Ganga Basin Water Balances - Data Extraction and Analysis using Available Hydrological Model outputs

Volume I: Major Ganga Sub basins Water Balance Analysis Report

INRM Consultants Pvt Ltd., New Delhi

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Draft Report

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Chapter 1

Objective and Methodology

Introduction

While hydrologic modelling of the Ganges Basin has been undertaken using the SWAT model as part of the World Bank lead Ganges Strategic Basin Assessment (SBA) and subsequent work on the Gangs River Basin Management Plan undertaken by the consortium of IITs for the Ministry of Environment, Forest and Climate Change, there remain a considerable gap in making this spatial and temporal information available at a spatial and temporal scale conducive to general as well as specific consumption at various levels

Objective

Therefore, the main objective of this project is to construct and visualize water balance for the Ganga basin at different temporal and spatial scales.

Scope of Work

The main job of the consultant therefore is to use data and outputs from the previous SWAT modelling exercise to construct water balance for the Ganga basin at different spatial and temporal scales to cater to the requirements of a large cross-section of stakeholders. The following broad categorisation has been envisaged to take care of this requirement:

1. Spatial Scale: The requirement for spatial scale and extent may vary considerably. Some people might be interested in knowing the water balance at the basin and sub-basin scale while the others might be interested in knwoing the water availability with respect to the administrative boundries of country, state or distict. Thus it has been decided to construct water balance for the following spatial units to cater to different requirements:
   a. the entire Ganges Basin upstream of Farakka
   b. the Indian portion of the basin upstream of Farakka
   c. the Nepalese portion of the basin
   d. the Chinese portion of the basin
   e. each of the Indian states of the basin
   f. each of the districts (as per 2011 census) of Indian states of the basin (analysis at this spatial scale is restricted to water balance components expressed in terms of equivalent depth of water in mm over the total district area).
2. Temporal Scale: Because of the temporal variability it is required that character of the basin and its other spatial units is captured to depict such variability. Therefore it has been decided to construct and present water balance for the above defined spatial units and for the following temporal levels:
   a. an average year
   b. an average month
3. Water Balance Components: Some of the major components of the water balance that are prominent for a comprehensive understanding of the various sub-areas of the basin are tracked. These are:
   a. Inflows to rivers of major tributaries
   b. Outflows from rivers of major tributaries
   c. Losses in river systems (Evapotranspiration, ground water recharge and conveyance loss),

      d. Water Use:
          i. sectoral disaggregation of the water use (domestic, Industrial and agriculture)
          ii. major crop wise water use.

4. Water Quality: Model outputs for select water quality parameters are tracked for
    a. Sediment transport
    b. BOD.

5. Indications of relative level of uncertainty: The modelling outputs have been obtained by making various assumptions under the non-availability of desired data, which has caused uncertainties in the outputs obtained. Therefore it is important to convey the associated level of uncertainty and what data are required to reduce this uncertainty. Thus attempt shall be made to:
    a. Define the extent of uncertainty wherever possible quantitatively (or qualitatively)
    b. List the additional data that would be required to reduce the uncertainty.

Methodology

The information and the analysis provided here is the outcome of a detailed modeling exercise carried out using the SWAT hydrological model under the World Bank lead Ganges Strategic Basin Assessment (SBA) study and some of the subsequent works on the hydrologic modelling of the Ganges Basin undertaken using the SWAT model.

The Soil and Water Assessment Tool (SWAT) model is a distributed parameter, continuous scale model that operates on a daily time-step although sub-daily model run is possible with Green and Ampt infiltration method. It divides the basin into a number of sub-basins based on topography. Each sub-basin is further divided into Hydrologic Response Units (HRUs), which are a unique combination of soil, landuse, and land management. The HRU is the smallest landscape component of SWAT, for computing the hydrologic processes including canopy interception of precipitation, infiltration, surface runoff, evapotranspiration, subsurface flow, soil moisture redistribution, and percolation to deep aquifer. The hydrological processes are divided into two phases: the land phase, where the model determines the upland loadings of flow, sediment, nutrients, and pesticides from each HRU, and then the loadings are area-weighted to sub-basin level; and the channel/floodplain phase, where the model routes the upland loadings from each sub-basin through the channel/stream network. The model also simulates water and pollutant routing through impoundments such as ponds, wetlands, and reservoirs. SWAT also simulates pollutant loading from point sources such as discharge from industries, wastewater treatment plants, and in-stream transformations of nitrogen, phosphorus, dissolved oxygen, carbonaceous biological oxygen demand. The rainfall records from the nearest rain gauge station will be assigned for each sub-basin. Tools have been developed to interpolate the rainfall amount and derive spatially variable rainfall inputs for the basin/sub-basin. A model provides a very comprehensive outputs for the land phase and the channel phase as well as at elaborate spatial and temporal scales.

The report utilizes such range of outputs obtained from the SWAT model for reorganising the information to be presented in different forms and levels of abstraction:

- River Flow

- o Components: Stream Flow - FLOW_IN and FLOW_OUT in the river reach
- o Units: BCM
- o Description: Outflow = Inflow (upstream inflow) + Generated in the intervening catchment - Use (irrigation +Domestic + Industrial) from reach – Conveyance Losses - change in storage
- o Spatial scale: At Country, State and major subbasins
- o Temporal scale: Long term average annual and monthly.
- Catchment Water balance
  - o Components: Water yield (WYLD), Actual evapotranspiration (ET)
  - o Units: mm of equivalent water depth
  - o Description: WYLD = Rainfall - ET - change in storage.
- Water Quality constituent balances
  - o Components: Sediment yield, Biochemical oxygen demand (BOD)
  - o Units: tons/ha, kg O_2
  - o Description: Load out at the catchment outlet = Load in (upstream Load in), if applicable + Load generated in the catchment - deposition/sinks.

Definitions of some of the key entities

A brief description of the important entities of the water balance is given below for bringing in clarity to the various forms of analysis made.

- Water yield (mm) - WYLD: The net amount of water that leaves the subbasin and contributes to stream flow in the reach during the time step. (WYLD = SURQ + LATQ + GWQ – TLOSS – pond abstractions)
- Direct Surface runoff (mm) - SURQ: Surface runoff contribution to stream flow during time step that contributes directly without going through the soil
- Lateral flow (mm) - LATQ: Lateral flow contribution to stream flow during the time step that enters the soil and then move laterally
- Base flow (mm) - GWQ: Groundwater contribution to stream flow that is composed of the water from the shallow aquifer that joins the river reach during the time step
- Actual evapotranspiration (mm) - ET: Actual evapotranspiration from the subbasin during the time step
- Percolation (mm) - PERC: Water that percolates past the root zone during the time step. There is potentially a lag between the time the water leaves the bottom of the root zone and reaches the shallow aquifer. Ground water Recharge = PERC-GWQ
- Sediment yield (tons/ha) - SYLD: Sediment from the subbasin that is transported into the river reach during the time step
- Stream In-Flow (m3/s) - FLOW_IN: Average daily stream flow into reach/stream (subbasin outlets) during the time step
- Stream Out-Flow(m3/s) - FLOW_OUT: Average daily stream flow out of reach (subbasin outlets) during the time step
- Biochemical oxygen demand-in (kg O2) - CBOD_IN: Carbonaceous biochemical oxygen demand of material transported into reach during the time step
- Biochemical oxygen demand-out (kg O2) - CBOD_OUT: Carbonaceous biochemical oxygen demand of material transported out of reach during the time step.

Spatