters which may affect the overall water balance of the basin, auto calibration was also carried out using SWAT CUP tool. This was done to narrow down the list of parameters which are sensitive w.r.t. streamflow and to know the range within which they may be adjusted to get a fair model performance.

SWAT-CUP (SWAT Calibration and Uncertainty Procedures) is a program designed to integrate various calibration/uncertainty analysis programs for SWAT (Soil & Water Assessment Tool) using the same interface. Currently the program can run SUFI2 (Abbaspour et al., 2007), GLUE (Beven and Binley, 1992), and ParaSol (van Griensven and Meixner, 2006). Each SWAT-CUP project contains one calibration method and allows user to run the procedure many times until convergence is reached.

Automated model calibration requires that the uncertain model parameters are systematically changed, the model is run, and the required outputs (corresponding to measured data) are extracted from the model output files.

Sensitivity Analysis

It is a known fact that downstream of Kalagarh dam in Ramganga basin the stream flow is mainly due to irrigation return flow in non monsoon months therefore global sensitivity analysis has been run for seven major parameters mainly ground water parameters on observed monthly flows, for which SWAT CUP gave following t-stat and p-stat value. The higher sensitivity is reflected by high t-stat value and low P-value as shown in Table 1 below. Model was run with 2000 simulations for the sensitivity analysis and results are presented in subsequent paragraphs.

In sensitivity analysis five main parameters were put to sensitivity analysis test as shown in Table 3.

Table 3: Sensitivity analysis of selected parameters

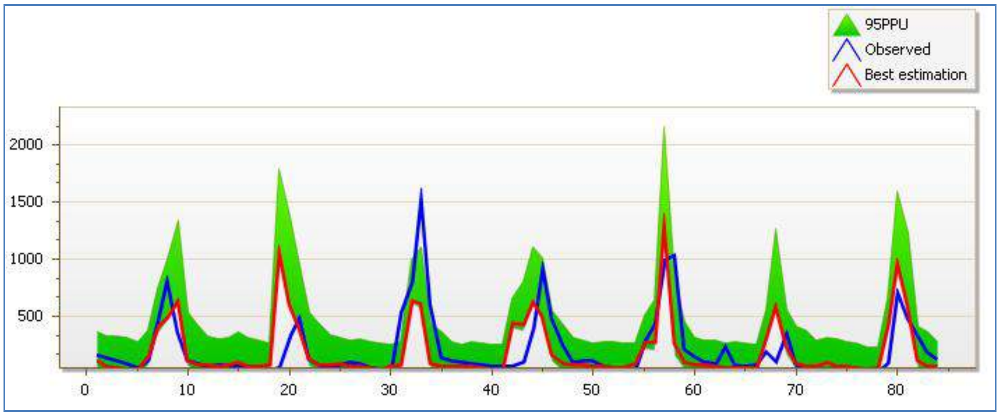
Parameter	Result
Curve Number	Not sensitive
Alpha base flow recession factor	Not sensitive
Groundwater delay	Not sensitive
Initial depth of water in the shallow aquifer, mm.	Sensitive
GWQMN, Threshold depth of water in the shallow aquifer required for return flow to occur	Sensitive

Apart from computing the sensitive parameters SWAT CUP also gives the fitted parameter value of best simulation according to parameter ranges we have given during model setup. These range are generally within realistic limits which comes from domain knowledge and experience gained over the years.

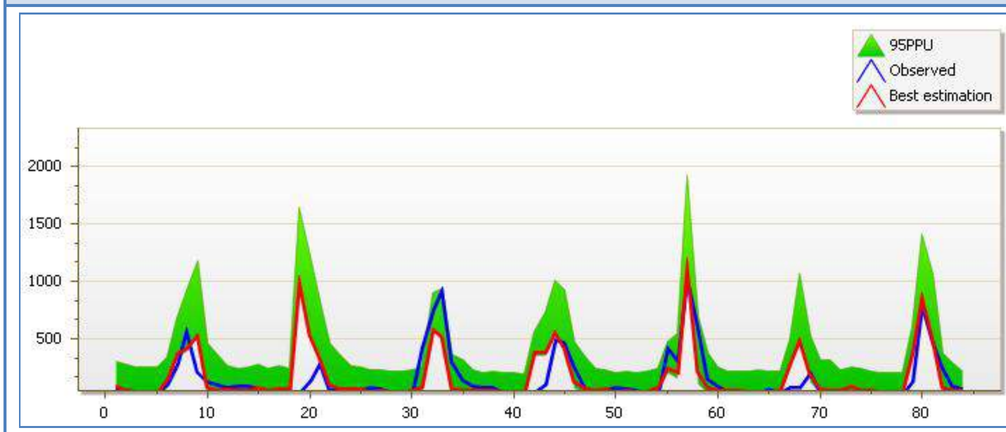
In SUFI-2, parameter uncertainty accounts for all sources of uncertainties such as uncertainty in driving variables (e.g., rainfall), conceptual model, parameters, and measured data. The degree to which all uncertainties are accounted for is quantified by a measure referred to as the P-factor, which is the percentage of measured data bracketed by the 95 percent prediction uncertainty (95PPU). The 95PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling, disallowing 5% of the very bad simulations. As all forms of uncertainties are reflected in the measured variables (e.g., discharge), the parameter uncertainties generating the 95PPU account for all uncertainties. Best simulation and 95PPU at three gauging sites is presented in .

Figure 6: Best simulation and 95 PPU plots at three gauging locations

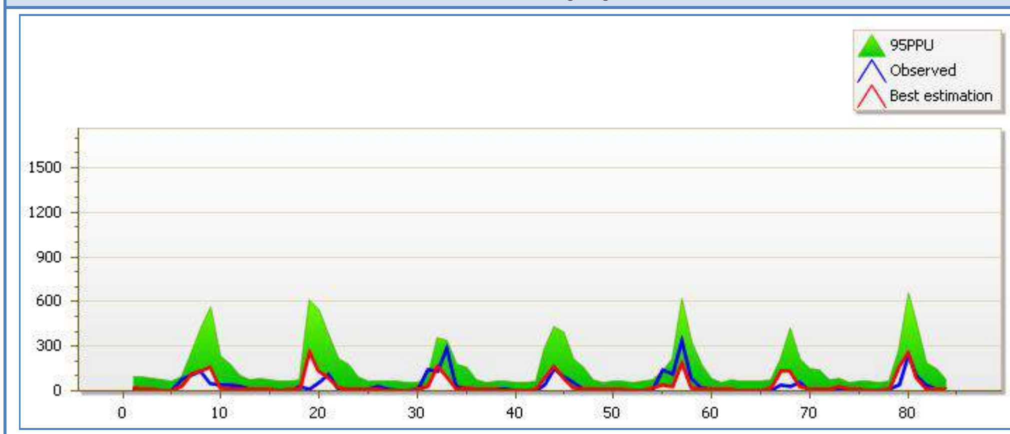
Dabri Gauging Site



Bareily Gauging Site



Moradabad Gauging Site



Although SWAT CUP gives a best simulation values as per observed data and absolute range provided still manual calibration has to be done because as we go downstream there are changes in cropping pattern, irrigation management etc. But SWAT CUP helps in narrow down among numerous parameters and give fair idea about the model parameter values to achieve fair calibration.

Observed stream flow data

WWF, India had provided stream flow records for four river gauge-discharge sites all located on the main stem of the river. The river gauge sites include Marchula, Katghar at Moradabad, Chaubari at Bareilly and Dabri. The details are provided in Table 4.

Table 4: Observed stream flow data details

Station Name	Location (Latitude-Longitude, DD)	Catchment Area CWC *(Modeled), sq km	Area Bias,%	Data Availability (monthly time series data)
Marchula	79.092731 - 29.605484	NA (1823.13)	-	1985-2010
Katghar Rly. Station, Moradabad	78.798898 - 28.823956	6807.00 (6,787.00)	-0.29	1978-2008
Chaubari at Barielly	79.370178 - 28.292556	18340.00 (18,200.00)	-0.76	1978-2008
Dabri	79.696158 - 27.497180	23919.00 (24,230.00)	1.30	1978-2008
***CWC(Area delineated by Central Water Commission)**				

Results and Analysis

Model has been run for a period of 39 years from 1973-2011. The monthly stream flow outputs at all eight EF sites (which include four calibration locations) were compiled and various analysis has been performed as described in subsequent paragraphs.

SWAT Model Performance

To assess the performance of model stream flow outputs w.r.t. observed flow data, model performance statistics were calculated. Monthly observed data was available for the period 1980-2007 which was compared with simulated flow series. The stream flow time series comparison is presented in whereas model performance and statistics is presented in Table 5.

It was observed that there was inconsistency in stream flow data (observed) and respective year rainfall for few years therefore those time period data was excluded from model performance evaluation.

Table 5: Model performance and statistics at selected calibration locations

Parameter	Marchula EF site	Katghar, Moradabad EF site	Chaubari, Bareilly EF site	Dabri EF site
Statistics*				
PBIAS, %++	34.4	0.80	18.60	6.30
RSR+	0.77	0.59	0.54	0.50
NSE**	0.41	0.66	0.71	0.75
Performance*				
PBIAS, %	Unsatisfactory	Very Good	Satisfactory	Very Good
RSR	Unsatisfactory	Good	Good	Very Good
NSE	Unsatisfactory	Good	Good	Good
Model parameter is shown in bracket, ** Nash-Sutcliffe coefficient (NSE), + Ratio of the root mean square error to the standard deviation of measured data (RSR), ++ Volume Bias (PBIAS)				
***Value-Performance Reference**				
Performance rating	*Very Good*	*Good*	*Satisfactory*	*Unsatisfactory*
Stream flow (Volume bias)	*PBIAS ≤ ±10*	*±10 ≤ PBIAS ≤ ±15*	*±15 ≤ PBIAS ≤ ±25*	*PBIAS ≥ ±25*
RSR	*0.00- 0.50*	*0.50-0.60*	*0.60-0.70*	*>0.70*
NSE	*0.75-1.00*	*0.65-0.75*	*0.50-0.65*	*<0.50*

Apart from Marchula gauge station site model performance at all other locations are Good. It is evident from Table 5 that at Marchula the performance statistics is unsatisfactory. It worth mentioning here that upstream of Marchula the water use for agriculture and direct withdrawals from stream is quite less. Considering these factors the difference between Regulated flow (which is should be close to Natural flow) and observed flow should have been less, whereas the difference between the simulated regulated flows and observed flows is quite large. It suggests that either there is some unknown extraction upstream or the observed data is erroneous.

Keeping this in view the Regulated simulated flows were compared with long term mean monthly inflow to Kalagarh and the results was found fairly good. The simulated mean monthly inflow to

Kalagarh dam is 91.5 cumecs while observed mean monthly inflow is 81.2 cumecs i.e. volume bias is only 9% as compared to Marchula where volume bias was 34%. This implies that simulated flows are comparable with observed flows and simulated flows at Marchula can be used for further analysis.

Figure 7: Time series plot and mean monthly plots of Simulated Vs Observed flows at 4 Observed Gauge Sites on Ramganga river

Marchula Bridge

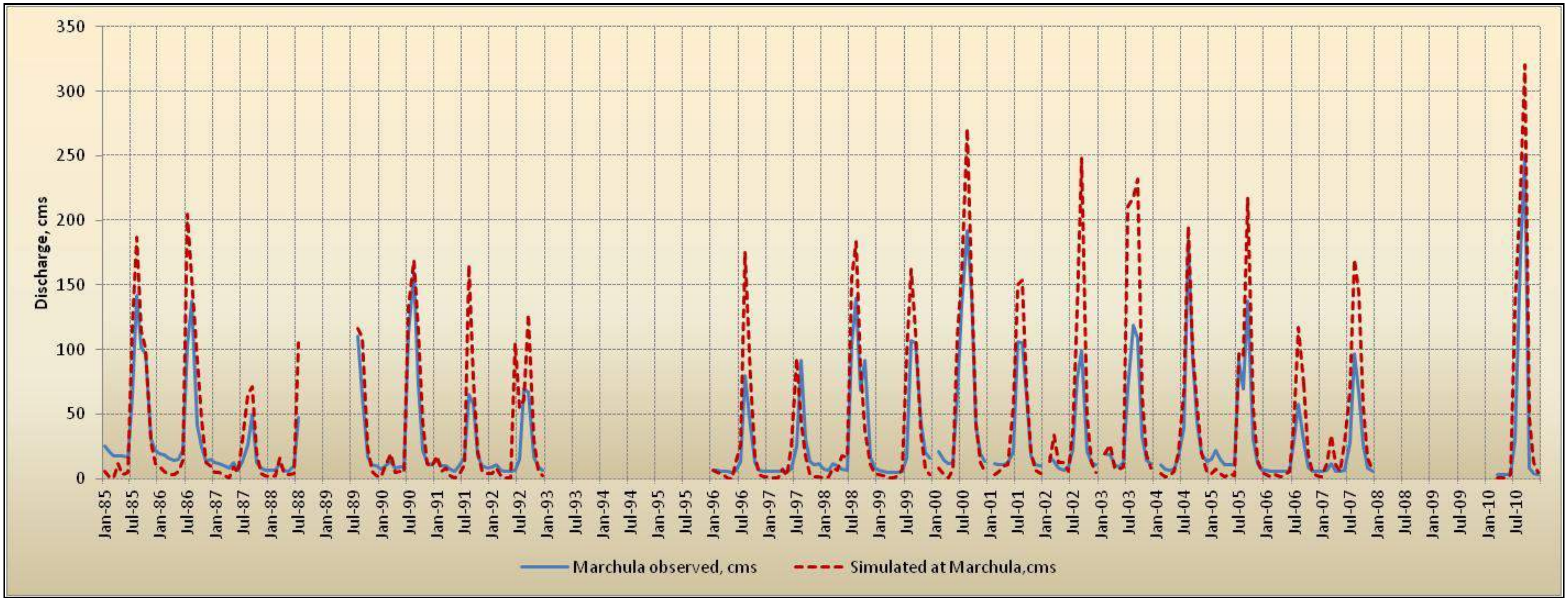


Figure 7: Time series plot and mean monthly plots of Simulated Vs Observed flows at 4 Observed Gauge Sites on Ramganga river

Katghar at Moradabad

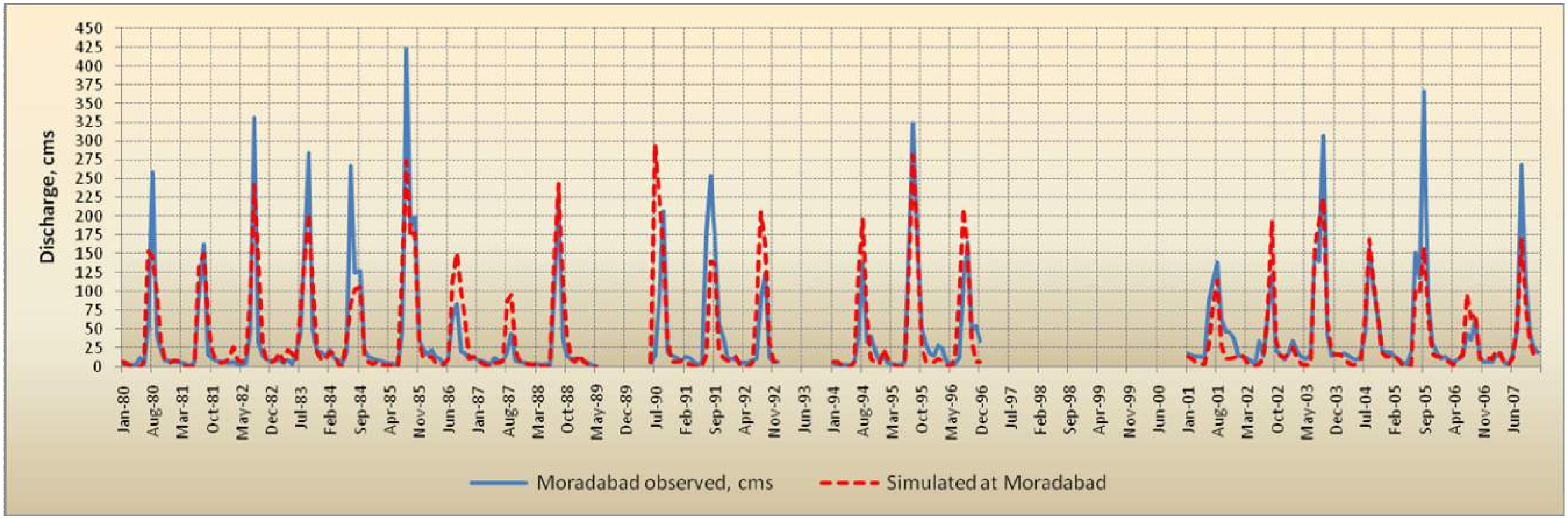


Figure 7: Time series plot and mean monthly plots of Simulated Vs Observed flows at 4 Observed Gauge Sites on Ramganga river

Chaubari at Bareilly

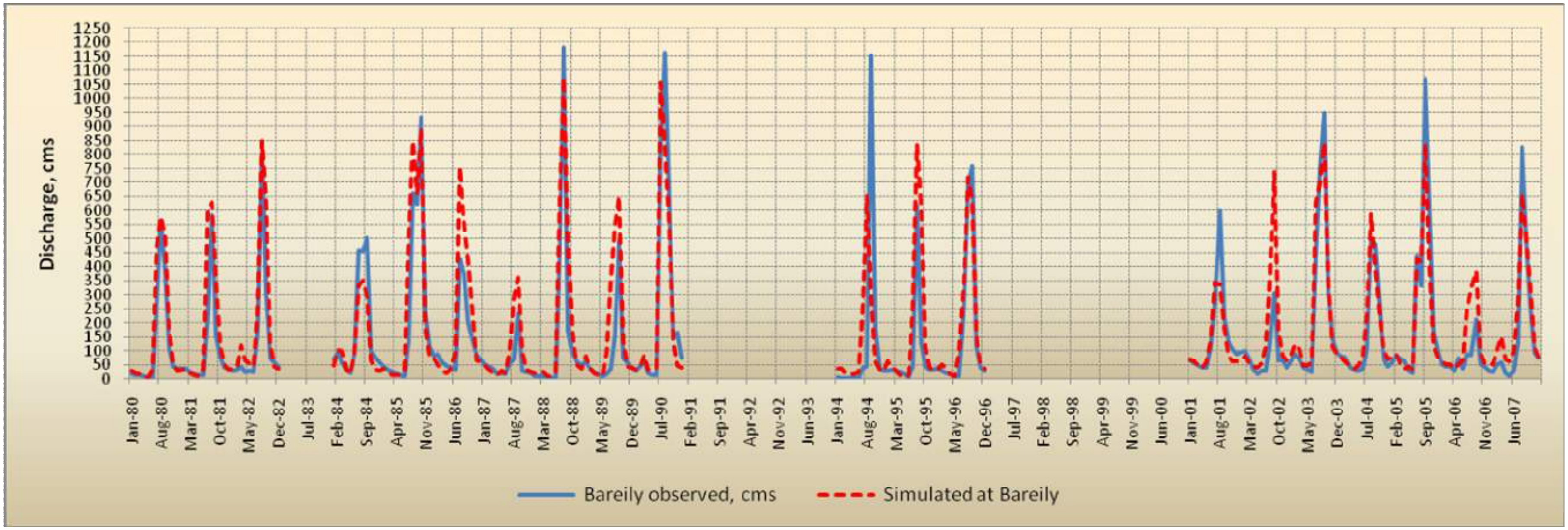


Figure 7: Time series plot and mean monthly plots of Simulated Vs Observed flows at 4 Observed Gauge Sites on Ramganga river

Dabri

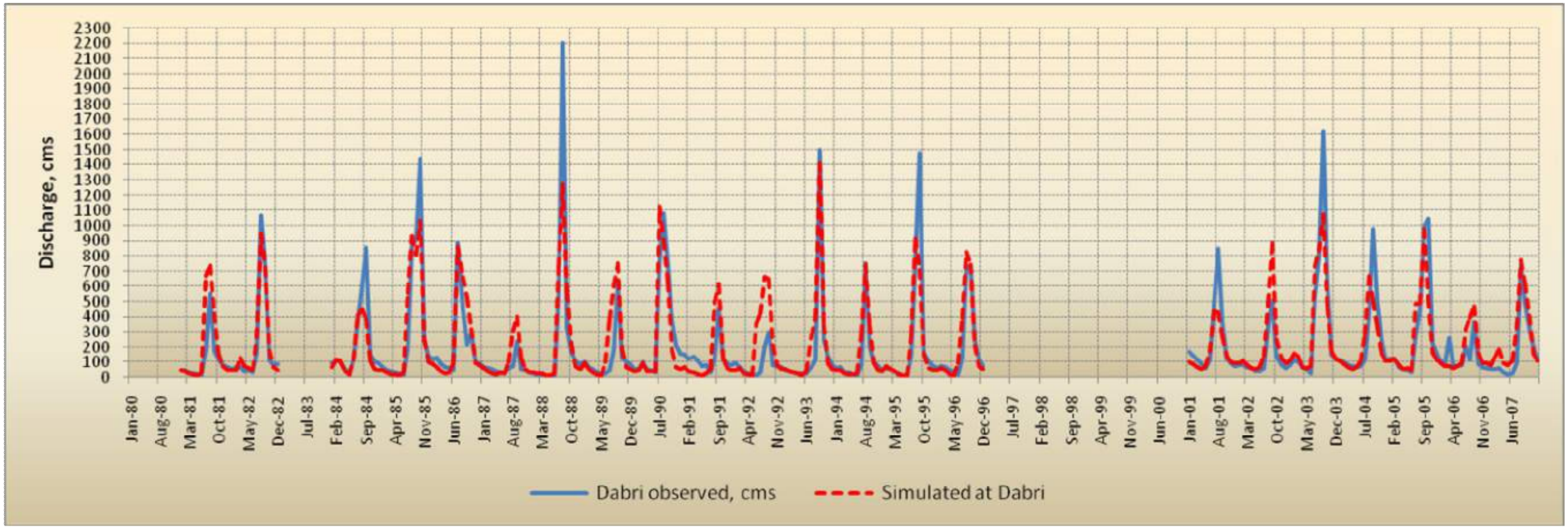
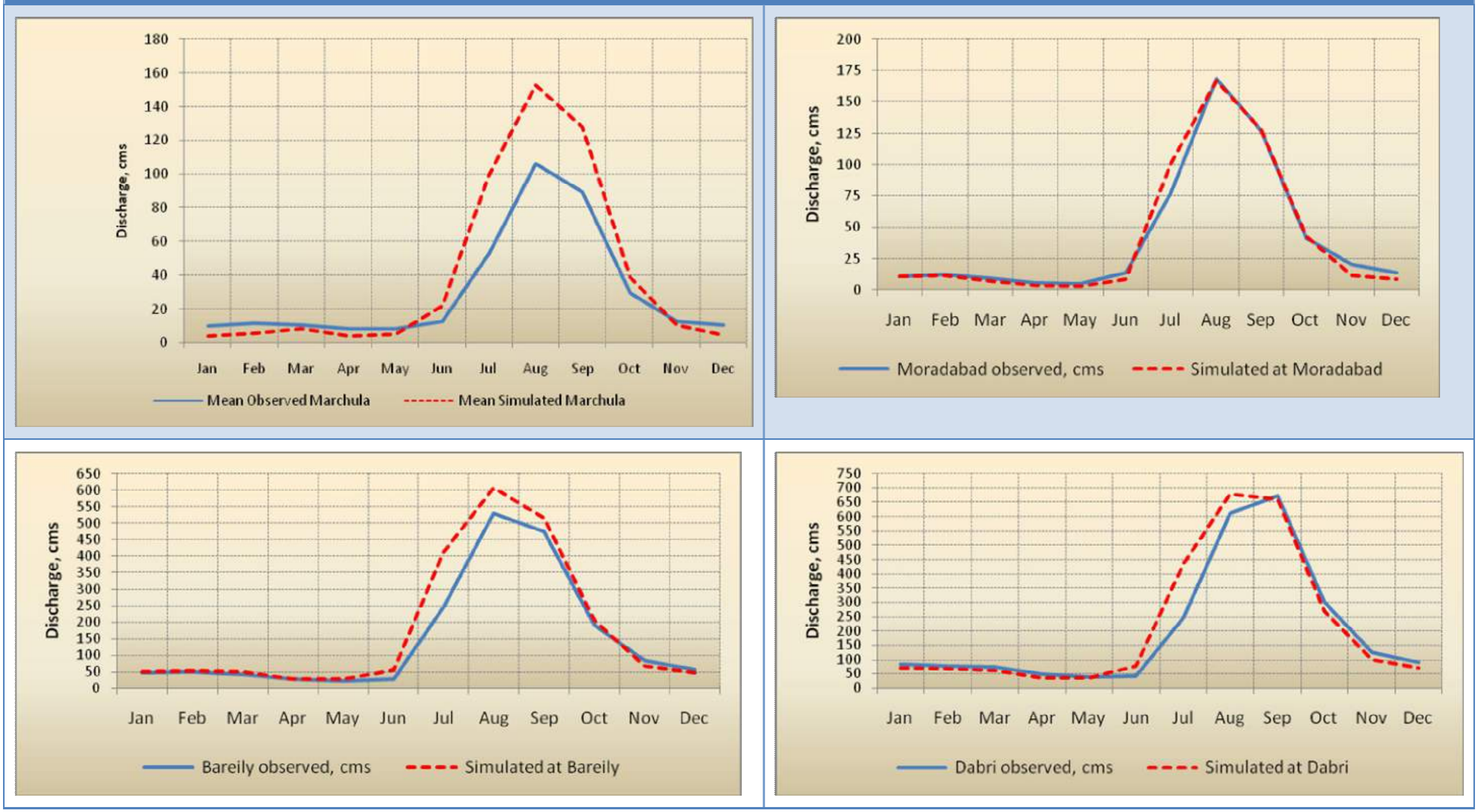


Figure 7: Time series plot and mean monthly plots of Simulated Vs Observed flows at 4 Observed Gauge Sites on Ramganga river



Flow Regime Characteristics

Model stream flow outputs were compiled at all target cross section sites for three scenarios as shown below:

- **Natural flow scenario** (Virgin scenario): Model was run with no interventions (Dams/Barrages/ponds) and with rain-fed agriculture (without external irrigation source, groundwater or canal).
- **Regulated scenario**: Regulated scenario represents the most recent condition of the basin (as if these conditions existed during the entire simulation period) which includes all interventions, water transfers and irrigated agriculture.
- **Unobstructed Flow Scenario**: Represents scenario where all interventions (Dams/Barrages/Ponds) are removed but keeping all other conditions similar to Regulated flow.

Comparison of flow regime in two scenarios will provide an idea of how much stream flow has been reduced after various developments in basin. This will form a base for planning of Environmental flows.

With above mentioned simulated scenarios various flow regime characteristics were generated at all eight EF site's as mentioned below:

- Annual Flow volumes for Regulated, Unobstructed and Natural scenario.
- Mean monthly flow regime: Depicts long term mean monthly flow variability and distribution in a year.
- Seasonal flow regime for Dry, Normal and Wet year:
    - Monthly flow regimes were aggregated into four seasons Jan-Feb (JF), March-April-May (MAM), June-July-Aug-Sept (JJAS) and Oct-Nov-Dec (OND).
    - The simulated flow was aggregated as total annual inflow and further classified into three hydro classes Dry year (flow dependability >75%), Normal (flow dependability between 25-75%) and Wet year (flow dependability <25%).
    - Seasonal flow outputs were compiled for all Dry, Normal and Wet years separately.
- Flow duration curves for driest (MAM) and wettest (JJAS) season: FDC is an aggregated way to illustrate the variability of flows and the range of flows experienced. The seasonal FDC's presented here are based on mean seasonal flows in each year during the simulation period 1973-2011.
- Ratio of present day (Regulated flow) to Natural (virgin flow): Signifies the water use/ withdrawals and storages upstream.

Dry/Normal/Wet years at EF sites

The classification is made on aggregated annual simulated stream flow in present Regulated condition. The details are presented in Table 6.

Table 6: Dry, Normal, Wet years at EF sites

Year	Bhikiasain	Marchula	Afzalgarh	Hareolli	Aghwanpur	Moradabad	Bareilly	Dabri
1973	Dry	Dry	Wet	Wet	Wet	Wet	Normal	Normal
1974	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry

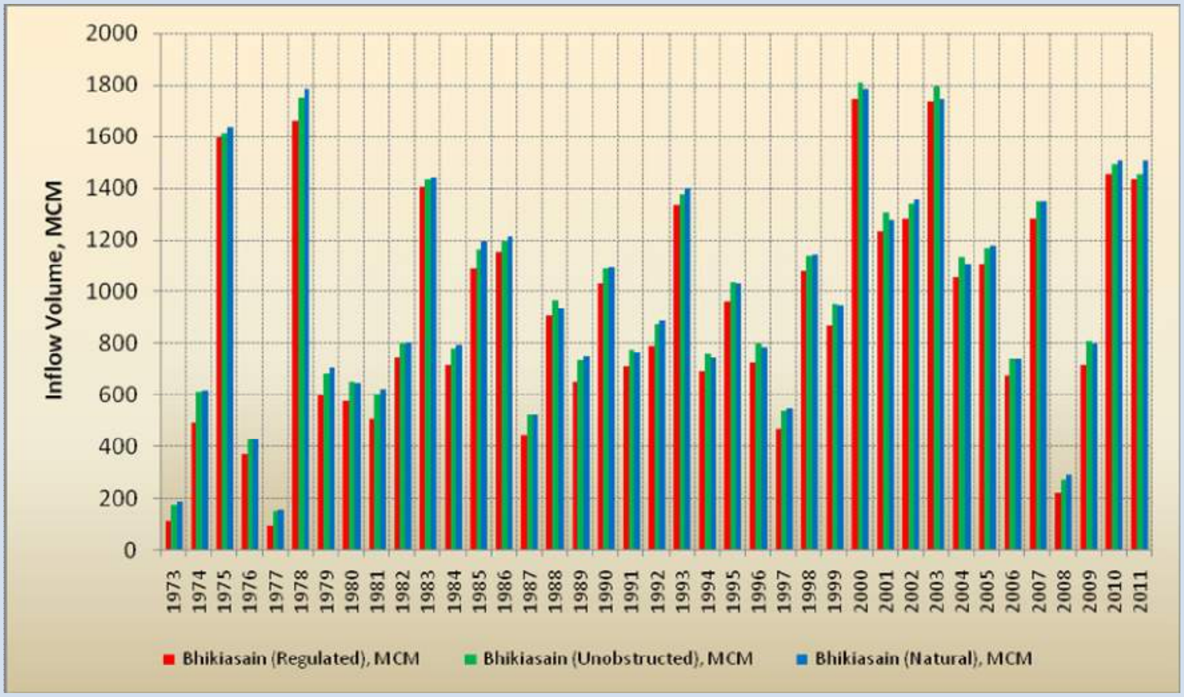
Year	Bhikiasain	Marchula	Afzalgarh	Hareolli	Aghwanpur	Moradabad	Bareilly	Dabri
1975	Wet	Wet	Wet	Wet	Normal	Wet	Wet	Wet
1976	Dry	Normal	Normal	Normal	Normal	Normal	Normal	Normal
1977	Dry	Dry	Normal	Normal	Normal	Normal	Normal	Normal
1978	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Wet
1979	Normal	Normal	Normal	Normal	Dry	Dry	Dry	Dry
1980	Dry	Normal	Normal	Normal	Normal	Normal	Normal	Normal
1981	Dry	Dry	Normal	Normal	Dry	Normal	Normal	Normal
1982	Normal	Normal	Wet	Normal	Normal	Normal	Normal	Normal
1983	Wet	Wet	Wet	Wet	Normal	Normal	Wet	Wet
1984	Normal	Normal	Normal	Normal	Normal	Normal	Dry	Dry
1985	Normal	Wet	Wet	Wet	Wet	Wet	Wet	Wet
1986	Normal	Normal	Normal	Wet	Normal	Normal	Normal	Normal
1987	Dry	Dry	Normal	Dry	Dry	Dry	Dry	Dry
1988	Normal	Normal	Wet	Normal	Normal	Normal	Normal	Normal
1989	Normal	Normal	Normal	Normal	Wet	Normal	Normal	Normal
1990	Normal	Normal	Normal	Wet	Wet	Wet	Wet	Wet
1991	Normal	Normal	Normal	Normal	Normal	Dry	Dry	Dry
1992	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal
1993	Wet	Wet	Normal	Normal	Normal	Normal	Normal	Normal
1994	Normal	Dry	Normal	Normal	Normal	Normal	Dry	Dry
1995	Normal	Normal	Wet	Wet	Wet	Wet	Normal	Normal
1996	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal
1997	Dry	Dry	Dry	Dry	Dry	Dry	Dry	Dry
1998	Normal	Normal	Normal	Normal	Wet	Wet	Normal	Normal
1999	Normal	Normal	Dry	Dry	Normal	Normal	Normal	Normal
2000	Wet	Wet	Dry	Normal	Normal	Normal	Wet	Wet
2001	Normal	Normal	Dry	Dry	Dry	Dry	Dry	Dry
2002	Wet	Wet	Normal	Normal	Dry	Normal	Normal	Normal
2003	Wet	Wet	Normal	Normal	Wet	Wet	Wet	Wet
2004	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal
2005	Normal	Normal	Normal	Normal	Normal	Normal	Wet	Wet
2006	Normal	Dry	Dry	Dry	Dry	Dry	Dry	Dry
2007	Wet	Normal	Dry	Dry	Normal	Normal	Normal	Normal
2008	Dry	Dry	Dry	Dry	Normal	Dry	Normal	Normal
2009	Normal	Normal	Dry	Dry	Dry	Dry	Normal	Normal
2010	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Wet
2011	Wet	Wet	Wet	Wet	Wet	Wet	Wet	Wet

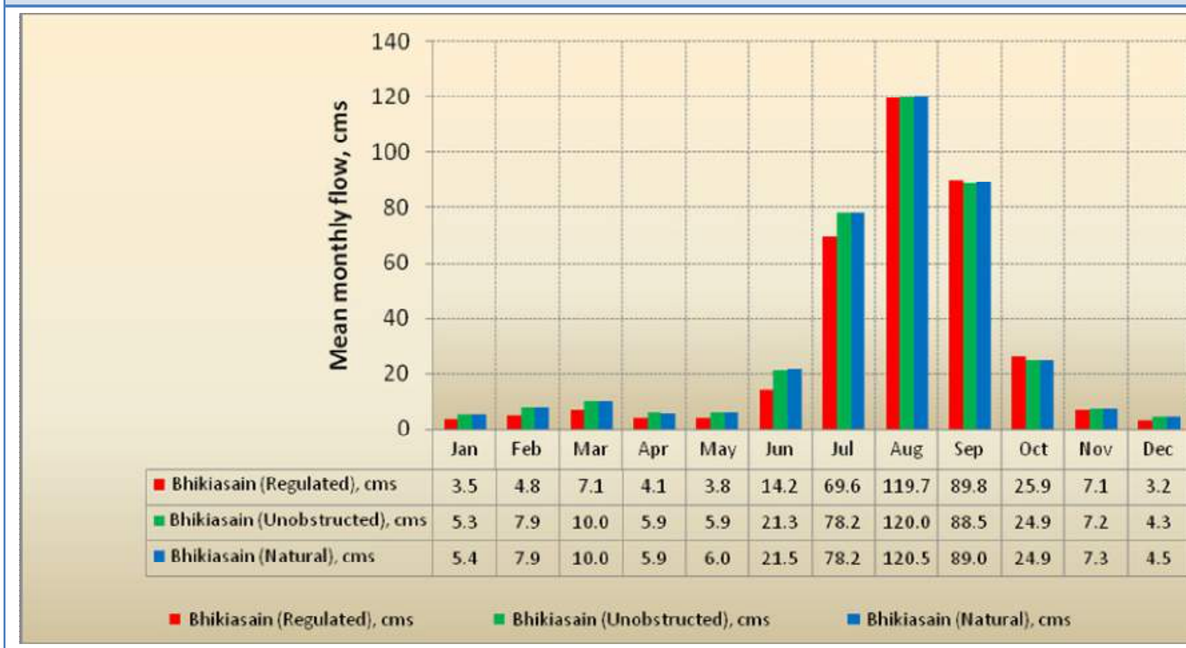
EF site wise flow regime characteristics are presented in subsequent sections.

Bhikiasain

Bhikiasain EF site is the first site on the river stretch and a headwater site with no upstream interventions. Annual flows and long term mean monthly flows for Regulated, Unobstructed and Natural scenario is presented in Figure 8. It is evident from that there is a small difference between Regulated flow and Natural flow regime which is due to the fact that water use upstream is quite less (no interventions and less area under Agriculture).

Figure 8: Annual flows and Mean monthly flow regime at Bhikiasain EF site



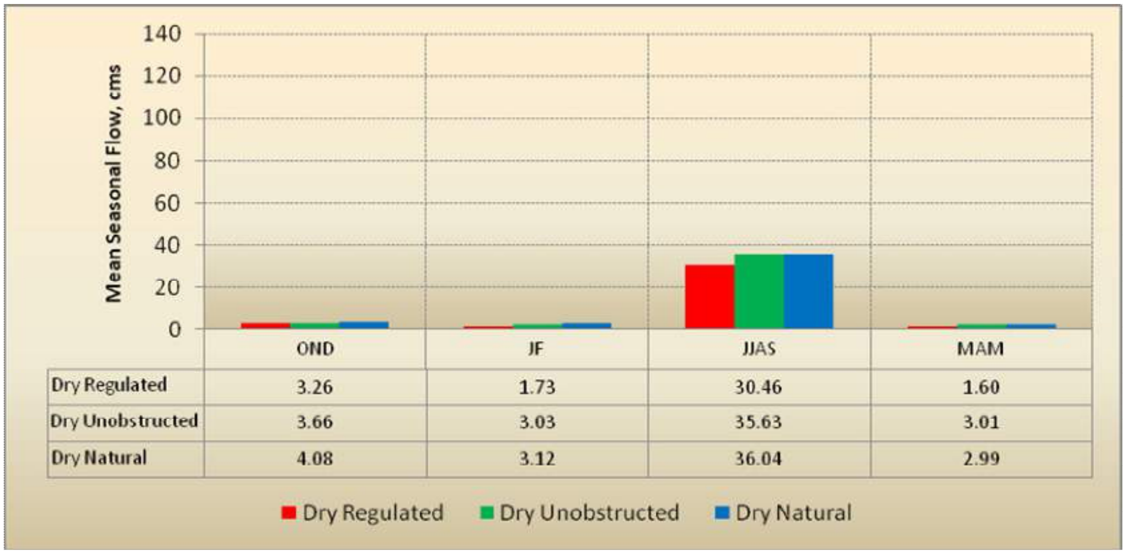


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bhikiasain (Regulated), cms	3.5	4.8	7.1	4.1	3.8	14.2	69.6	119.7	89.8	25.9	7.1	3.2
Bhikiasain (Unobstructed), cms	5.3	7.9	10.0	5.9	5.9	21.3	78.2	120.0	88.5	24.9	7.2	4.3
Bhikiasain (Natural), cms	5.4	7.9	10.0	5.9	6.0	21.5	78.2	120.5	89.0	24.9	7.3	4.5

Annual flows were classified as Dry, Normal or Wet year as per classification mentioned earlier. For each hydro class mean seasonal flows were compiled and are presented in

Figure 9: Seasonal flows for various hydro class at Bhikiasain

Dry Year



Normal Year

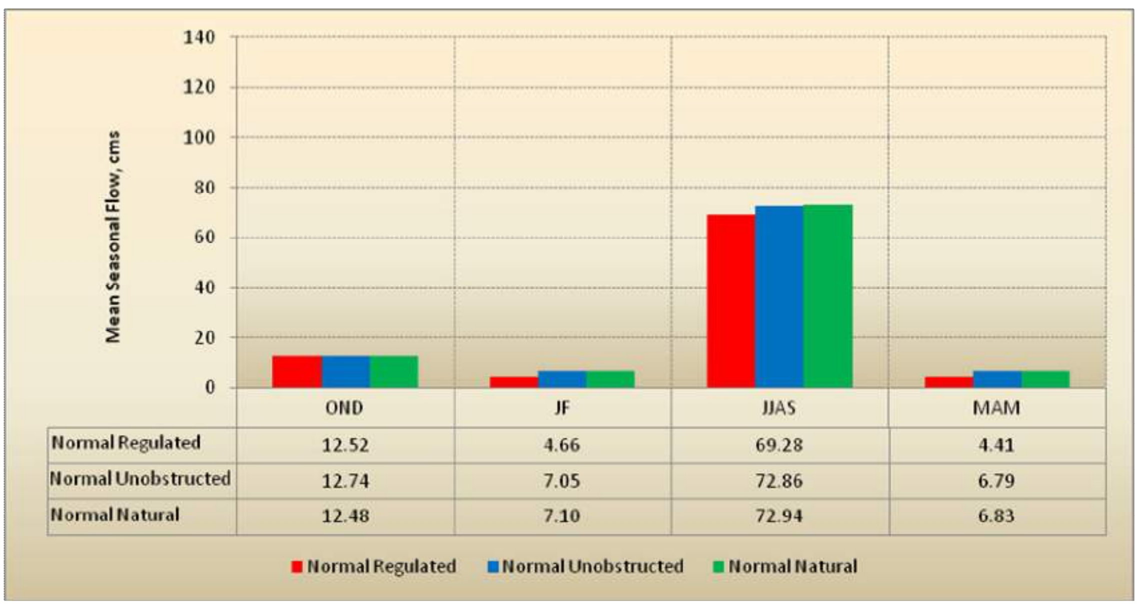


Figure 9: Seasonal flows for various hydro class at Bhikiasain

Wet Year

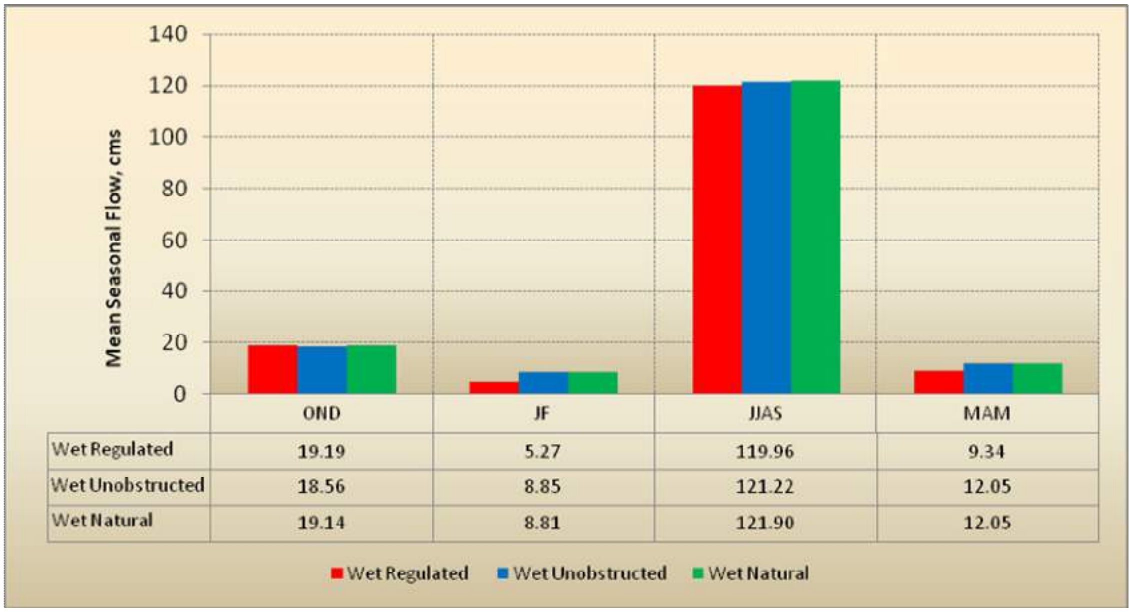


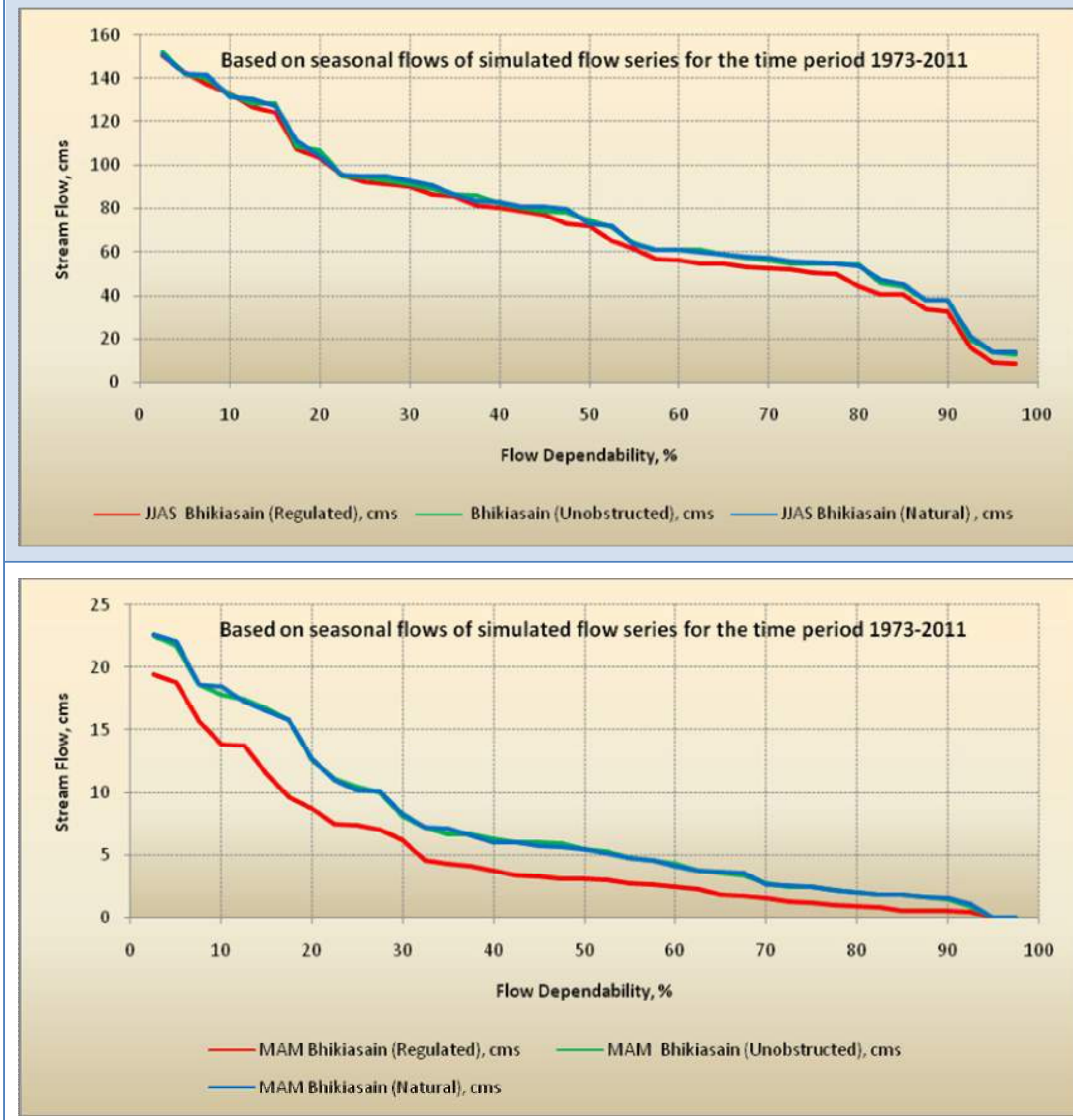
Table 7: Present day Regulated flow w.r.t. Natural (virgin) flow at Bhikiasain EF site

Season	Ratio of Regulated flow to Natural flow (Dry Year)	Ratio of Regulated flow to Natural flow (Normal Year)	Ratio of Regulated flow to Natural flow (Wet Year)
OND	0.80	1.00	1.00
JF	0.55	0.66	0.60
JJAS	0.85	0.95	0.98
MAM	0.53	0.65	0.78

From Table 7 it is evident that in driest season (MAM) the ratio of Regulated flows to Natural flow range from 0.53-0.78. This reflects that the water use and withdrawals is less in upstream catchment area.

Flow duration curves for wettest and driest seasons are presented in Figure 10 while dependable values for all three scenarios are presented in **Appendix 1**.

Figure 10: Flow duration curves for wettest (JJAS) and driest (MAM) season at Bhikiasain EF site

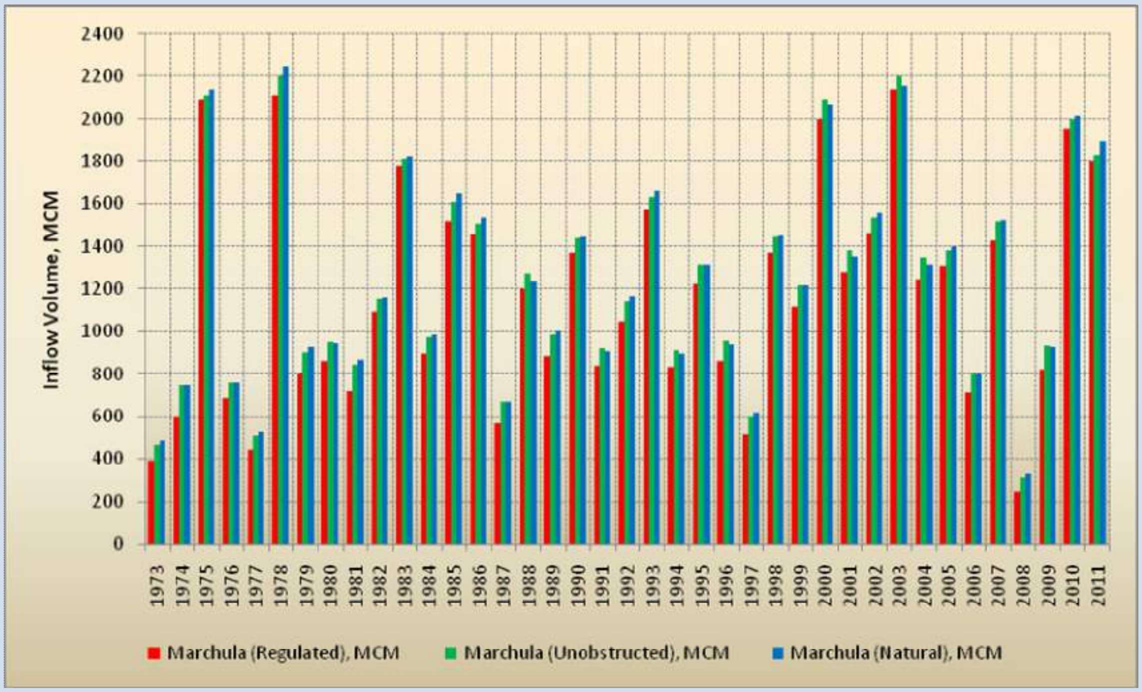


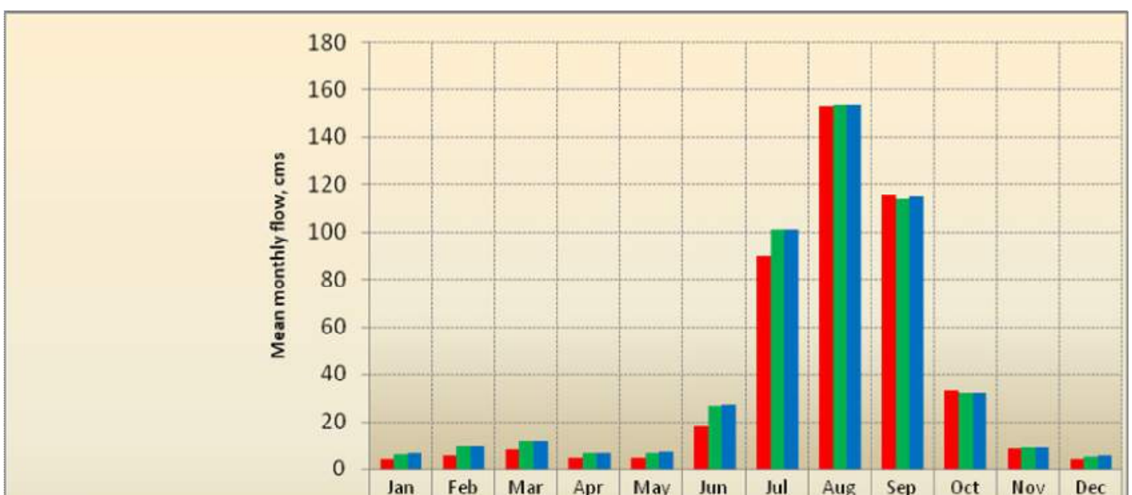
From Figure 10 it is evident that there is considerable flow throughout the year. At 75% dependability Regulated flow during driest season is 1.19 cumecs while Natural flow is 2.51 cumecs.

Marchula Bridge

Marchula bridge EF site is the second site on the river stretch 32 km d/s of Bhikiasain, with no upstream interventions. Annual flows and long term mean monthly flows for present day Regulated and Natural scenario is presented in .

Figure 11: Annual flows and Mean monthly flow regime at Marchula EF site



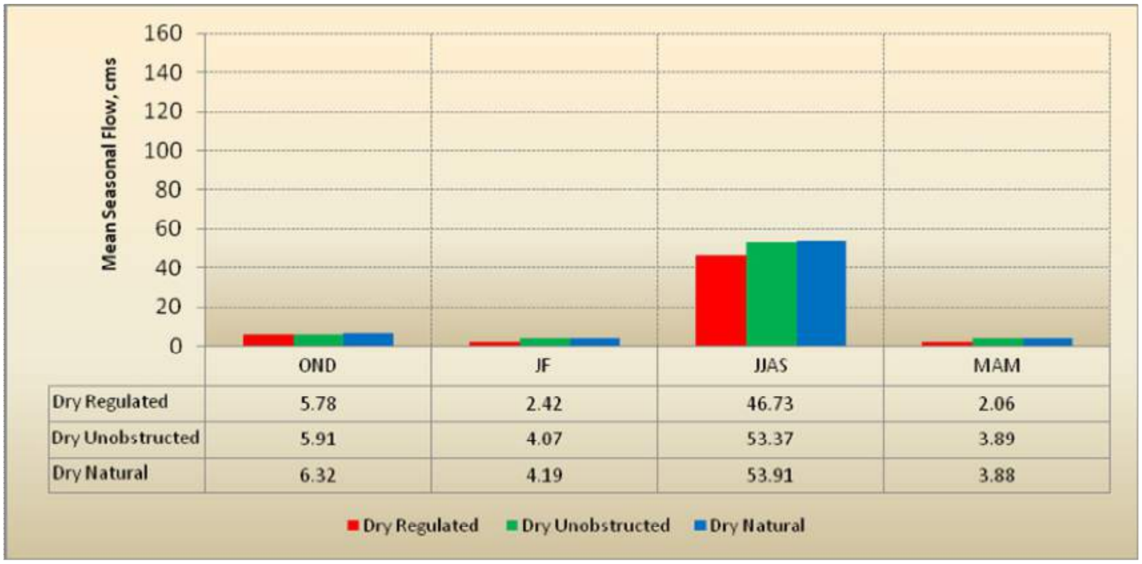


	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Marchula (Regulated), cms	4.1	5.7	8.2	4.6	4.3	17.6	89.8	152.4	115.3	32.9	8.7	3.9
Marchula (Unobstructed), cms	6.3	9.5	11.6	6.8	6.8	26.6	101.0	153.0	113.7	31.8	8.9	5.2
Marchula (Natural), cms	6.5	9.5	11.6	6.8	6.9	26.9	100.9	153.1	114.6	32.0	9.1	5.4

Annual flows were classified as Dry, Normal or Wet year as per classification mentioned earlier. For each hydro class mean seasonal flows were compiled and are presented in .

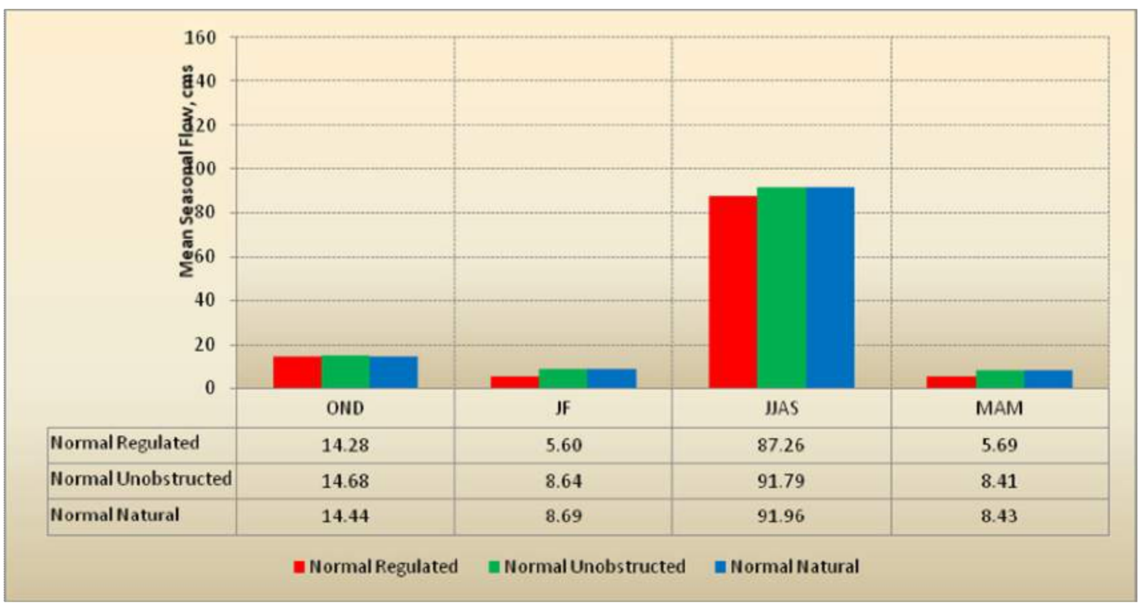
Figure 12: Seasonal flows for various hydro class at Marchula EF site

Dry Years



	OND	JF	JJAS	MAM
Dry Regulated	5.78	2.42	46.73	2.06
Dry Unobstructed	5.91	4.07	53.37	3.89
Dry Natural	6.32	4.19	53.91	3.88

Normal years



	OND	JF	JJAS	MAM
Normal Regulated	14.28	5.60	87.26	5.69
Normal Unobstructed	14.68	8.64	91.79	8.41
Normal Natural	14.44	8.69	91.96	8.43

Figure 12: Seasonal flows for various hydro class at Marchula EF site

Wet years

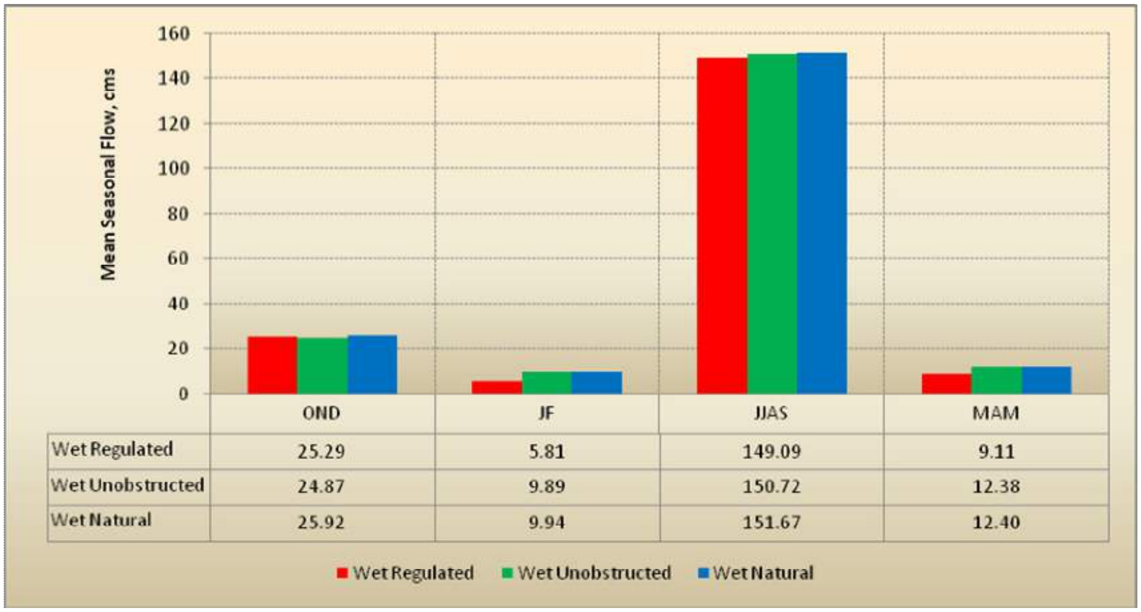


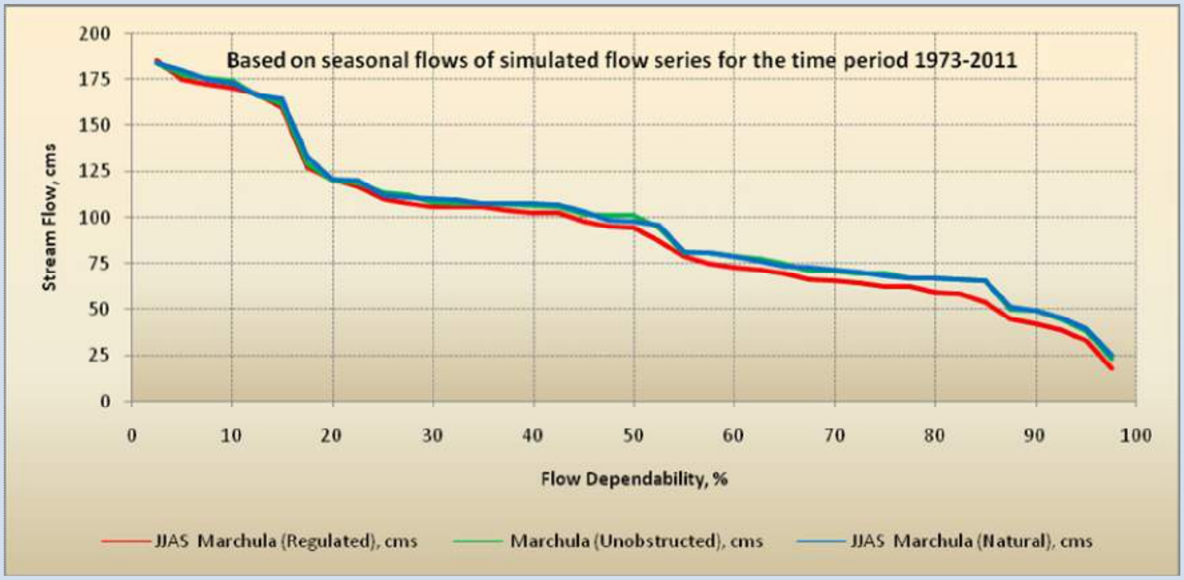
Table 8: Present day Regulated flow w.r.t. Natural (virgin) flow at Marchula EF site

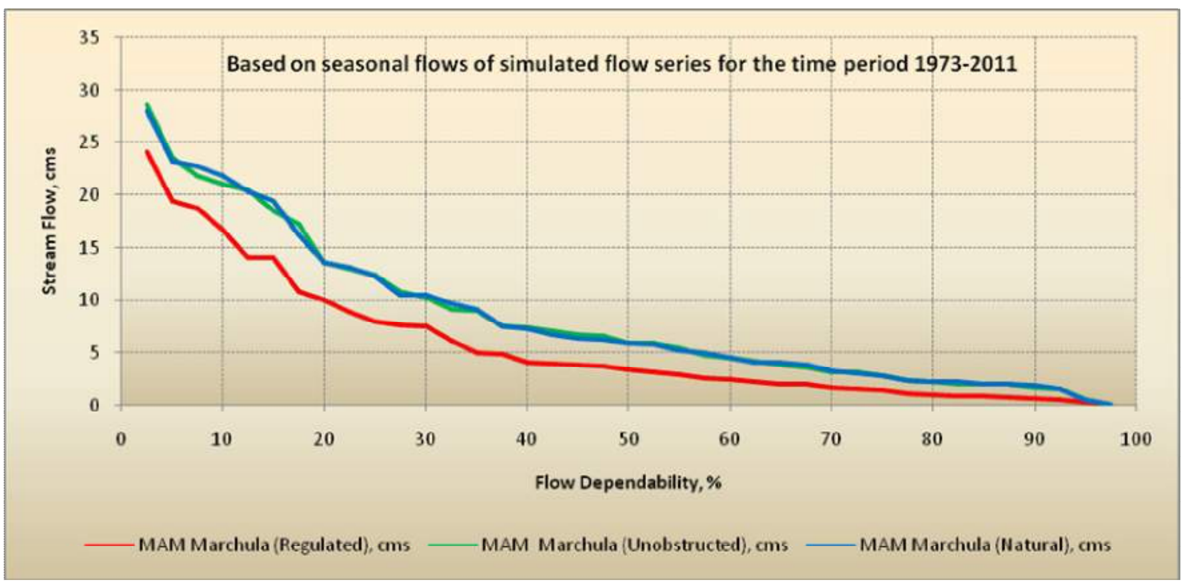
Season	Ratio of Regulated flow to Natural flow (Dry Year)	Ratio of Regulated flow to Natural flow (Normal Year)	Ratio of Regulated flow to Natural flow (Wet Year)
OND	0.91	0.99	0.98
JF	0.58	0.64	0.58
JJAS	0.87	0.95	0.98
MAM	0.53	0.67	0.73

From Table 8 it is evident that ratio of Regulated flow to Natural flow ranges from 0.53-0.73 in driest season (MAM). It reflects that there is less water withdrawals and water use upstream.

Flow duration curves for wettest and driest seasons are presented in Figure 13 while dependable values for all three scenarios are presented in Appendix 1

Figure 13: Flow duration curves for wettest (JJAS) and driest (MAM) season at Marchula EF site





From Figure 13 it is evident that there is considerable flow throughout the year in both wettest and driest seasons. The margin between Natural and Regulated flow is small which is attributed to less water use upstream. At 75% dependability Regulated flow during driest season is 1.40 cumecs while Natural flow is 2.87 cumecs.

Afzalgarh Barrage (D/s of Kalagarh)

Afzalgarh barrage EF site is the third site on the river stretch 52 km d/s of Marchula bridge where it is located just immediate downstream of Kalagarh dam. The flows here are all regulated in terms of releases from Kalagarh dam. A small portion of water is taken from half weir at the site to be used for irrigation. Annual flows and long term mean monthly flows for present day Regulated and Natural scenario is presented in .

Figure 14: Annual flows and Mean monthly flow regime at Afzalgarh barrage EF site

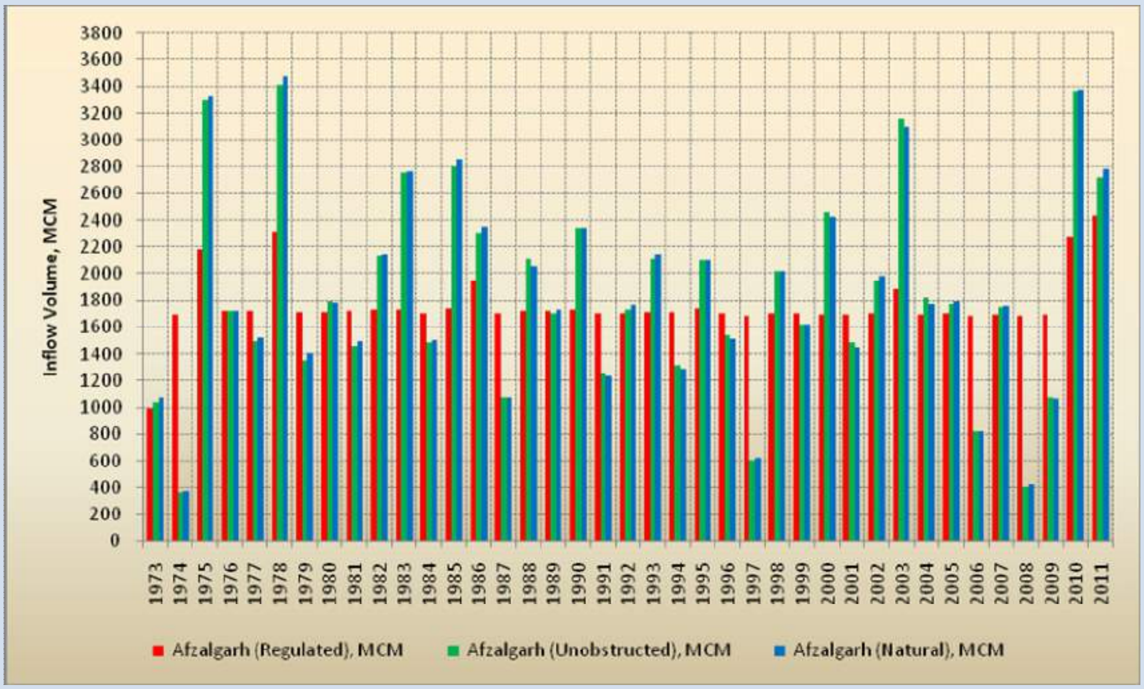
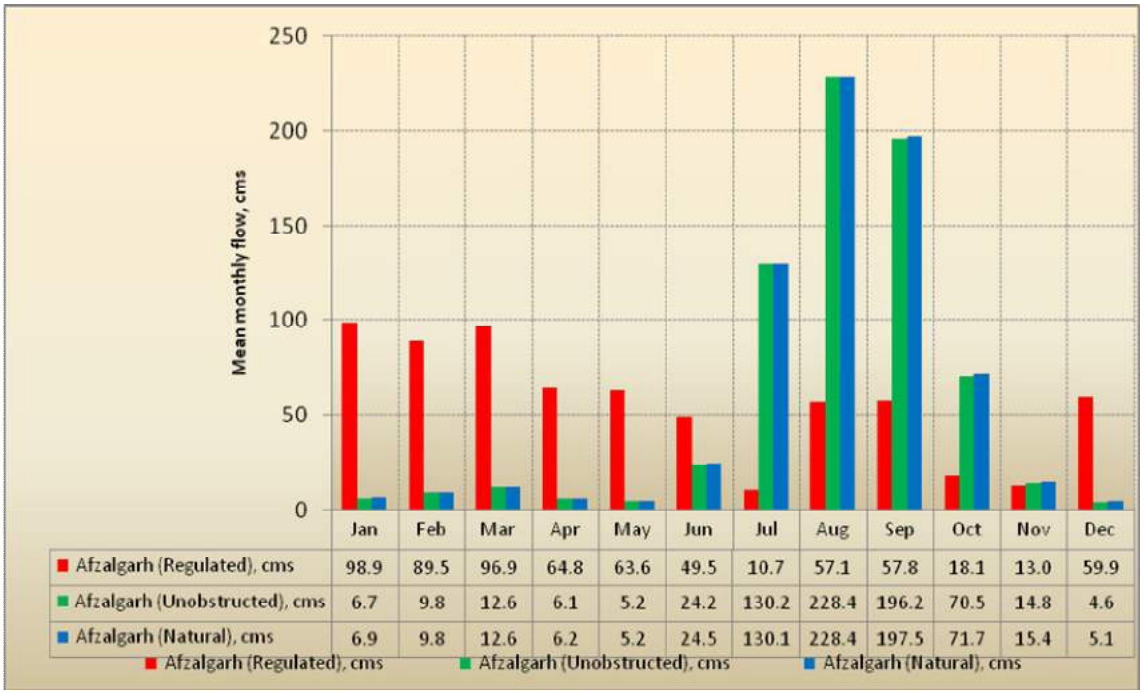


Figure 14: Annual flows and Mean monthly flow regime at Afzalgarh barrage EF site



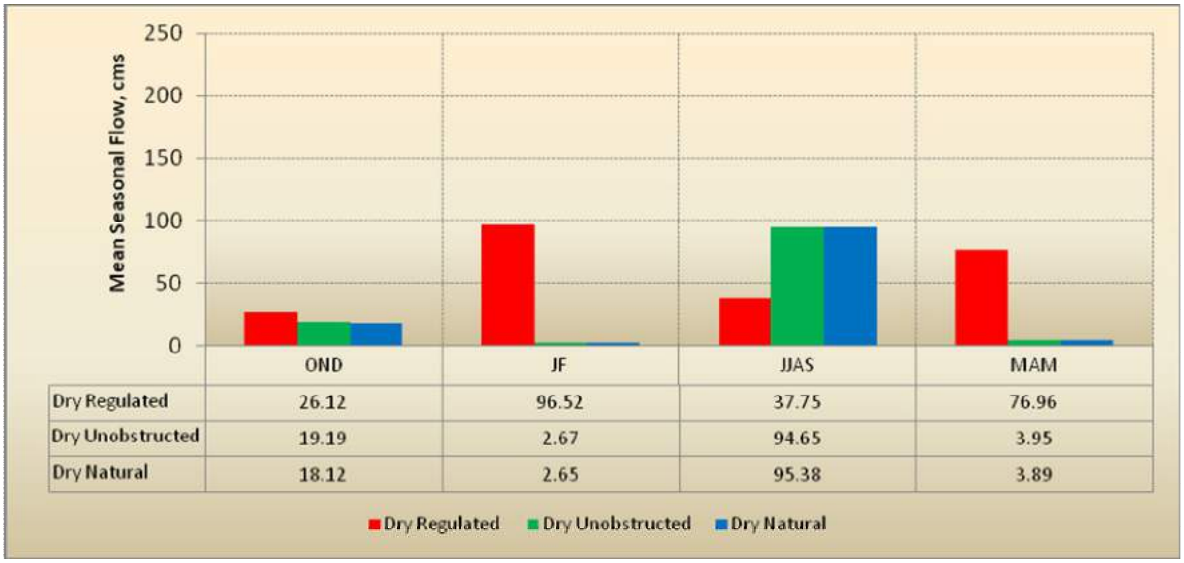
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Afzalgarh (Regulated), cms	98.9	89.5	96.9	64.8	63.6	49.5	10.7	57.1	57.8	18.1	13.0	59.9
Afzalgarh (Unobstructed), cms	6.7	9.8	12.6	6.1	5.2	24.2	130.2	228.4	196.2	70.5	14.8	4.6
Afzalgarh (Natural), cms	6.9	9.8	12.6	6.2	5.2	24.5	130.1	228.4	197.5	71.7	15.4	5.1

From it is evident that the maximum streamflow occurs in non monsoon months (especially from Jan-March). The inflow during monsoon months to Kalagarh dam is stored and only small amount of water is released downstream. The margin between Unobstructed flow and Natural flow is quite small due to less water use upstream. The Regulated flow regime at Afzalgarh does not follow normal flow regime due to highly regulated flow from Kalagarh dam.

Annual flows were classified as Dry, Normal or Wet year as per classification mentioned earlier. For each hydro class mean seasonal flows were compiled and are presented in .

Figure 15: Seasonal flows for various hydro class Afzalgarh barrage EF site

Dry Years



Normal years

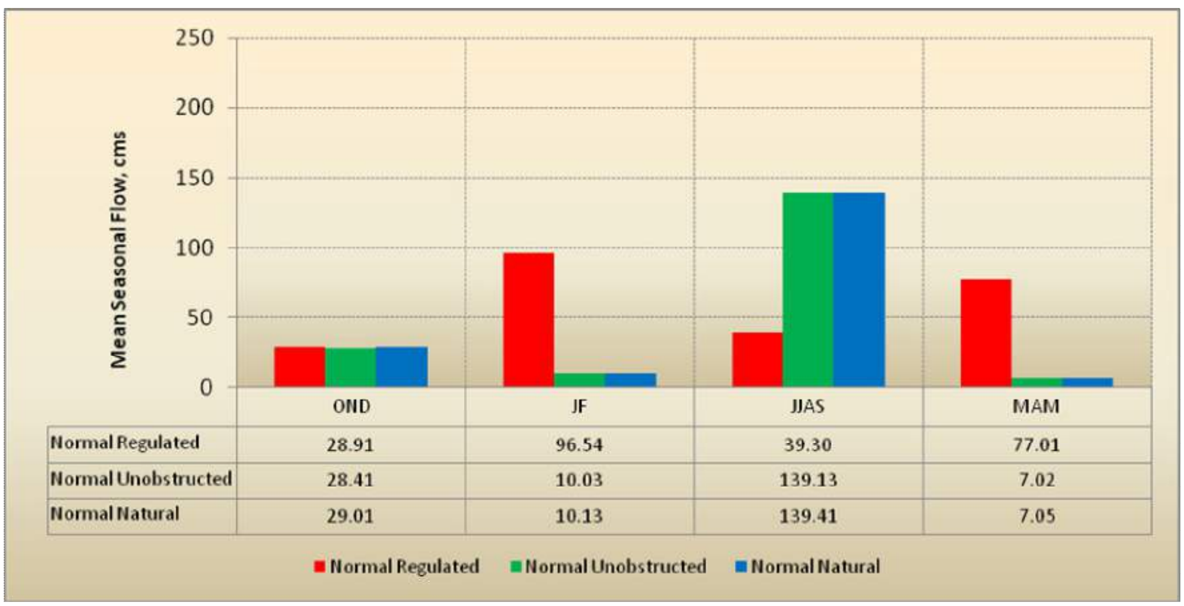


Figure 15: Seasonal flows for various hydro class Afzalgarh barrage EF site

Wet Years

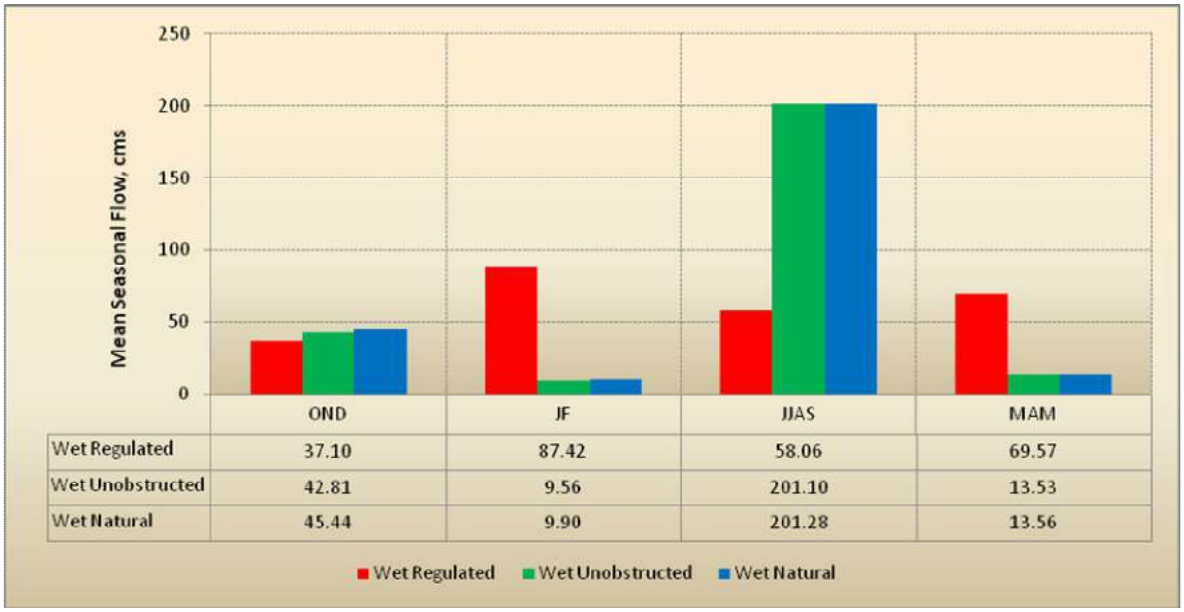


Table 9: Present day Regulated flow w.r.t. Natural (virgin) flow Afzalgarh barrage EF site

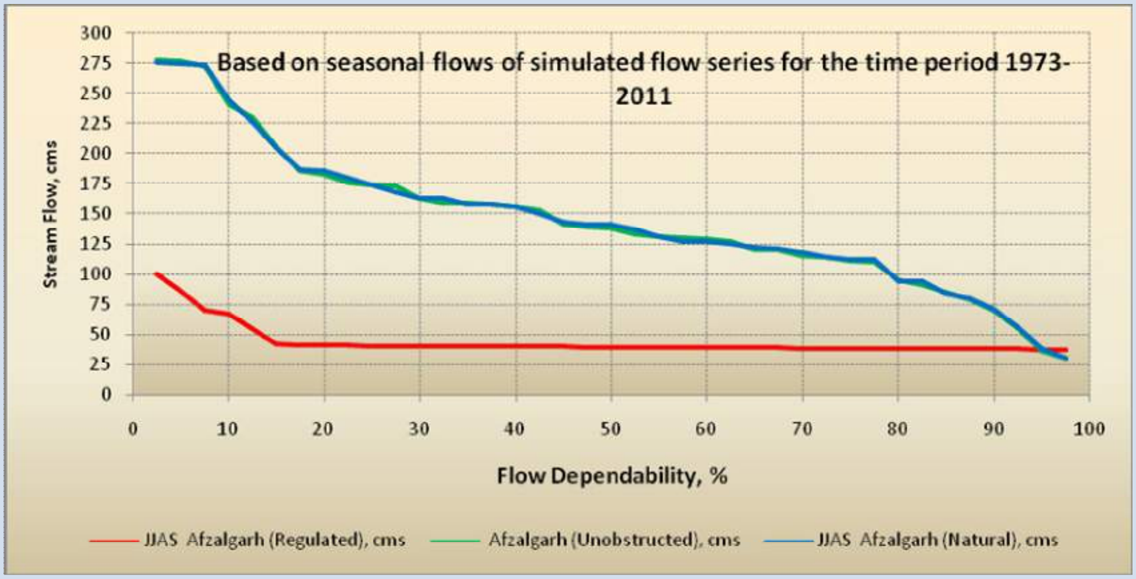
Season	Ratio of Regulated flow to Natural flow (Dry Year)	Ratio of Regulated flow to Natural flow (Normal Year)	Ratio of Regulated flow to Natural flow (Wet Year)
OND	1.44	1.00	0.82
JF	36.39	9.53	8.83
JJAS	0.40	0.28	0.29
MAM	19.81	10.92	5.13

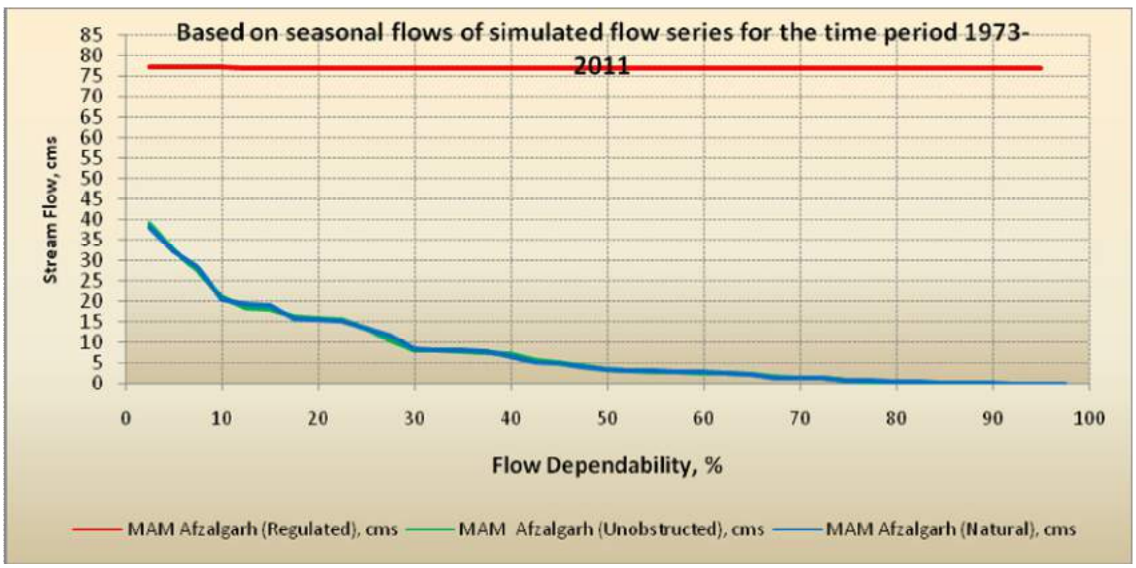
From it is evident that maximum Regulated flows occur in winter (JF) season followed by driest (MAM) season.

It is evident that ratio of Regulated flow to Natural flow ranges from 5.13-19.81 in driest season (MAM) while it ranges from 8.83-36.39 in winter (JF) season. During driest season the Regulated dependable flows exceeds Natural and Unobstructed flows.

Flow duration curves for wettest and driest seasons are presented in Figure 16 while dependable values for all three scenarios are presented in Appendix 1.

Figure 16: Flow duration curves for wettest (JJAS) and driest (MAM) season Afzalgarh barrage EF site





From Figure 16 it is evident that the flow has reduced to large extent and during dry season the flow is negligible. It is attributed to the reason that the flow at this EF site is all regulated from upstream Kalagarh dam. At 75% dependability Regulated flow during driest season is 76.9 cumecs while Natural flow is 0.74 cumecs.

Hareolli Barrage

Hareolli barrage EF site is the fourth site on the river stretch 23 km d/s of Afzalgarh barrage, the flows here also are all regulated flow in terms of releases from Kalagarh dam. And almost entire volume of water released from Kalagarh is transferred from main canals to Kho barrage. Flows d/s of Hareolli barrage is mainly due to irrigation return flow, small flash release and leakages from barrage gates. Annual flows and long term mean monthly flows for present day Regulated, Unobstructed and Natural scenario is presented in .

Figure 17: Annual flows and mean monthly flow regime at Hareolli barrage EF site

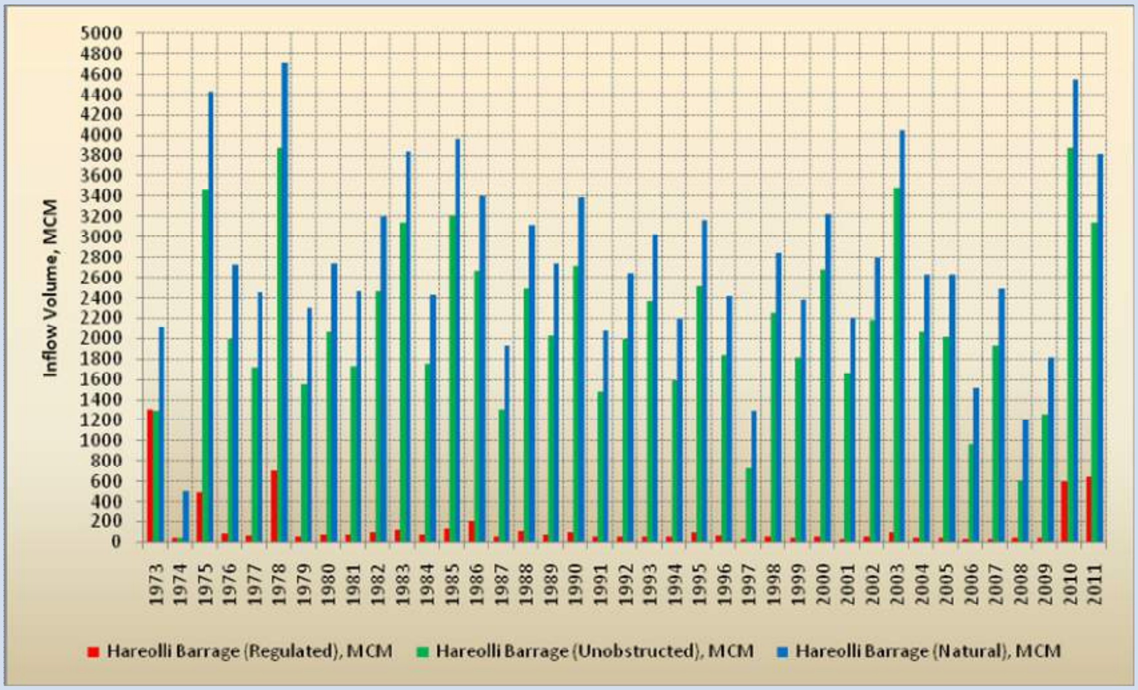
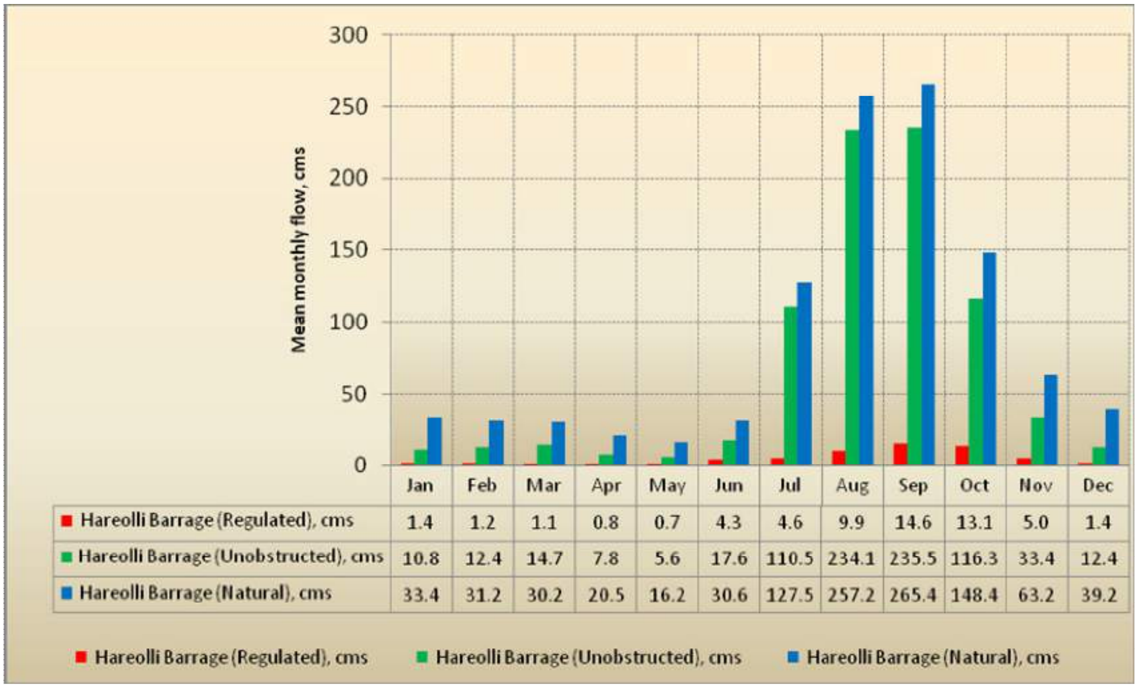


Figure 17: Annual flows and mean monthly flow regime at Hareolli barrage EF site



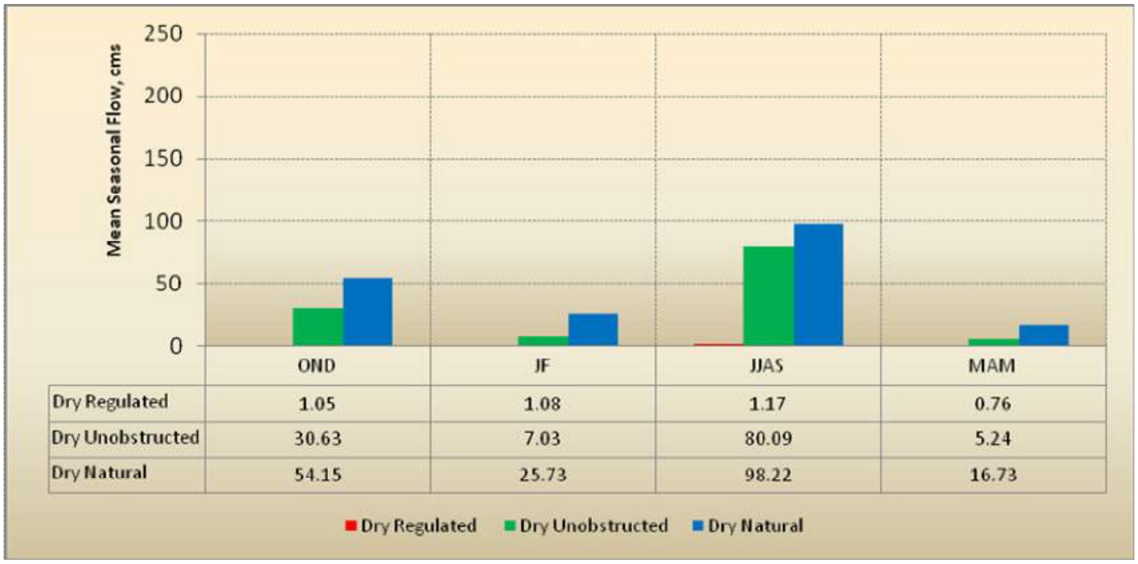
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Hareolli Barrage (Regulated), cms	1.4	1.2	1.1	0.8	0.7	4.3	4.6	9.9	14.6	13.1	5.0	1.4
Hareolli Barrage (Unobstructed), cms	10.8	12.4	14.7	7.8	5.6	17.6	110.5	234.1	235.5	116.3	33.4	12.4
Hareolli Barrage (Natural), cms	33.4	31.2	30.2	20.5	16.2	30.6	127.5	257.2	265.4	148.4	63.2	39.2

From it is evident that there is negligible Regulated flows d/s of Hareolli barrage as compared to Natural/Unobstructed flows.

Annual flows were classified as Dry, Normal or Wet year as per classification mentioned earlier. For each hydro class mean seasonal flows were compiled and are presented in .

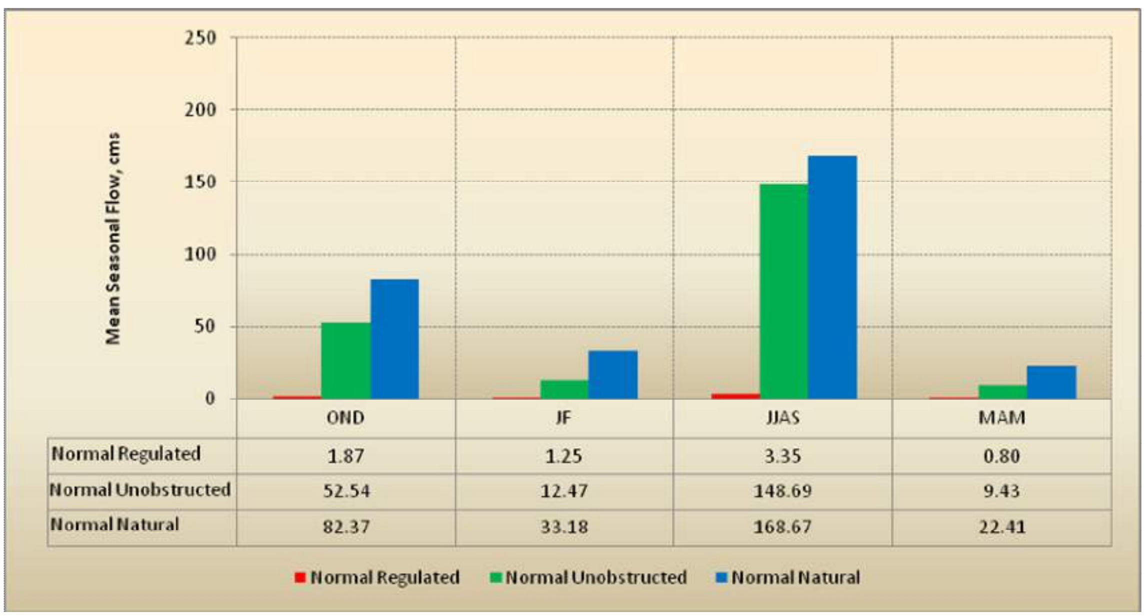
Figure 18: Seasonal flows for various hydro class at Hareolli barrage EF site

Dry Years



	OND	JF	JJAS	MAM
Dry Regulated	1.05	1.08	1.17	0.76
Dry Unobstructed	30.63	7.03	80.09	5.24
Dry Natural	54.15	25.73	98.22	16.73

Normal years



	OND	JF	JJAS	MAM
Normal Regulated	1.87	1.25	3.35	0.80
Normal Unobstructed	52.54	12.47	148.69	9.43
Normal Natural	82.37	33.18	168.67	22.41

Wet years

Figure 18: Seasonal flows for various hydro class at Hareolli barrage EF site

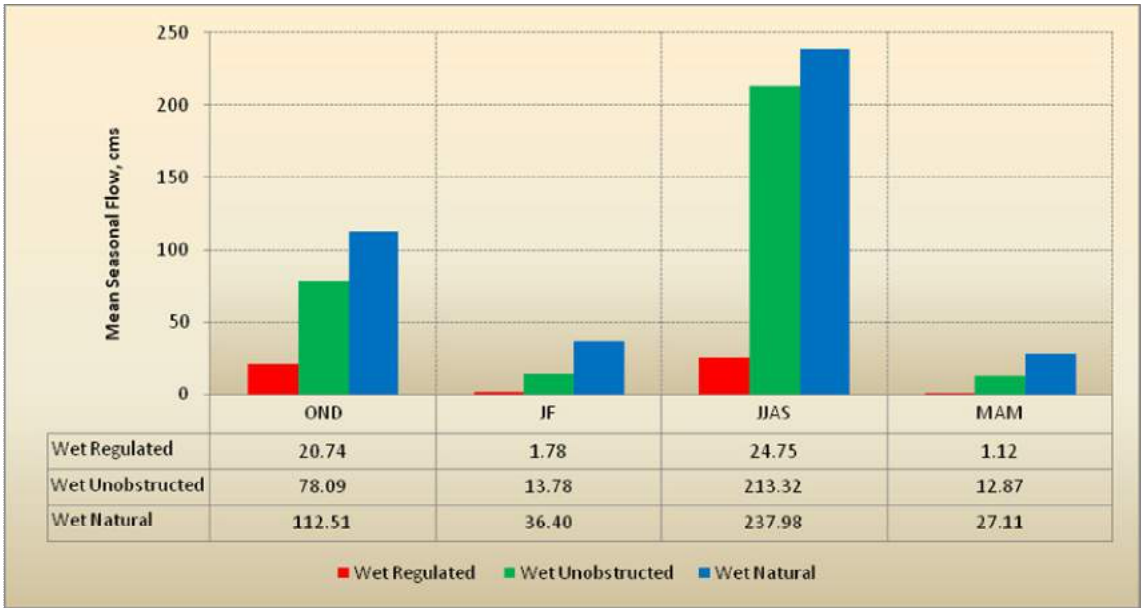


Table 10: Present day Regulated flow w.r.t. Natural (virgin) flow at Hareolli barrage EF site

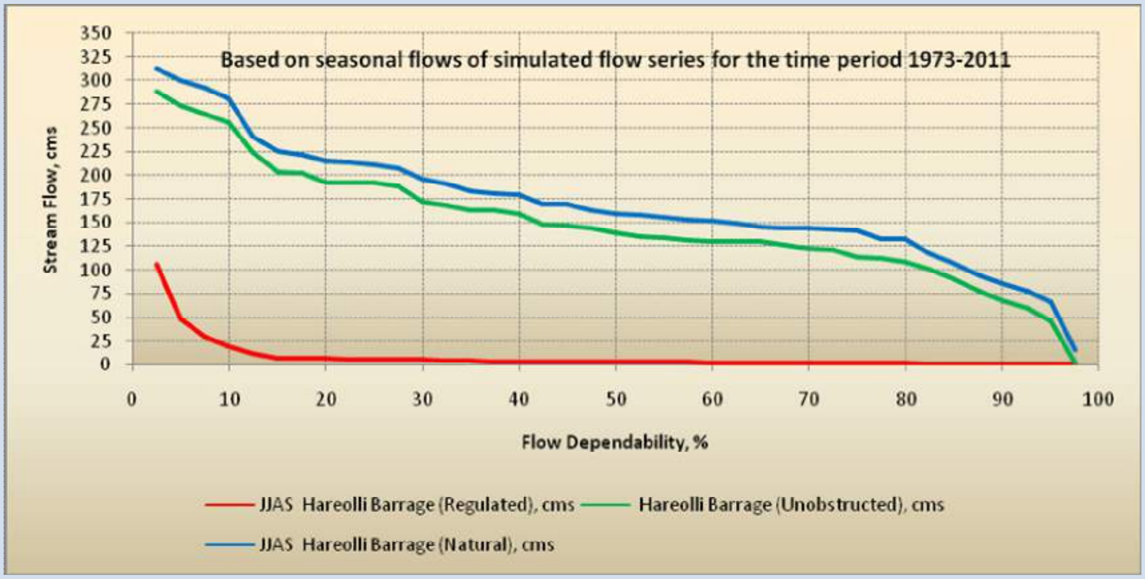
Season	Ratio of Regulated flow to Natural flow (Dry Year)	Ratio of Regulated flow to Natural flow (Normal Year)	Ratio of Regulated flow to Natural flow (Wet Year)
OND	0.02	0.02	0.18
JF	0.04	0.04	0.05
JJAS	0.01	0.02	0.10
MAM	0.05	0.04	0.04

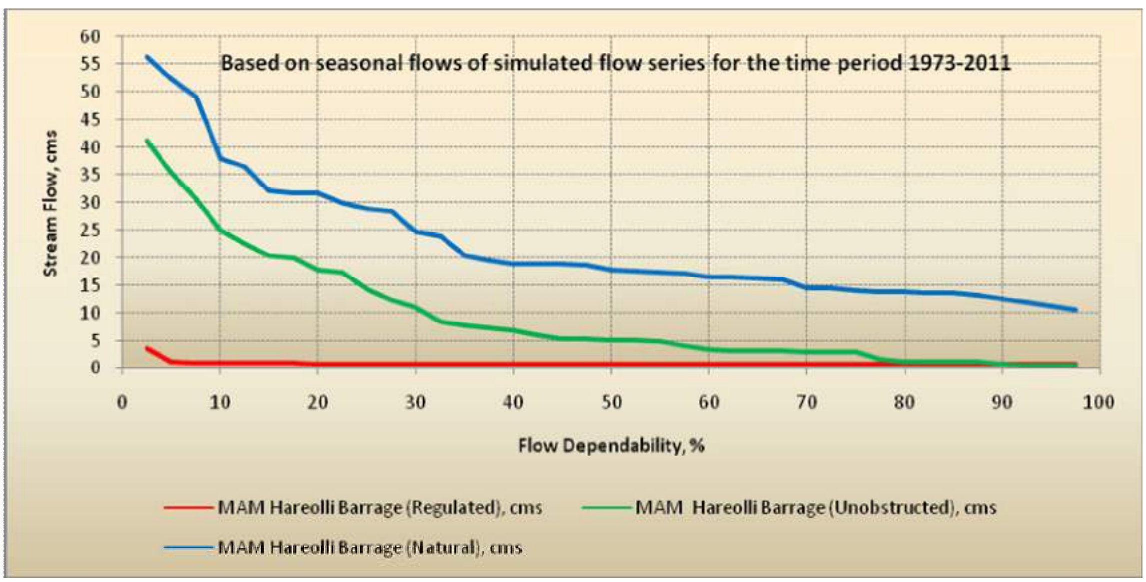
From

Table 10 it is evident that the Natural flow has been altered to large extent and present Regulated flow is negligible proportion of Natural flow. Ratio of Regulated to Natural flows ranges from 0.04-0.05 in driest season (MAM) which signifies that there is large water withdrawals and water use upstream of barrage where water is transferred through canal to Kho barrage.

Flow duration curves for wettest and driest seasons are presented in Figure 19 while dependable values for all three scenarios are presented in Appendix 1

Figure 19: Flow duration curves for wettest (JJAS) and driest (MAM) season at Hareolli barrage EF site





From Figure 19 it is evident that the flow has reduced to large extent and during both dry and wet season the flow is negligible. It is attributed to the reason that the flow at this EF site is all regulated from barrage. At 75% dependability, the Regulated flow during driest season is 0.75 cumecs while Natural flow is 13.96 cumecs.

Aghwanpur

Aghwanpur EF site is the fifth site on the river stretch 86 km d/s of Hareolli barrage, the stream flows during non monsoon seasons are mainly due to irrigation return flow. Annual flows and long term mean monthly flows for Regulated, Unobstructed and Natural scenario is presented in .

Figure 20: Annual flows and mean monthly flow regime at Aghwanpur EF site

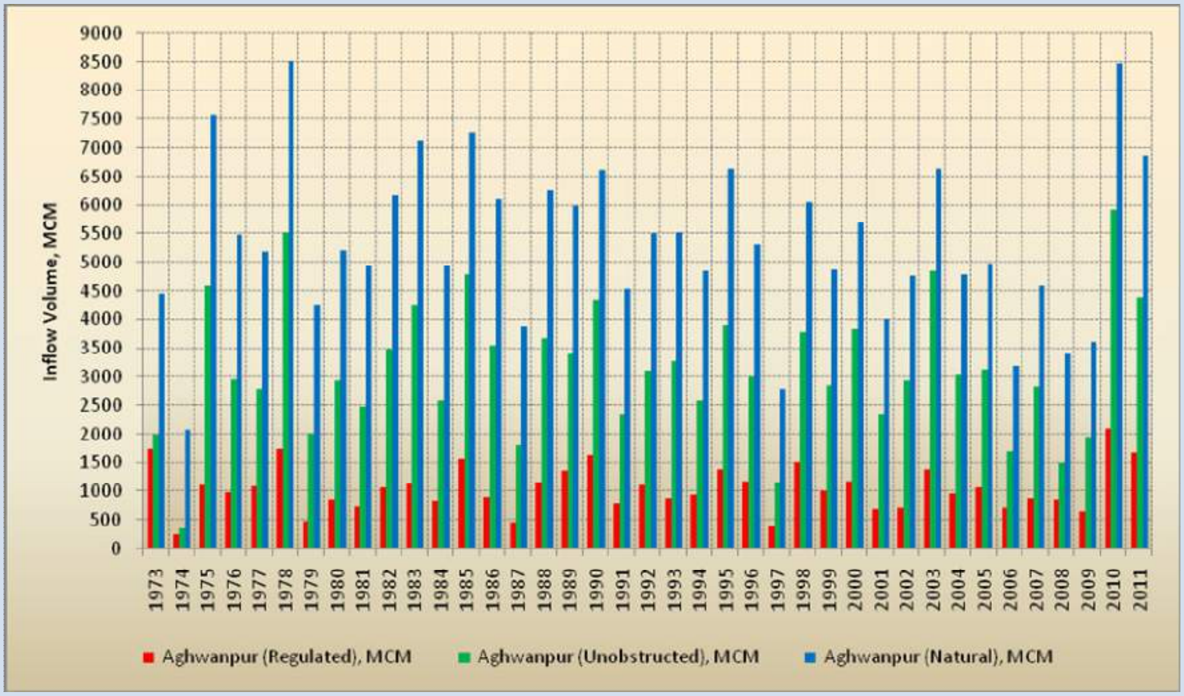
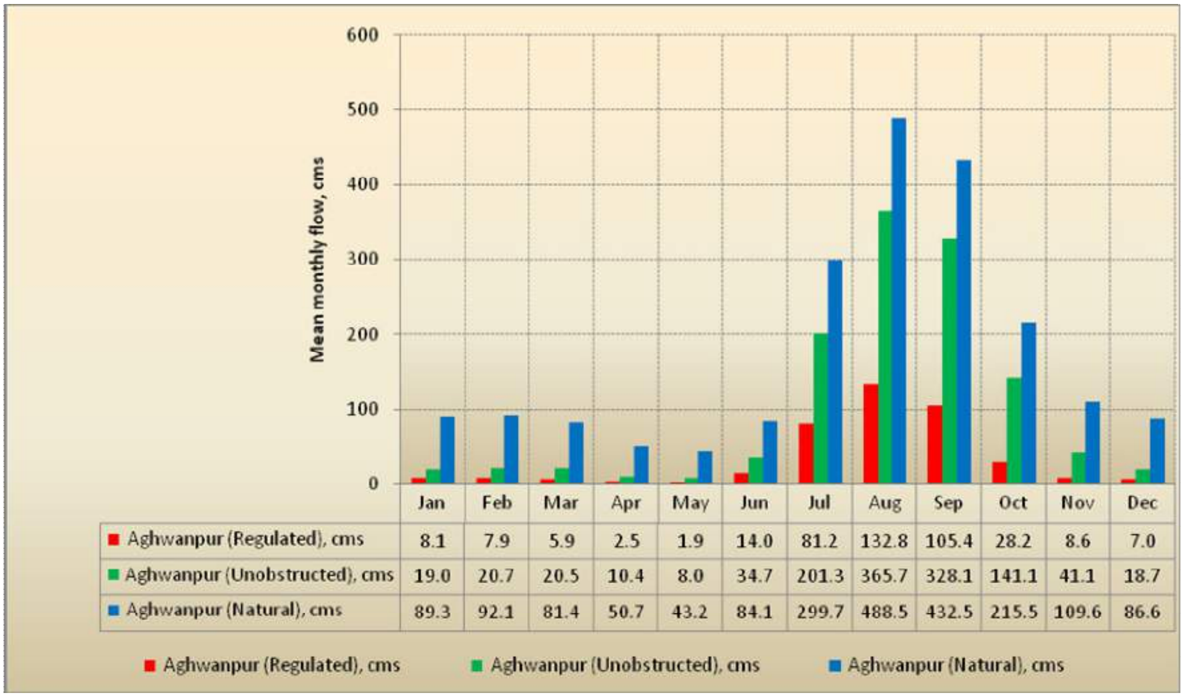


Figure 20: Annual flows and mean monthly flow regime at Aghwanpur EF site



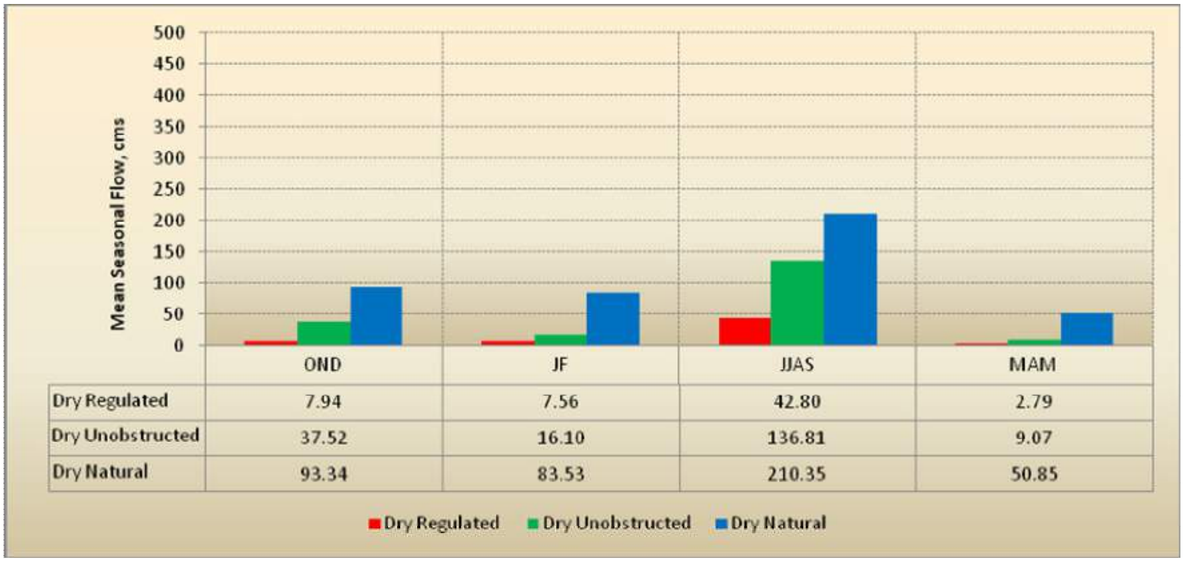
From it is evident that maximum regulated flow occurs in month of august while lowest in month of May. It is also observed that regulated flows had increased as compared to upstream Hareolli EF site which is due to the contribution of irrigation return flow from intermediate catchment.

Annual flows were classified as Dry, Normal or Wet year as per classification mentioned earlier. For each hydro class mean seasonal flows were compiled and are presented in .

Figure 21: Seasonal flows for various hydro class at Aghwanpur EF site

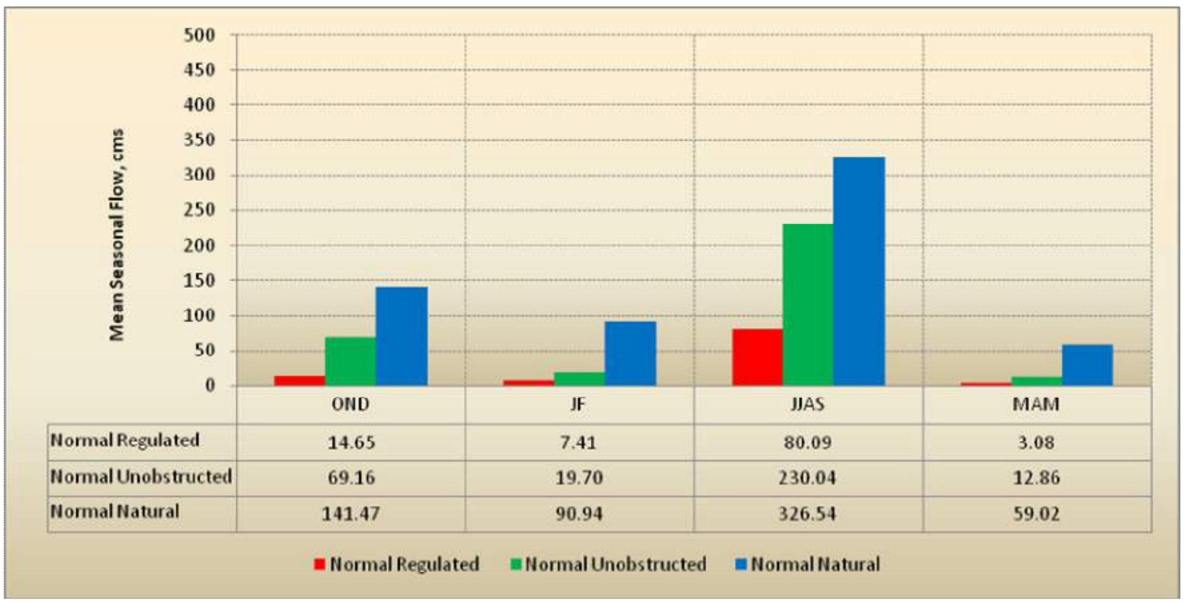
Dry years

Figure 21: Seasonal flows for various hydro class at Aghwanpur EF site



	OND	JF	JJAS	MAM
Dry Regulated	7.94	7.56	42.80	2.79
Dry Unobstructed	37.52	16.10	136.81	9.07
Dry Natural	93.34	83.53	210.35	50.85

Normal years



	OND	JF	JJAS	MAM
Normal Regulated	14.65	7.41	80.09	3.08
Normal Unobstructed	69.16	19.70	230.04	12.86
Normal Natural	141.47	90.94	326.54	59.02

Figure 21: Seasonal flows for various hydro class at Aghwanpur EF site

Wet years

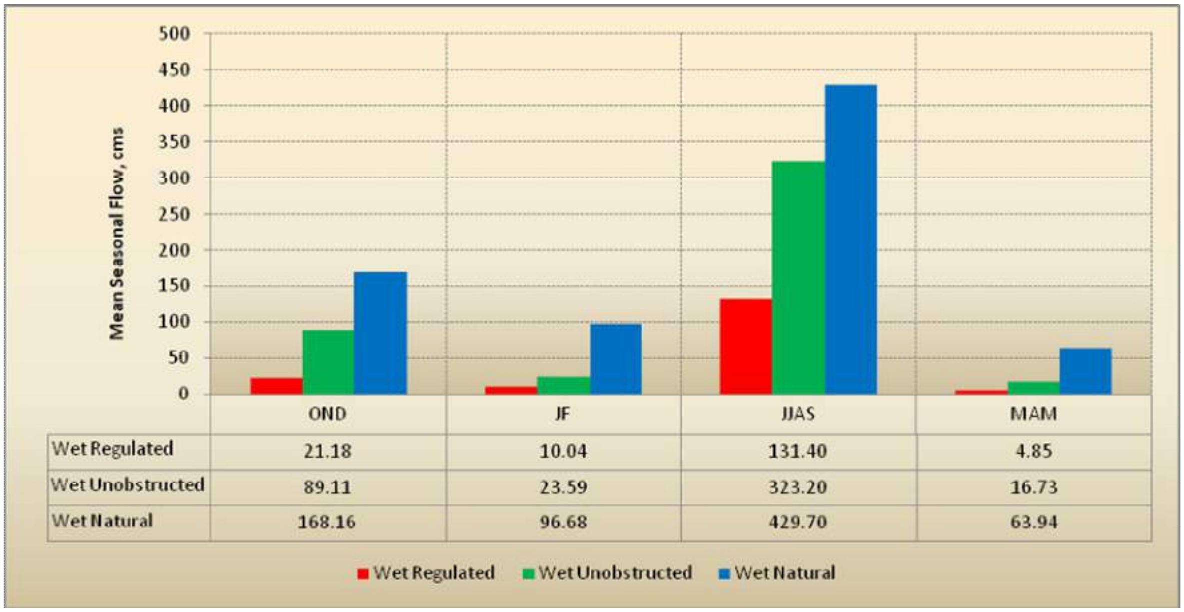


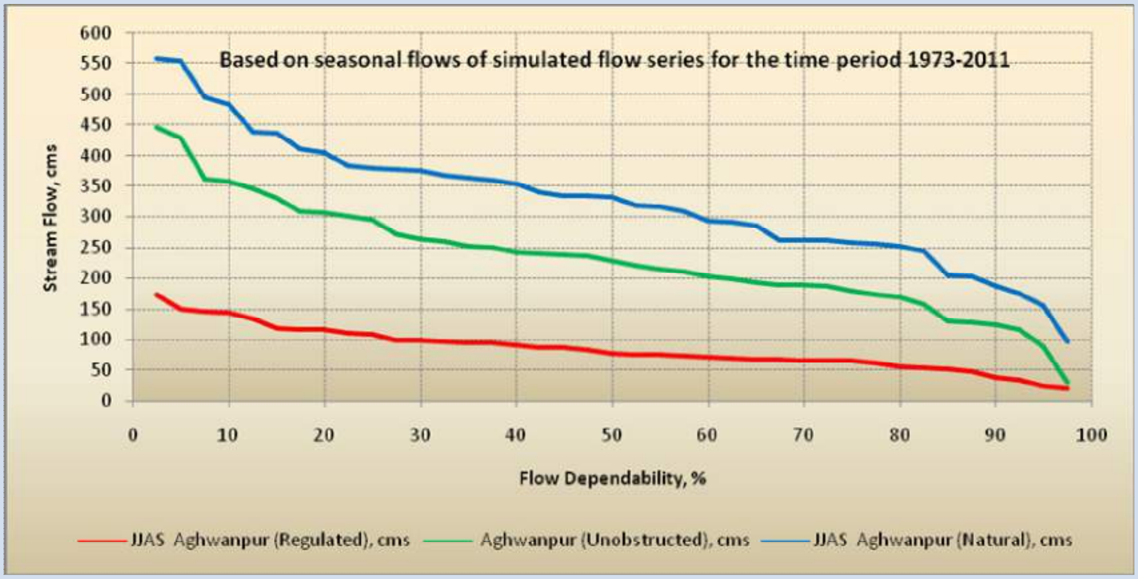
Table 11: Present day Regulated flow w.r.t. Natural (virgin) flow at Aghwanpur EF site

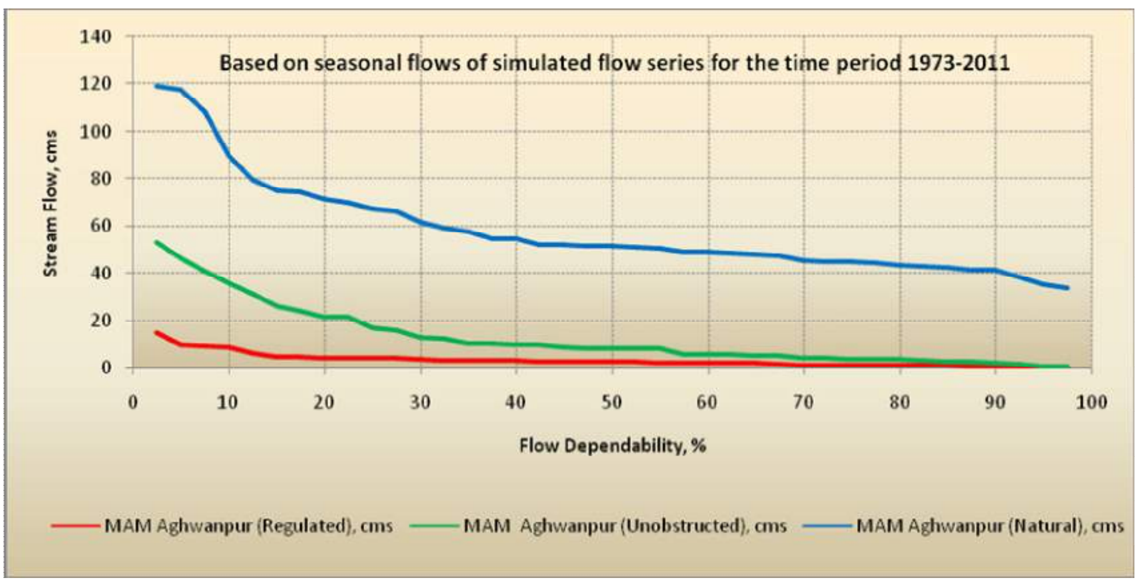
Season	Ratio of Regulated flow to Natural flow (Dry Year)	Ratio of Regulated flow to Natural flow (Normal Year)	Ratio of Regulated flow to Natural flow (Wet Year)
OND	0.09	0.10	0.13
JF	0.09	0.08	0.10
JJAS	0.20	0.25	0.31
MAM	0.05	0.05	0.08

Mean seasonal flows has increased as compared to Hareolli barrage EF site, mainly due to increase in catchment area which brings more water from agriculture lands in terms of irrigation return flow. It is evident from Table 11 that ratio of Regulated flow to Natural flow ranges from 0.05-0.08 in driest season (MAM).

Flow duration curves for wettest and driest seasons are presented in Figure 22 while dependable values for all three scenarios are presented in Appendix 1.

Figure 22: Flow duration curves for wettest (JJAS) and driest (MAM) season at Aghwanpur EF site





From Figure 22 it is evident that the flow has increased w.r.t. Hareolli barrage EF site. Even in driest season 1.29 cumecs of water (regulated flow) flowing in the stream at 75% dependability.

Katghar Railway bridge, Moradabad

Moradabad EF site is the sixth site on the river stretch 22 km d/s of Aghwanpur. The stream flows during non monsoon seasons are mainly due to irrigation return flow and small amount of sewage water from Moradabad city which is directly dumped into river at EF site. Annual flows and long term mean monthly flows for Regulated, Unobstructed and Natural scenario is presented in

.

Figure 23: Annual flows and Mean monthly flow regime at Katghar Railway bridge, Moradabad EF site

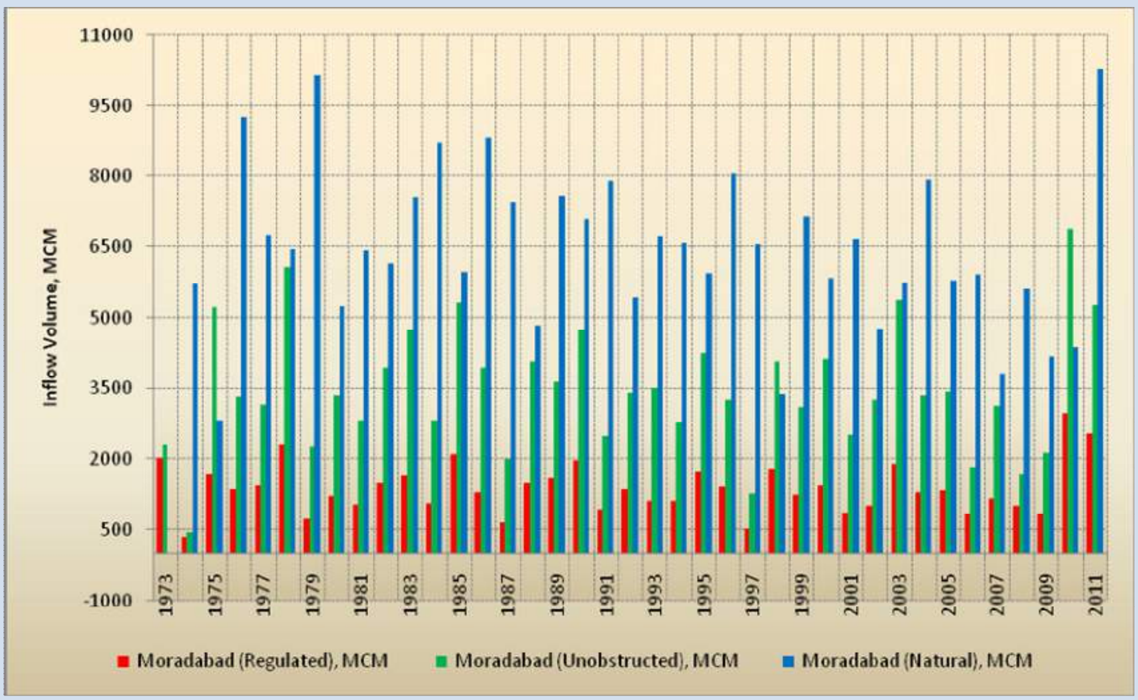
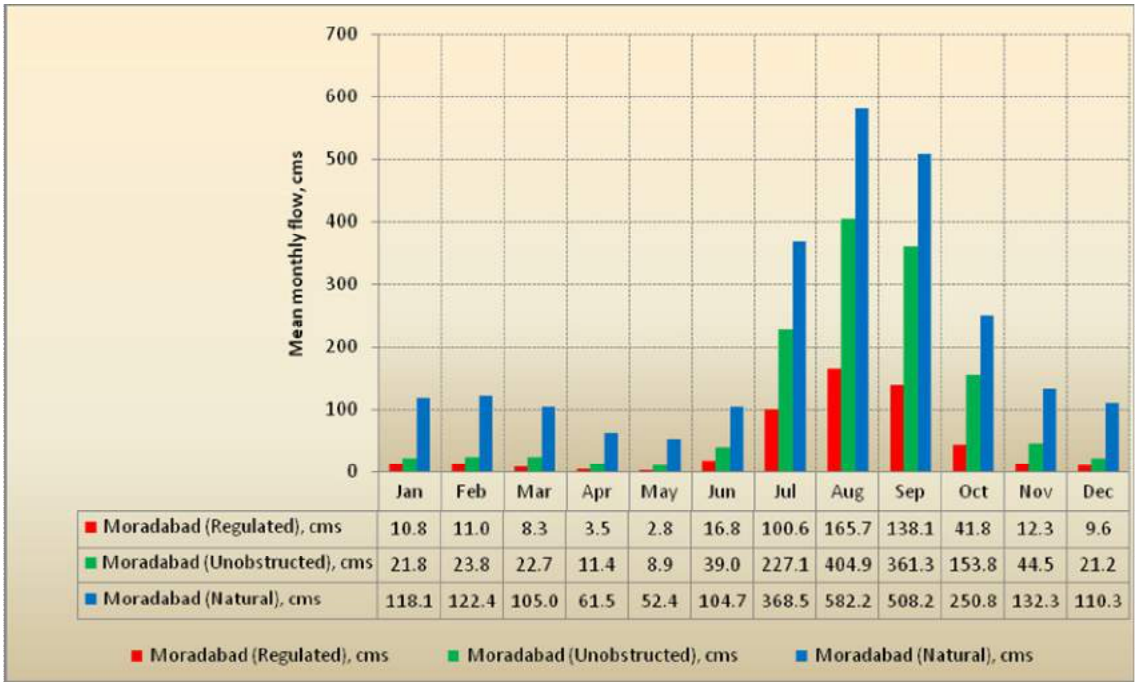


Figure 23: Annual flows and Mean monthly flow regime at Katghar Railway bridge, Moradabad EF site



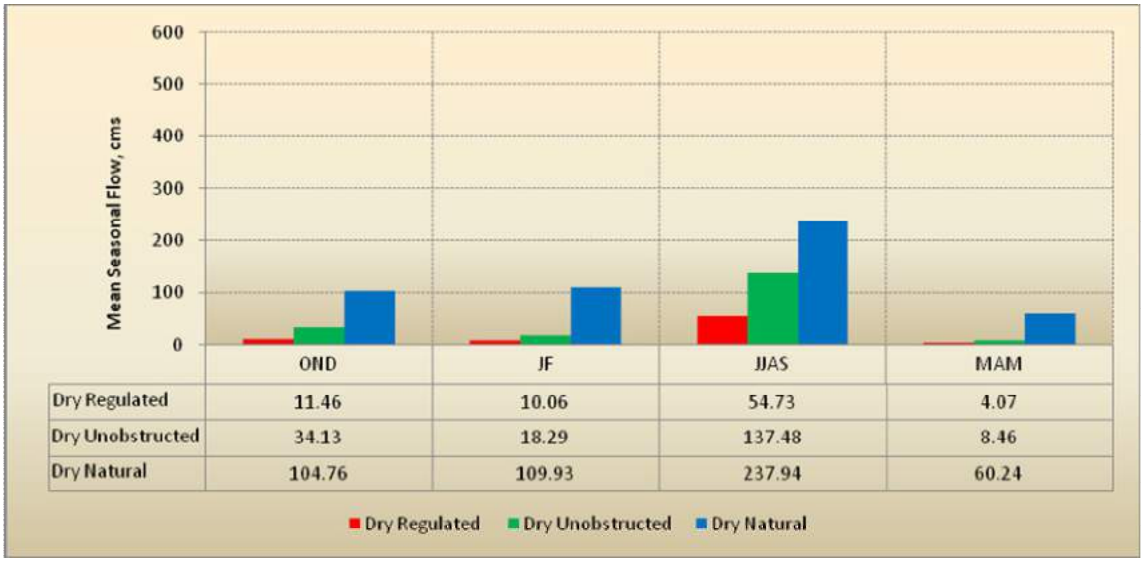
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Moradabad (Regulated), cms	10.8	11.0	8.3	3.5	2.8	16.8	100.6	165.7	138.1	41.8	12.3	9.6
Moradabad (Unobstructed), cms	21.8	23.8	22.7	11.4	8.9	39.0	227.1	404.9	361.3	153.8	44.5	21.2
Moradabad (Natural), cms	118.1	122.4	105.0	61.5	52.4	104.7	368.5	582.2	508.2	250.8	132.3	110.3

From it is evident that mean monthly regulated flow is maximum in August (165.7 cumecs) and minimum in month of May (2.8 cumecs).

Annual flows were classified as Dry, Normal or Wet year as per classification mentioned earlier. For each hydro class mean seasonal flows were compiled and are presented in .

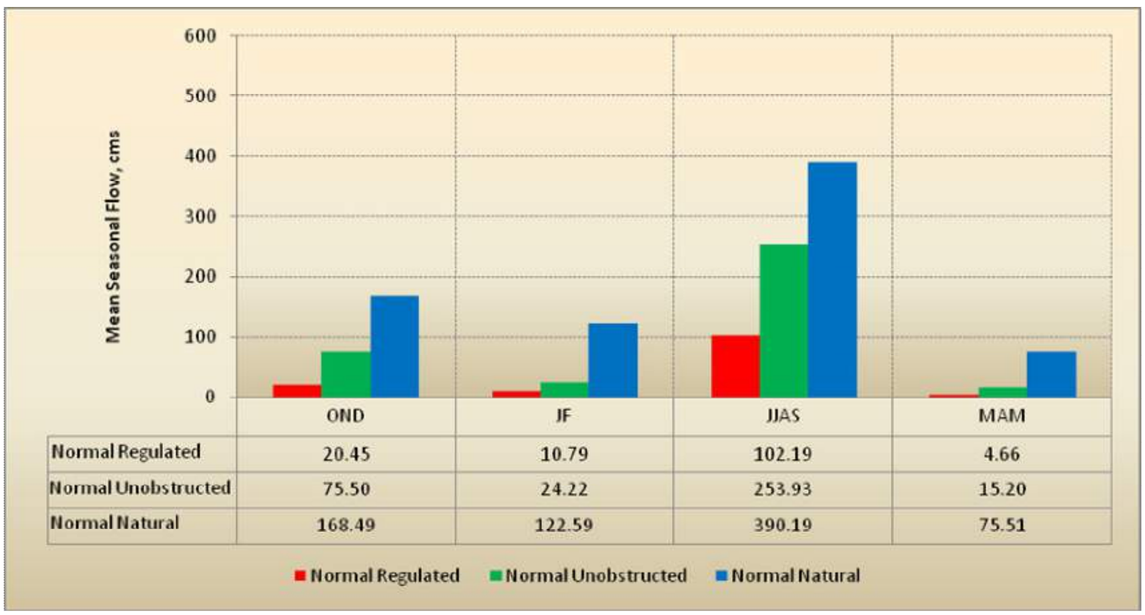
Figure 24: Seasonal flows for various hydro class at Katghar Railway bridge, Moradabad EF site

Dry years



	OND	JF	JJAS	MAM
Dry Regulated	11.46	10.06	54.73	4.07
Dry Unobstructed	34.13	18.29	137.48	8.46
Dry Natural	104.76	109.93	237.94	60.24

Normal years



	OND	JF	JJAS	MAM
Normal Regulated	20.45	10.79	102.19	4.66
Normal Unobstructed	75.50	24.22	253.93	15.20
Normal Natural	168.49	122.59	390.19	75.51

Figure 24: Seasonal flows for various hydro class at Katghar Railway bridge, Moradabad EF site

Wet years

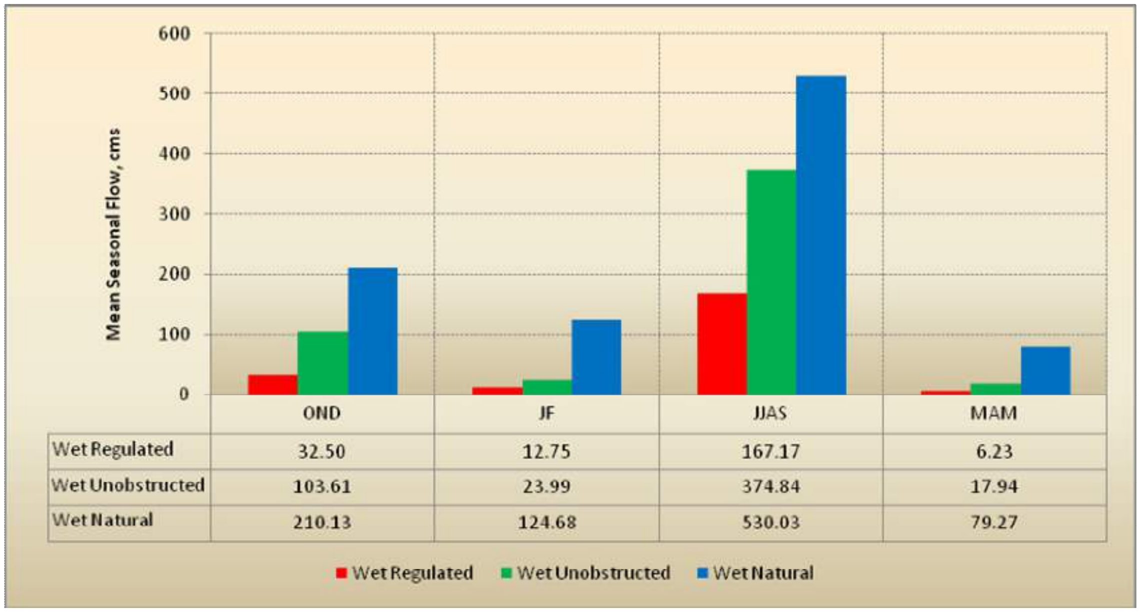


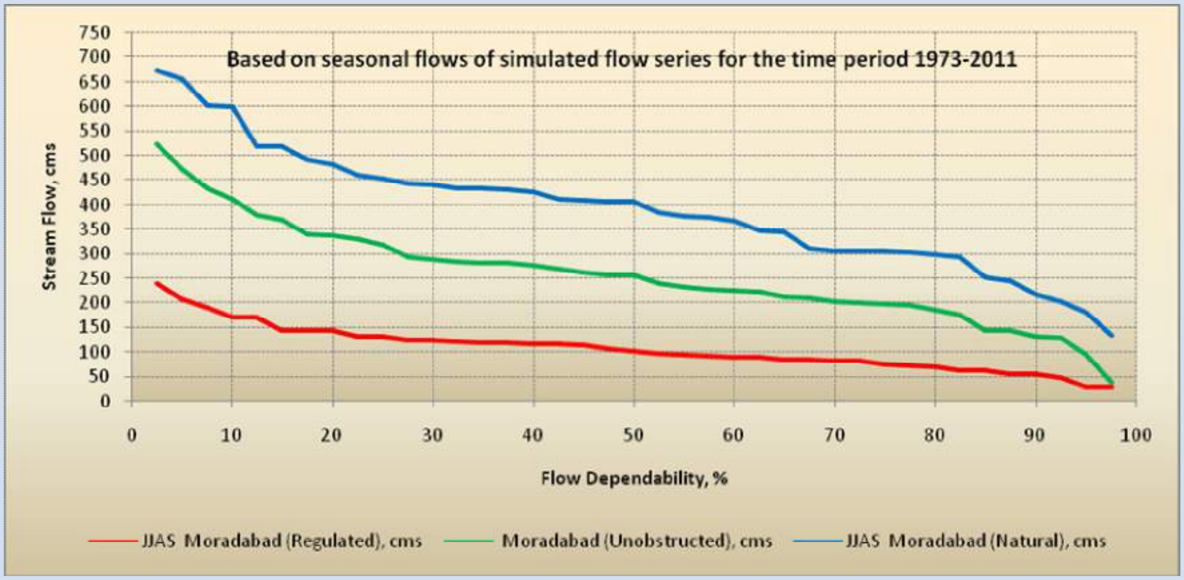
Table 12: Present day Regulated flow w.r.t. Natural (virgin) flow at Katghar Railway bridge, Moradabad EF site

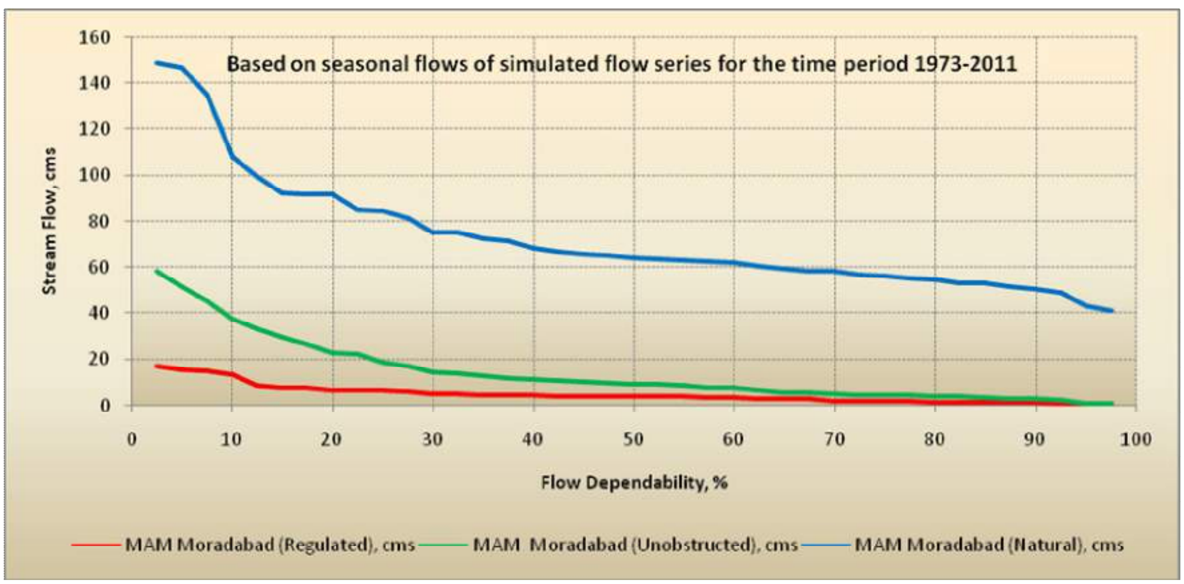
Season	Ratio of Regulated flow to Natural flow (Dry Year)	Ratio of Regulated flow to Natural flow (Normal Year)	Ratio of Regulated flow to Natural flow (Wet Year)
OND	0.11	0.12	0.15
JF	0.09	0.09	0.10
JJAS	0.23	0.26	0.32
MAM	0.07	0.06	0.08

Mean non monsoon seasonal flows has increased as compared to Aghwanpur barrage EF site, mainly due to increase in catchment area which brings more water from agriculture lands in terms of irrigation return flow. From Table 12 it is evident that ratio of Regulated flow to Natural flow ranges from 0.06-0.08 in driest season (MAM).

Flow duration curves for wettest and driest seasons are presented in Figure 25 while dependable values for all three scenarios are presented in Appendix 1.

Figure 25: Flow duration curves for wettest (JJAS) and driest (MAM) season at Katghar Railway bridge, Moradabad EF site





From Figure 25 it is evident that the flow (wettest and driest season) has increased w.r.t. Aghwanpur EF site. Even in driest season there is 1.87 cumecs of water flowing in the stream at 75% dependability.

Chaubari, Bareilly

Chaubari near Bareilly EF site is the seventh site on the river stretch 108 km d/s of Moradabad EF site. The stream flows during non monsoon seasons are mainly due to irrigation return flow. Annual flows and long term mean monthly flows for Regulated, Unobstructed and Natural scenario is presented in .

Figure 26: Annual flows and mean monthly flow regime at Chaubari, Bareilly EF site

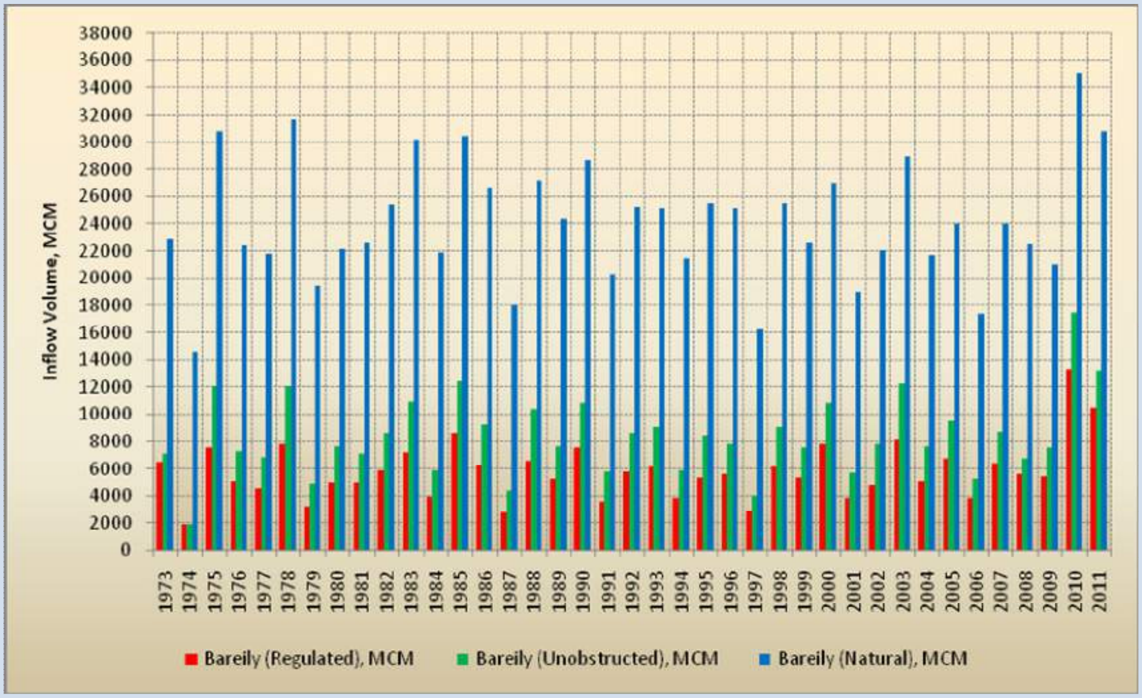
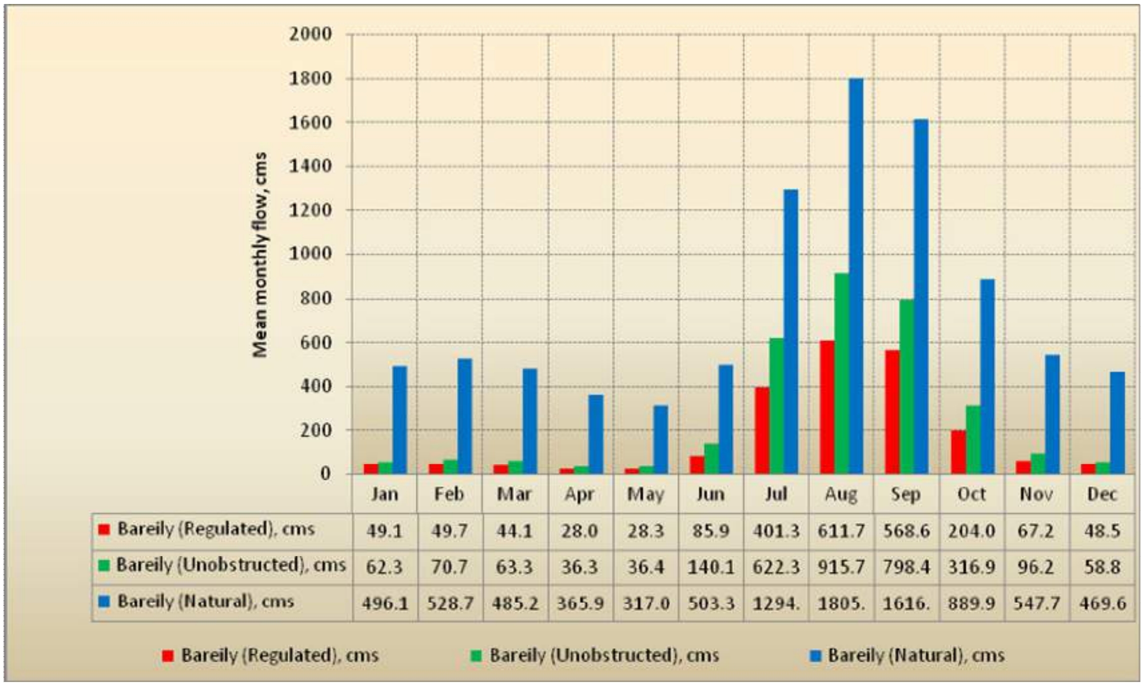


Figure 26: Annual flows and mean monthly flow regime at Chaubari, Bareilly EF site



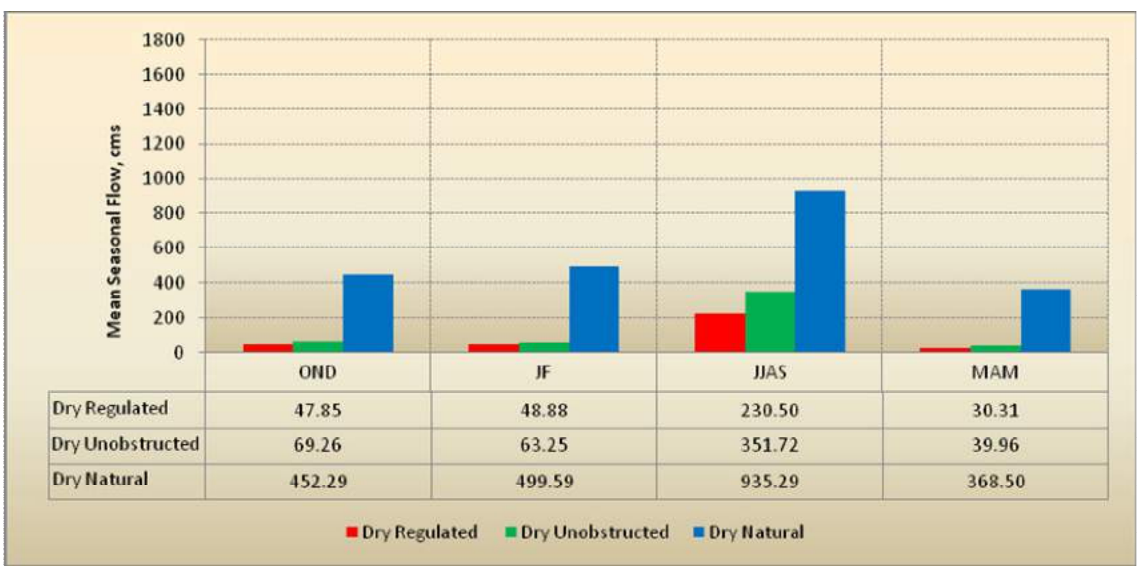
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bareily (Regulated), cms	49.1	49.7	44.1	28.0	28.3	85.9	401.3	611.7	568.6	204.0	67.2	48.5
Bareily (Unobstructed), cms	62.3	70.7	63.3	36.3	36.4	140.1	622.3	915.7	798.4	316.9	96.2	58.8
Bareily (Natural), cms	496.1	528.7	485.2	365.9	317.0	503.3	1294.	1805.	1616.	889.9	547.7	469.6

From it is evident that mean monthly regulated flows is maximum in month of august (611.7 cumecs) while it is minimum in months of Arpil-May (28 cumecs).

Annual flows were classified as Dry, Normal or Wet year as per classification mentioned earlier. For each hydro class mean seasonal flows were compiled and are presented in .

Figure 27: Seasonal flows for various hydro class Chaubari, Bareilly EF site

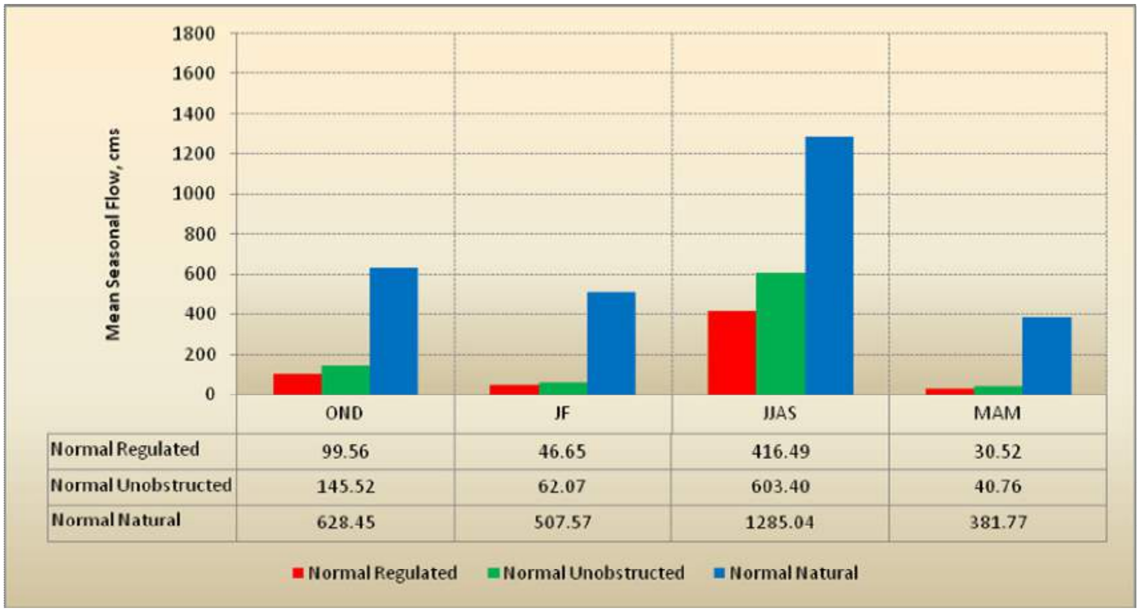
Dry years



	OND	JF	JJAS	MAM
Dry Regulated	47.85	48.88	230.50	30.31
Dry Unobstructed	69.26	63.25	351.72	39.96
Dry Natural	452.29	499.59	935.29	368.50

Figure 27: Seasonal flows for various hydro class Chaubari, Bareilly EF site

Normal years



	OND	JF	JJAS	MAM
Normal Regulated	99.56	46.65	416.49	30.52
Normal Unobstructed	145.52	62.07	603.40	40.76
Normal Natural	628.45	507.57	1285.04	381.77

Figure 27: Seasonal flows for various hydro class Chaubari, Bareilly EF site

Wet years

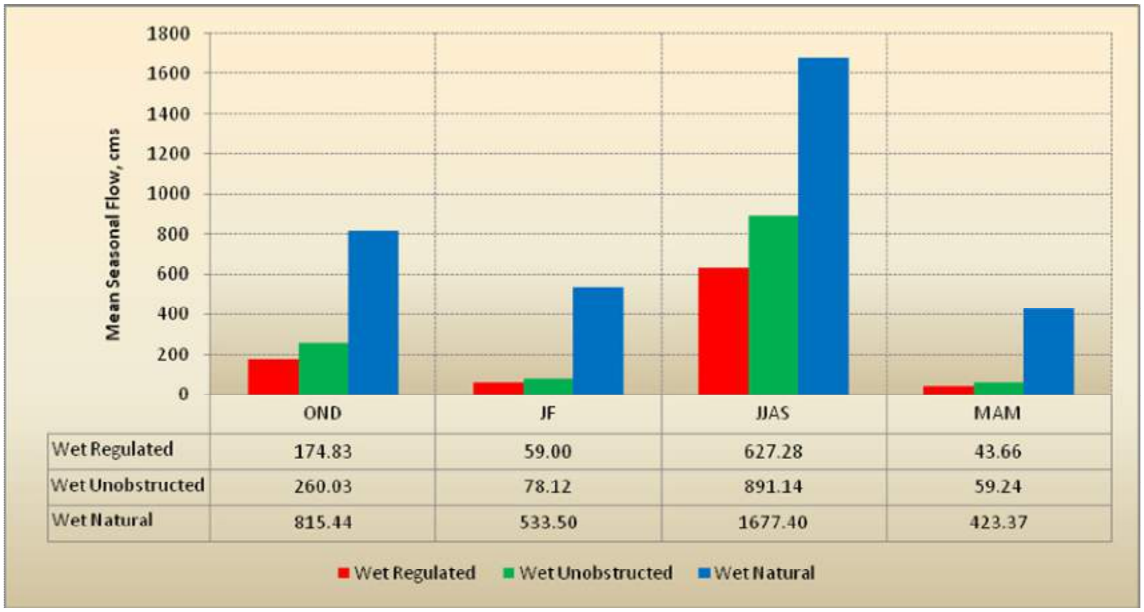


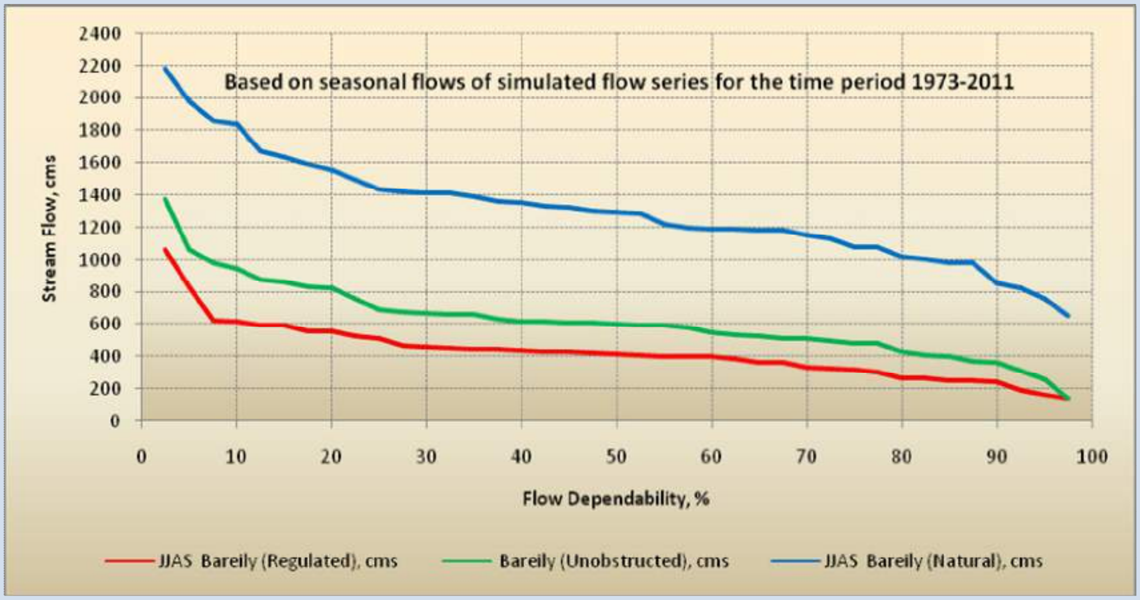
Table 13: Present day Regulated flow w.r.t. Natural (Virgin) flow Chaubari, Bareilly EF site

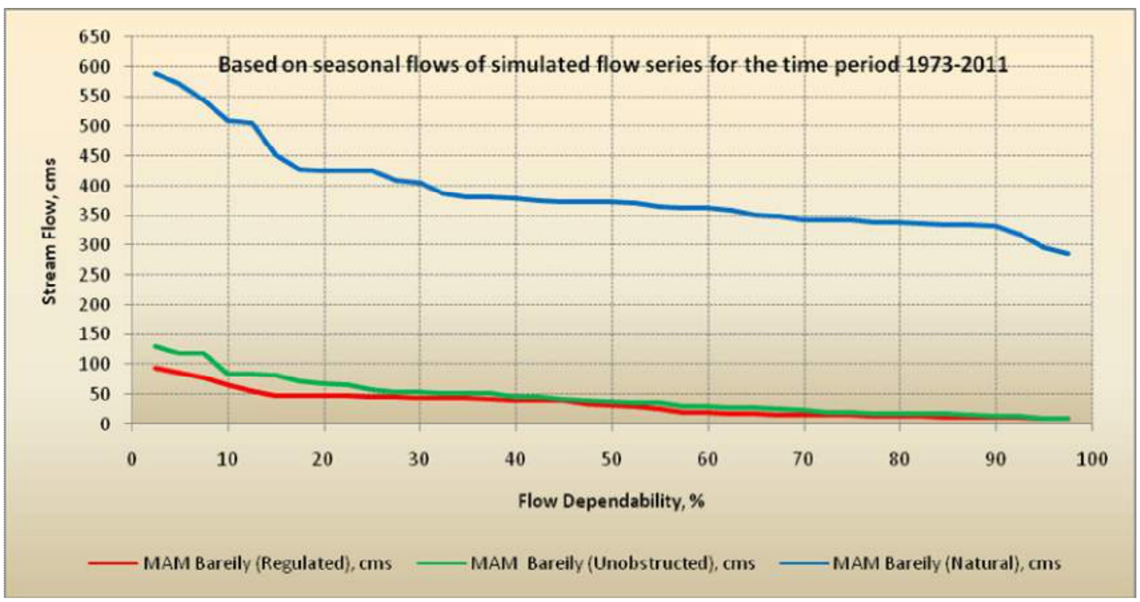
Season	Ratio of Regulated flow to Natural flow (Dry Year)	Ratio of Regulated flow to Natural flow (Normal Year)	Ratio of Regulated flow to Natural flow (Wet Year)
OND	0.11	0.16	0.21
JF	0.10	0.09	0.11
JJAS	0.25	0.32	0.37
MAM	0.08	0.08	0.10

Mean non monsoon seasonal flows have increased as compared to Katghar EF site; mainly due to increase in catchment area which brings more water from agriculture lands in terms of irrigation return flow. From Table 13 it is evident that ratio of Regulated flow to Natural flow ranges from 0.08-0.10 in driest season (MAM).

Flow duration curves for wettest and driest seasons are presented in Figure 28 while dependable values for all three scenarios are presented in Appendix 1.

Figure 28: Flow duration curves for wettest (JJAS) and driest (MAM) season Chaubari, Bareilly EF site





From Figure 28 it is evident that the flow (wettest and driest season) has increased w.r.t. Katghar EF site. Even in driest season there is 15.40 cumecs of water (regulated) flowing in the stream at 75% dependability. The margin between Regulated and Unobstructed flow is quite narrow during driest season.

Dabri

Dabri EF site is the eighth and last site on the river stretch 162 km d/s of Chaubari, Bareilly EF site and 60 km upstream of Ramganga and Ganga river confluence. The stream flows during non monsoon seasons are mainly due to irrigation return flow. Annual flows and long term mean monthly flows for Regulated, Unobstructed and Natural scenario is presented in .

Figure 29: Annual flows and mean monthly flow regime at Dabri EF site

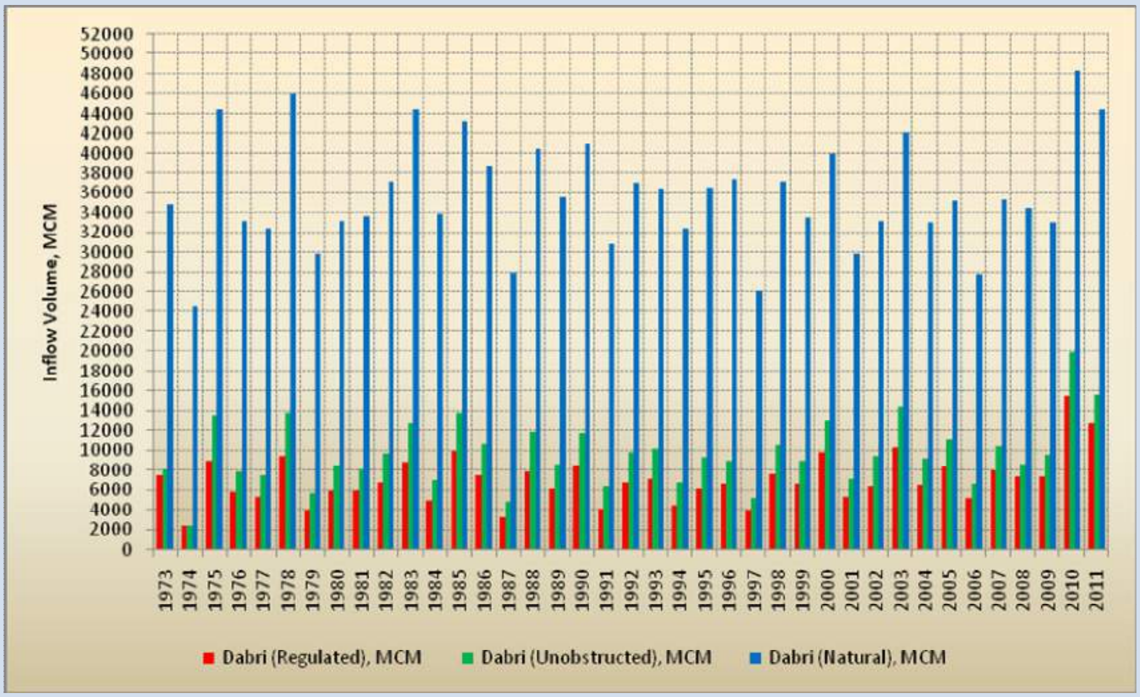
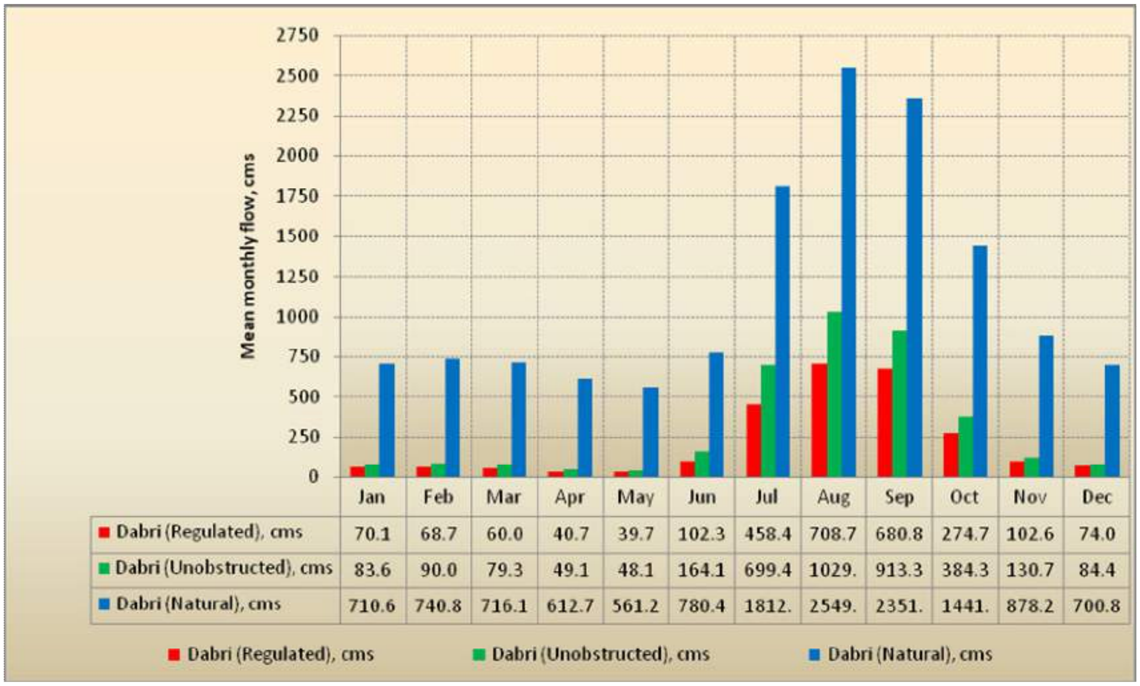


Figure 29: Annual flows and mean monthly flow regime at Dabri EF site



From its is evident that mean monthly regulated flow is maximum in month of August (708.7 cumecs) while minimum in month of May (39.7 cumecs).

Annual flows were classified as Dry, Normal or Wet year as per classification mentioned earlier. For each hydro class mean seasonal flows were compiled and are presented in .

Figure 30: Seasonal flows for various hydro class at Dabri EF site

Dry years

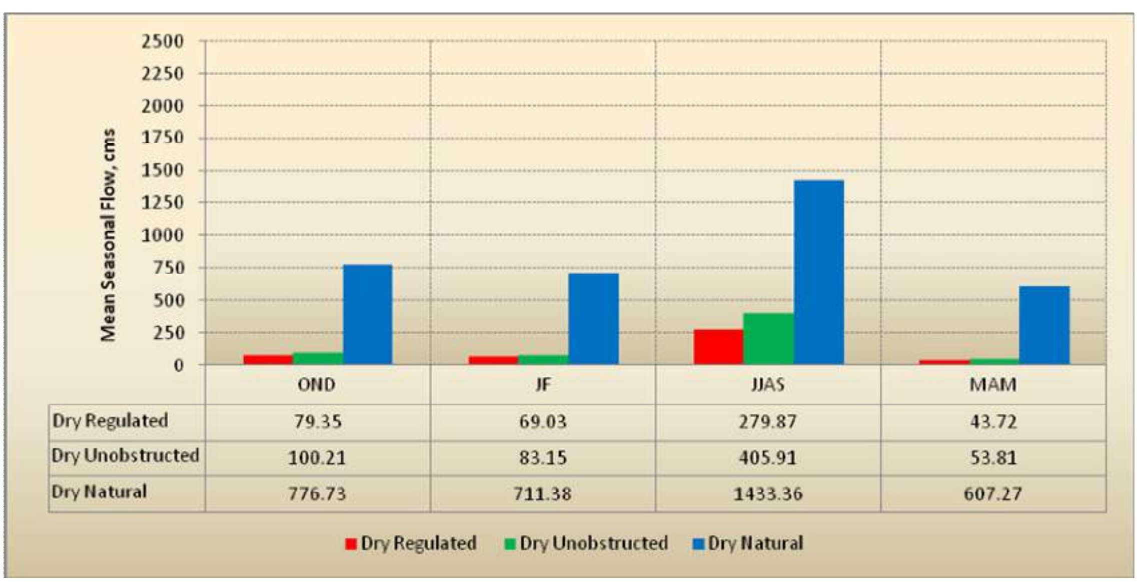
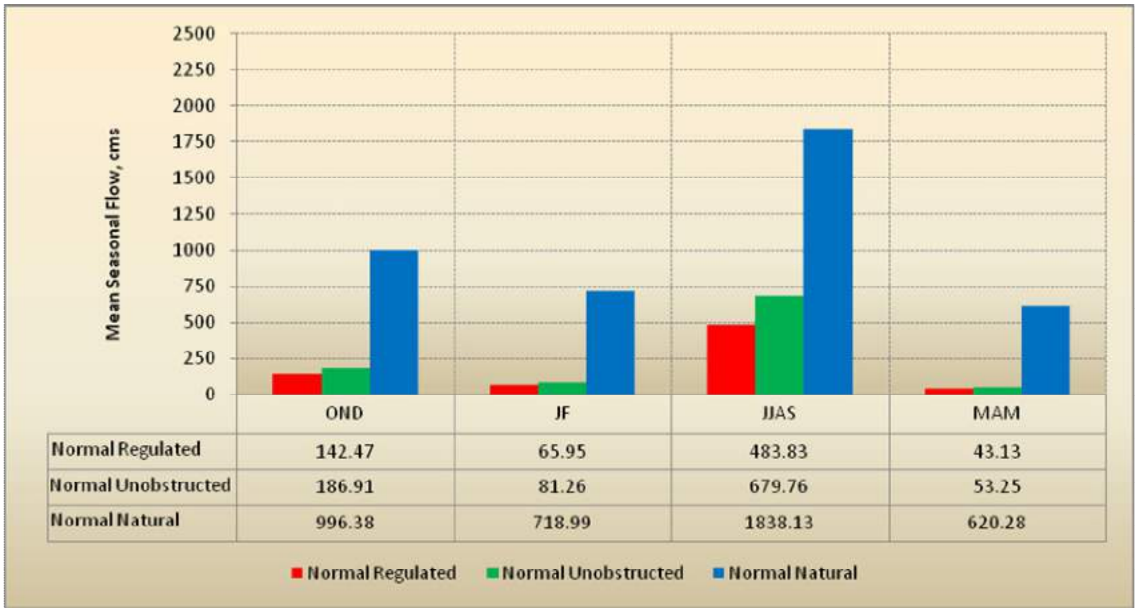


Figure 30: Seasonal flows for various hydro class at Dabri EF site

Normal years



	OND	JF	JJAS	MAM
Normal Regulated	142.47	65.95	483.83	43.13
Normal Unobstructed	186.91	81.26	679.76	53.25
Normal Natural	996.38	718.99	1838.13	620.28

Figure 30: Seasonal flows for various hydro class at Dabri EF site

Wet years

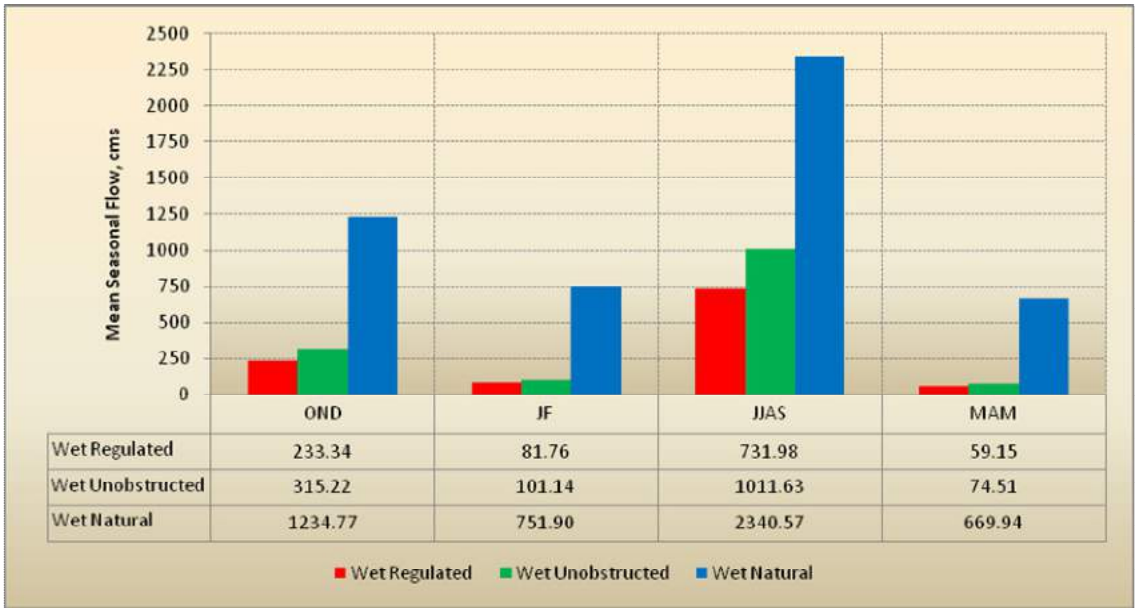


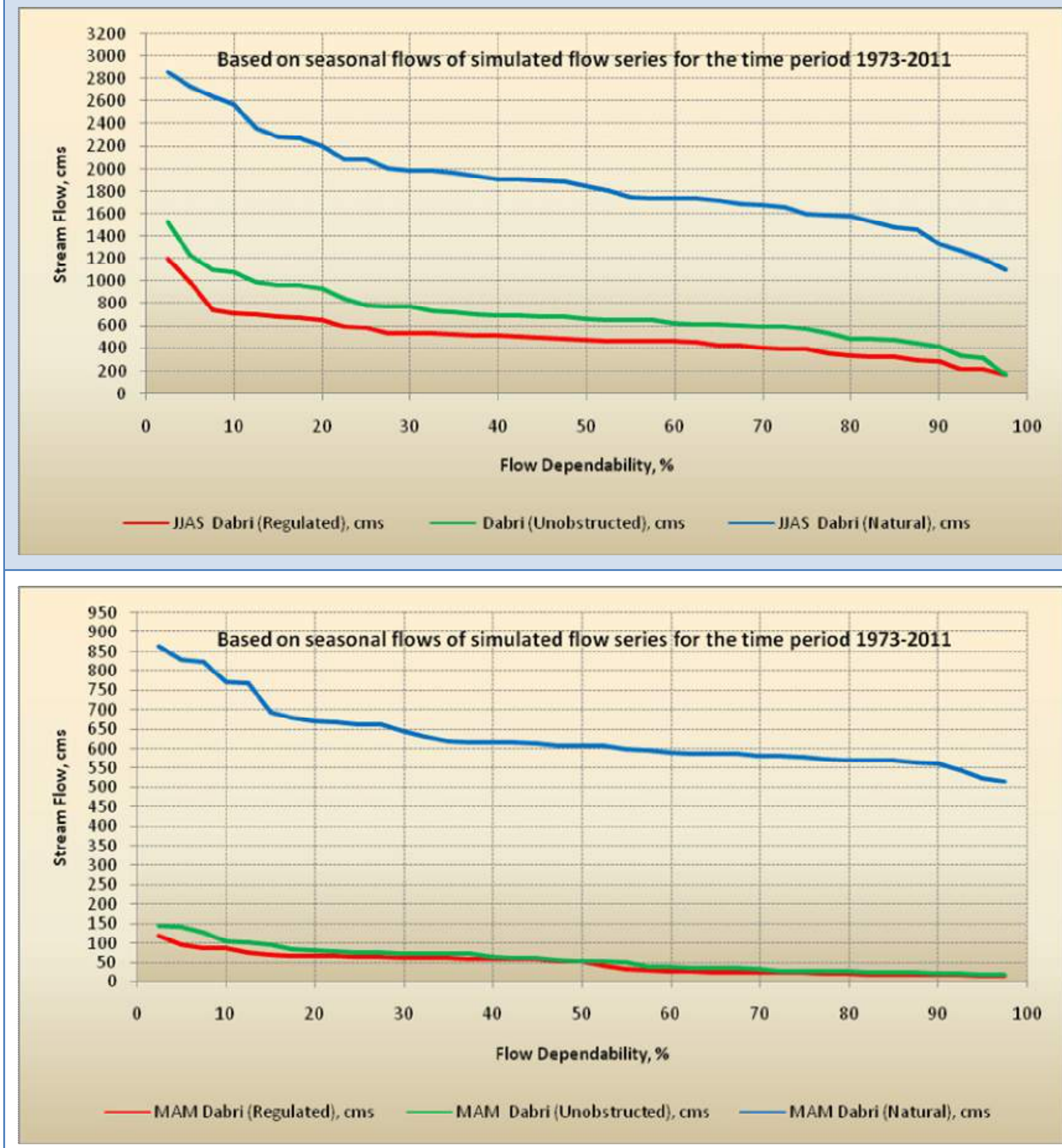
Table 14: Present day Regulated flow w.r.t. Natural (virgin) flow at Dabri EF site

Season	Ratio of Regulated flow to Natural flow (Dry Year)	Ratio of Regulated flow to Natural flow (Normal Year)	Ratio of Regulated flow to Natural flow (Wet Year)
OND	0.10	0.14	0.19
JF	0.10	0.09	0.11
JJAS	0.20	0.26	0.31
MAM	0.07	0.07	0.09

Mean non monsoon seasonal flows have increased as compared to Chaubari EF site, mainly due to increase in catchment area which brings more water from agriculture lands in terms of irrigation return flow. From Table 14 it is evident that ratio of Regulated flow to Natural flow ranges from 0.07-0.09 in driest season (MAM).

Flow duration curves for wettest and driest seasons are presented in Figure 31 while dependable values for all three scenarios are presented in Appendix 1.

Figure 31: Flow duration curves for wettest (JJAS) and driest (MAM) season at Dabri EF site



From Figure 28 it is evident that the flow (wettest and driest season) has increased w.r.t. Chaubari, Bareilly EF site. Even in driest season there is 23.24 cumecs of water flowing in the stream at 75% dependability.

Flow Health

Flow Health, developed by the International Water Centre in 2009-2012 for the Australia China Environment Development Program (ACEDP) was used for assessing the River health and environmental flow in China (Gippel et al, 2012). It is an application to assist in the design and management of river flow regimes thereby providing a “flow health score” assigned for the river based on the magnitude and frequency of the flows.

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

Flow Health assist in the assessment, design and management of river flow regimes. Its main purpose is to provide a score for hydrology in river health assessments, but it can also be used as a tool to assist environmental flow assessment.

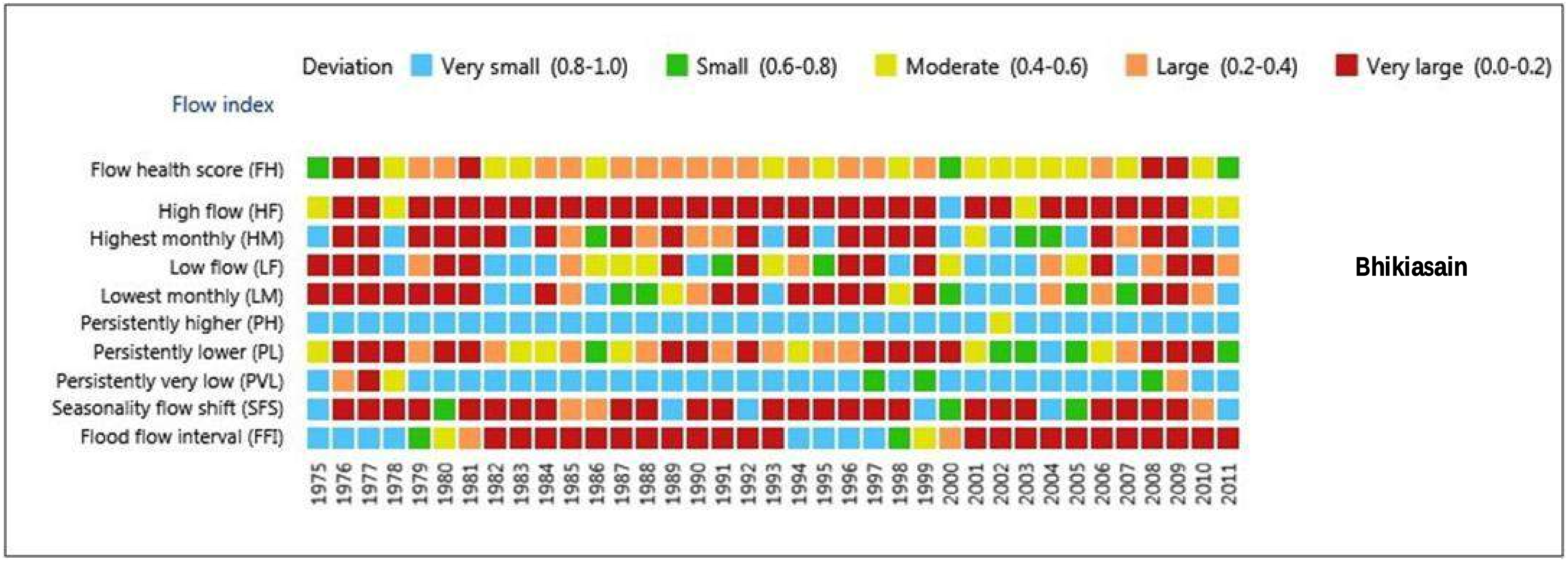
Flow Health has three main functions:

- To provide the hydrology indicator in river health assessment. Flow Health analyses time series of flow data based on a comparison with a reference condition (i.e. pre-regulation flow time series, or modelled unregulated flow) to derive scores for 8 pre-defined indicators of flow deviation. A score of 1 is close to reference and a score of 0 is distant from reference. The indicator scores are aggregated to form an overall Flow Health score for each year of record.
- To recommend a low risk minimum monthly environmental flow regime. Flow Health automatically produces the minimum monthly flow regime that has a Flow Health score of 1.
- To test the hydrological health of any monthly flow regime for environmental flow assessment flow health can be used interactively to design a monthly flow regime, with continuous updating of Flow Health indicator and overall scores.

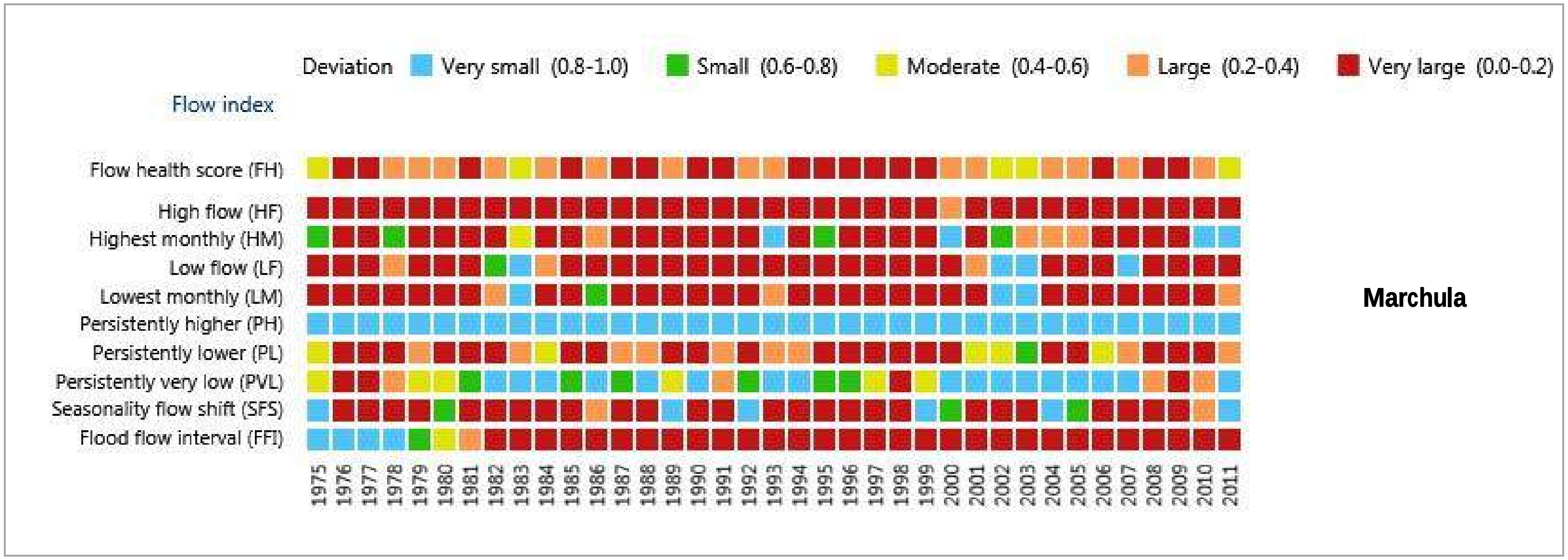
Flow health of the river was generated using Natural flow series as reference and present day Regulated flow series as test series for the simulation period 1974-2010. The flow health card for all eight sites is shown in Figure 32.

Figure 32: Flow health card for eight EF sites on Ramganga river

Flow health card
Bhikiasain

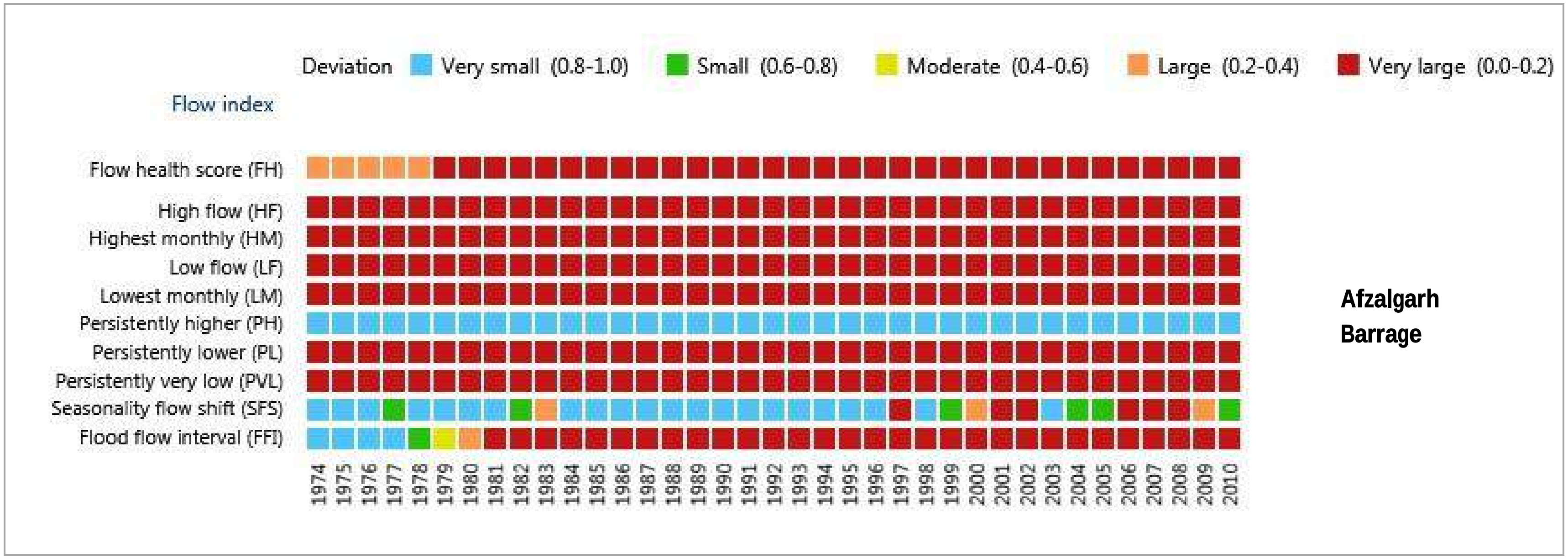


Flow health card
Marchula

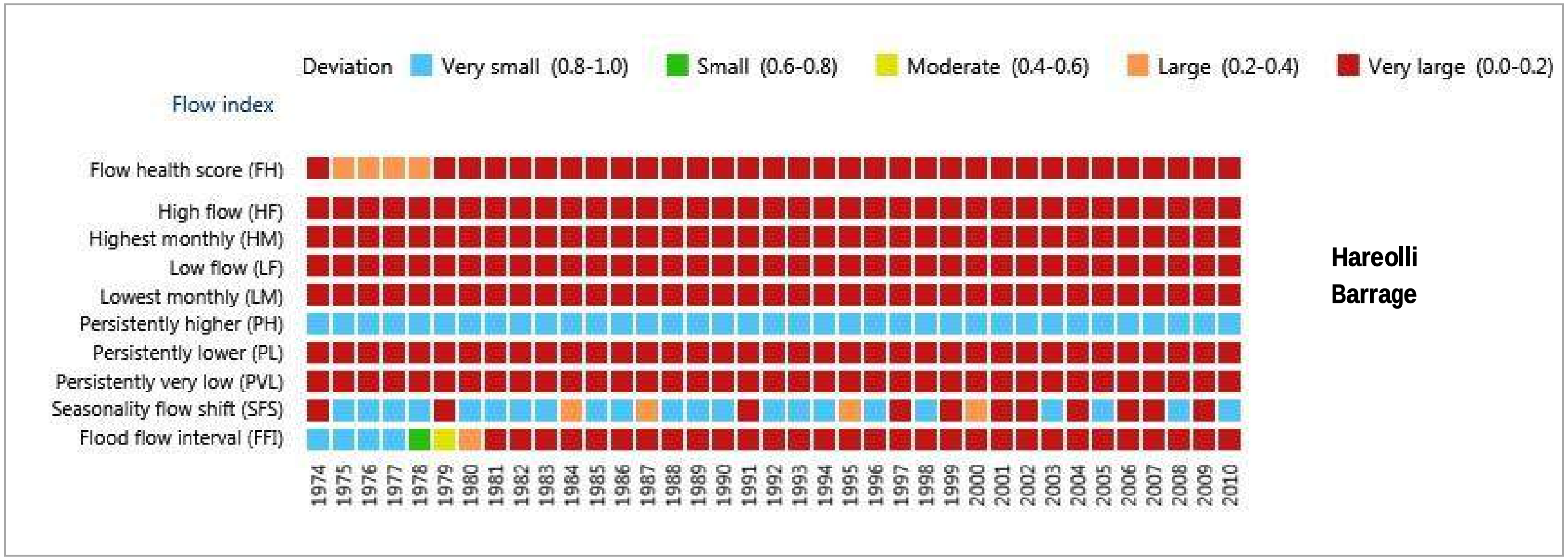


Flow health card

Afzalgarh Barrage

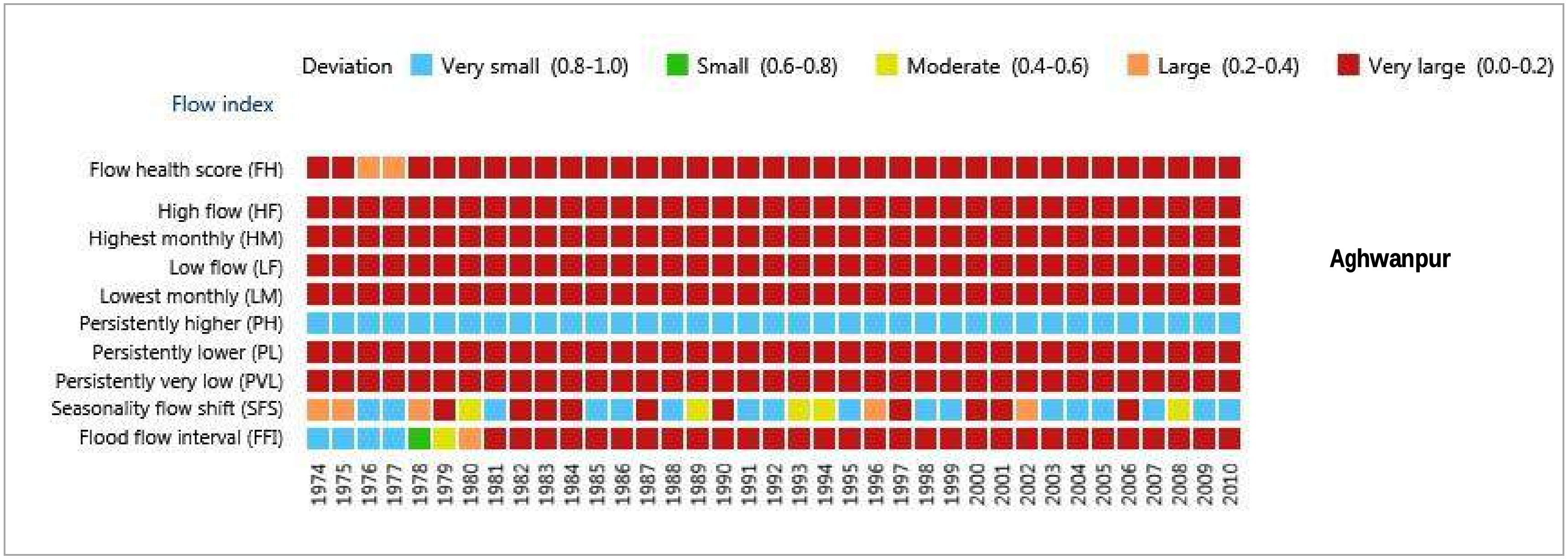


Flow health card
Hareolli Barrage

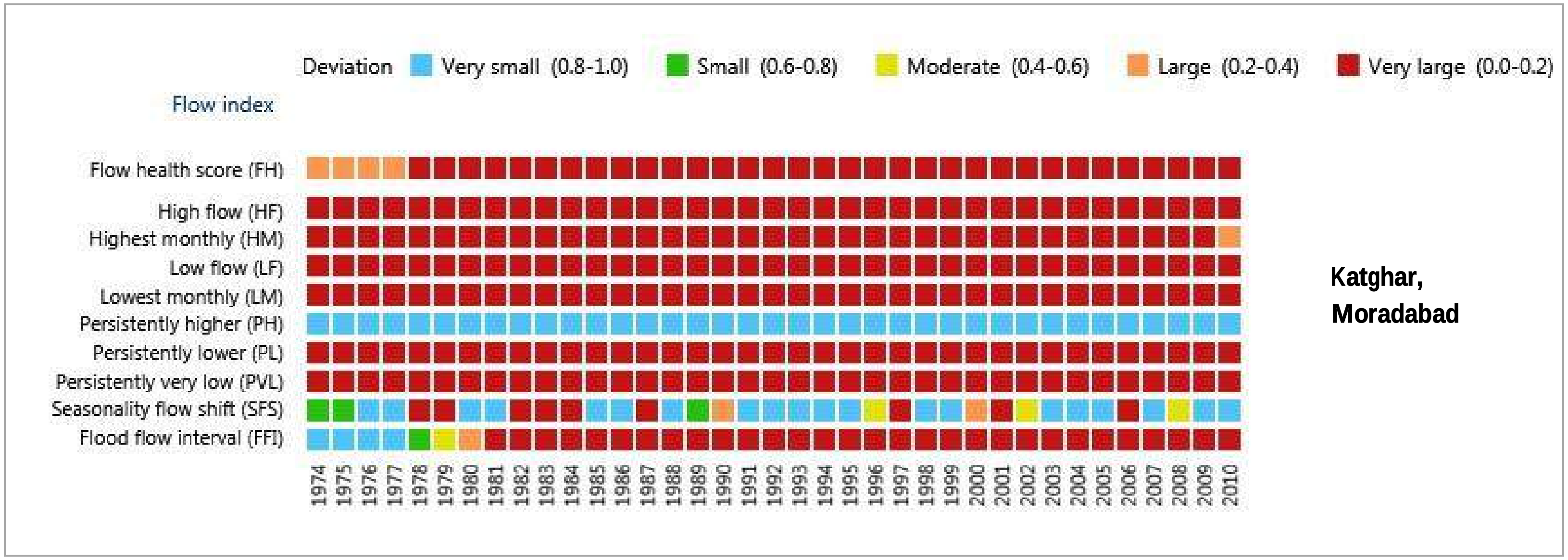


Flow health card

Aghwanpur

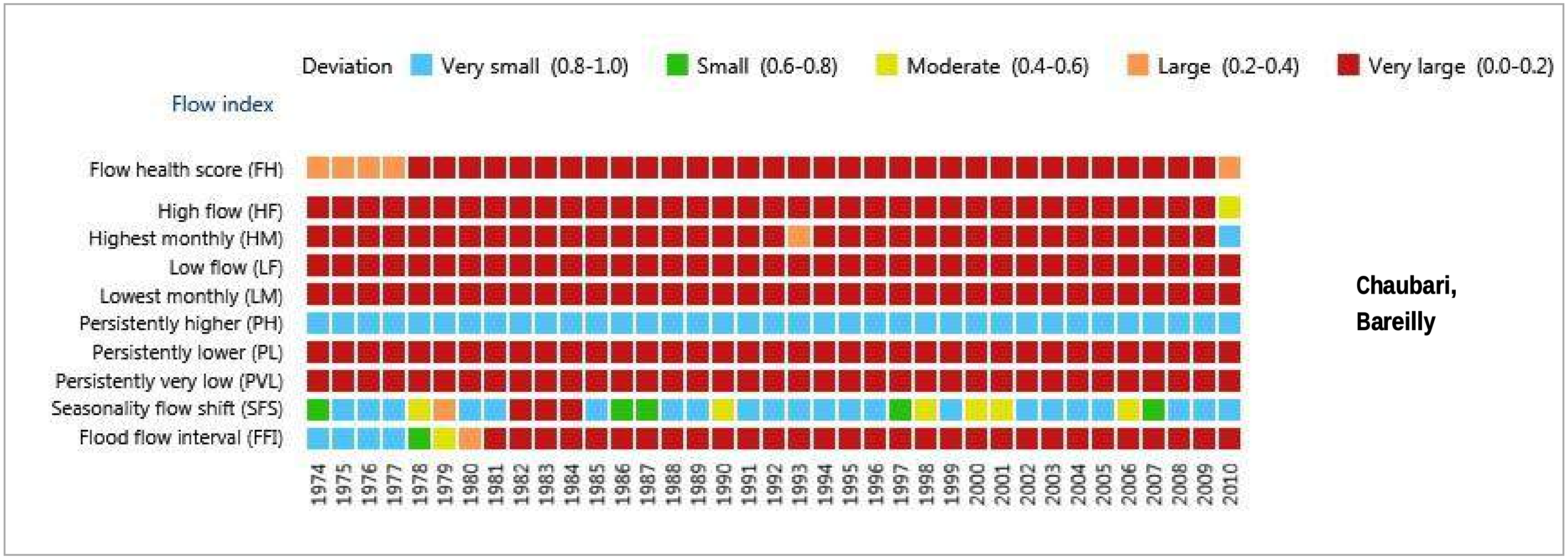


Flow health card
Katghar, Moradabad



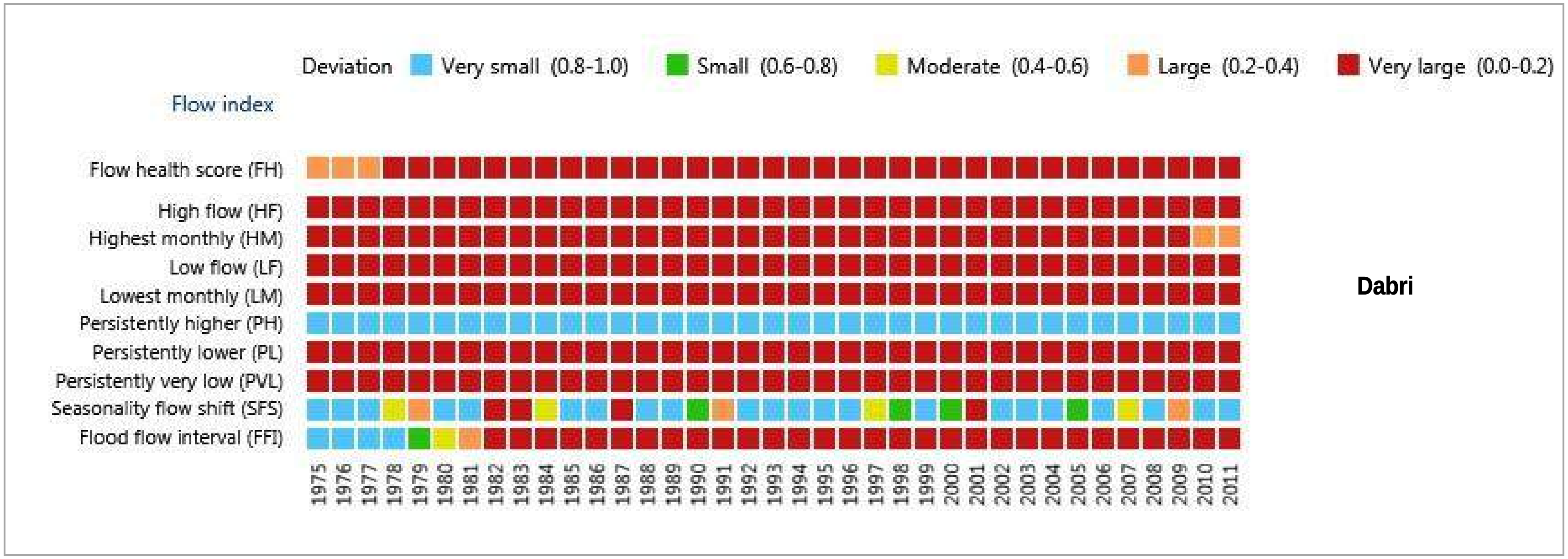
Flow health card

Chaubari, Bareilly



Flow health card

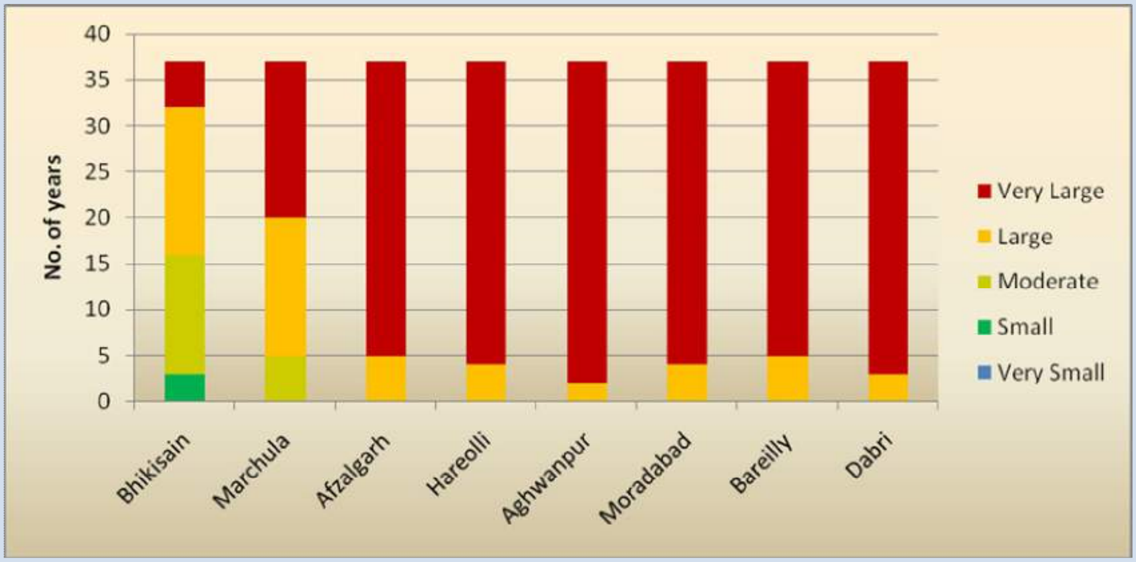
Dabri



From Figure 32 it can be observed that there is a large deviation in flow health index when present day Regulated flow was compared with Natural flow series. There is a low-moderate deviation from Natural flow at Bhikiasain site as compared to d/s Marchula site where the flows are unregulated (with no upstream intervention).

As one moves d/s of Kalagarh dam it is evident that the flow is regulated and there is a large deviation of Regulated flow from Natural flow. The flow health card index shows a large deviation from Natural flow in almost all the years.

Figure 33: Count of Flow health scores



From Figure 33 it is evident that the deviation in overall flow health score increases, as we move downstream. The deviation at EF sites upstream of Kalagarh dam (at Bhikiasain and Marchula) is low as compared to EF sites downstream which is mainly due to regulated flow of Kalagarh dam.

Summary and Conclusions

The following observations and conclusions can be drawn with the hydrological modeling results and analysis:

- Flow at EF sites located d/s of Kalagarh dam is highly influenced by the storage structure.
- The ratio of Natural flow and present day Regulated flow in driest season (MAM) is close to one at Bhikiasain (0.60-0.76) and Marchula (0.45-0.65) EF sites. This signifies that water use/withdrawals and storage upstream is not significant and area less area under agriculture. The flow at 75 % dependability in driest season (MAM) at Bhikiasain and Marchula is 3.31 and 3.54 cumecs respectively.
- At Afzalgarh barrage (d/s of Kalagarh dam) the flow is highly regulated and streamflow occur only due to releases from Kalagarh dam. Even in wettest season (JJAS) the ratio of Natural flow and present day Regulated flow is in range of 0.04-0.12 which reflects the flow regulation. The flow at 75 % dependability in driest season (MAM) at Afzalgarh barrage is 1.24 cumecs.
- At d/s of Hareolli barrage EF site streamflow here is also regulated by barrage. The streamflow occurs mainly due to leakages from barrage gates and some random flash releases along with small fraction of irrigation return flow. The nature of flow here is erratic and is not continuous which is evident from the fact that even in wettest season (JJAS) the ratio of Natural flow and present day Regulated flow is 0.01-0.06. This implies that water withdrawal/storage is very large. The flow at 75 % dependability in driest season (MAM) at Hareolli barrage is 0.69 cumecs.
- At Aghwanpur EF site there is an increase in intermediate catchment area which contributes more water from irrigation return flow. The ratio of Natural flow and present day Regulated flow in direst months (MAM) increases to 0.04-0.06 as compared to Hareolli barrage EF site. The flow at 75 % dependability in driest season (MAM) at Aghwanpur is 1.29 cumecs.
- At Katghar, Moradabad EF site in addition to increment in irrigation return flow there is a contribution of large amount sewage water from Moradabad city. The ratio of Natural flow and present day Regulated flow is of the range 0.05-0.07. The flow at 75 % dependability in driest season (MAM) at Katghar is 1.87 cumecs.
- At Chaubari, Bareilly EF site there is large contribution from East and West Baigul Rivers from left bank. The irrigation return flow increases with increase in contributing area and ratio of Natural flow and present day Regulated flow increases to range of 0.08- 0.10 in driest season(MAM). The flow at 75 % dependability in driest season (MAM) at Chaubari is 15.40 cumecs.
- At Dabri EF site the contributing area increases further but ratio of Natural flow and present day Regulated flow remains almost comparable (0.07-0.09) to Chaubari EF site. This indicates some water withdrawals direct from stream for various uses. The flow at 75 % dependability in driest season (MAM) at Dabri is 23.24 cumecs.
- EF can only be suggested between the range of Natural flow and present day Regulated flow depending upon the water demand from other thematic groups and availability at Kalagarh dam considering if it is a Dry, Normal or Wet year.

Appendix 1

Dependable flows at four dependability levels are presented in Table 15 and Table 16.

Table 15: Wettest season (JJAS) dependable flows for Regulated, Unobstructed and natural Scenarios for eight EF sites

Site	Scenario	25%	50%	75%	90%
Bhikiasain	Regulated	92.21	71.94	50.18	32.45
	Unobstructed	94.17	74.65	54.64	37.89
	Natural	95.17	72.86	54.93	37.62
Marchula Bridge	Regulated	110.38	94.84	62.50	42.58
	Unobstructed	113.29	101.06	69.71	49.70
	Natural	112.10	97.70	68.67	49.66
Afzalgarh Barrage	Regulated	40.34	39.16	38.27	37.74
	Unobstructed	173.72	138.39	111.04	70.43
	Natural	173.48	141.06	111.75	70.58
Hareolli barrage	Regulated	5.99	3.31	1.69	1.02
	Unobstructed	191.84	138.86	113.16	68.58
	Natural	211.62	159.89	141.52	86.28
Aghwanpur	Regulated	108.85	76.94	64.71	37.25
	Unobstructed	295.61	227.58	179.52	124.64
	Natural	379.22	333.30	258.35	186.73
Katghar, Moradabad	Regulated	132.80	102.05	75.48	55.30
	Unobstructed	319.00	255.92	197.31	132.66
	Natural	453.27	405.55	304.64	218.42
Chaubari, Bareilly	Regulated	513.87	412.30	318.46	242.06
	Unobstructed	692.63	600.28	485.02	363.69
	Natural	1436.93	1297.53	1082.43	853.00
Dabri	Regulated	583.42	476.86	392.13	287.52
	Unobstructed	778.83	662.03	575.55	419.19
	Natural	2085.38	1844.78	1594.78	1333.05

Table 16: Driest season (MAM) dependable flows for Regulated, Unobstructed and natural Scenarios for eight EF sites

Site	Scenario	25%	50%	75%	90%
Bhikiasain	Regulated	7.36	3.16	1.19	0.58
	Unobstructed	10.51	5.51	2.47	1.54
	Natural	10.25	5.47	2.51	1.61
Marchula Bridge	Regulated	7.99	3.35	1.40	0.64
	Unobstructed	12.48	5.94	2.79	1.72
	Natural	12.31	5.88	2.87	1.93
Afzalgarh Barrage	Regulated	77.03	76.98	76.95	76.94
	Unobstructed	13.49	3.55	0.71	0.10
	Natural	13.37	3.46	0.74	0.12
Hareolli barrage	Regulated	0.81	0.77	0.75	0.73
	Unobstructed	14.22	5.11	2.88	0.77
	Natural	28.77	17.76	13.96	12.52
Aghwanpur	Regulated	4.40	2.63	1.29	1.01
	Unobstructed	16.93	8.53	3.95	2.43
	Natural	67.55	51.72	44.76	41.56
Katghar, Moradabad	Regulated	6.38	3.97	1.87	1.48
	Unobstructed	18.83	9.25	4.39	2.89
	Natural	84.77	64.28	56.51	50.42
Chaubari, Bareilly	Regulated	46.54	31.50	15.40	10.99
	Unobstructed	57.80	37.28	19.43	14.02
	Natural	424.90	372.37	341.90	331.93
Dabri	Regulated	64.91	52.37	23.24	18.83
	Unobstructed	76.95	54.65	27.34	22.75
	Natural	663.87	607.10	578.77	562.50

Glossary

Annual flow	Cumulative streamflow over a year
Auto calibration	Automatic adjustments of parameters influencing flow regime to calibrate the hydrological model when compared with observed datasets
Basin	A drainage basin is an extent or an area of land where surface water from rain converges to a single point at a lower elevation, usually the exit of the basin
Consumptive use	Water taken out of the system for irrigation/industrial/drinking purpose
Crop management operations	Operations which lays down the actual irrigation schedules and crop grown in a particular season and area
Dry year	A year is considered dry year when annual inflow of water in stream has a probability of occurrence which is >75%dependability
Environmental Flows	The quantity and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well being that depend on these ecosystems
Flow dependability	Probability of occurrence of a particular volume of flow at a given location
Flow duration curves	Cumulative frequency curve that show the percent of time specified discharges were equaled or exceeded during a given period.
Flow regime	The prevailing pattern of water flow over a given time.
Hydrological modelling	Conceptual representations of various parts of the hydrologic cycle which are primarily used for hydrologic prediction using known input datasets like rainfall, temperature, landuse, soil etc
Regulated flows	Represents the most recent condition of the basin (as if these conditions existed during the entire simulation period) which includes all interventions, water transfers and irrigated agriculture.
Mean Seasonal flow	Long term average of flows during particular season
Natural flows	Scenario where flow is generated with no interventions and agriculture is rain fed
Normal Year	A year is considered Normal year when annual inflow of water in stream has a probability of occurrence which is between 25-75% dependability
Rainfed agriculture	Scenario where water used for irrigation only comes from rainfall (no irrigation structure in place like canals, tube wells)
Seasonal flows	Aggregate of various monthly flows to constitute a particular season
Sensitivity analysis	Assessment of sensitive parameters influencing the flow characteristics of an area
Watersheds	An area of land that drains all the streams and rainfall to a common outlet such as the outflow of a reservoir, river confluence points or point along a stream channel.
Wet year	A year is considered Wet year when annual inflow of water in stream has a probability of occurrence which is < 25% dependability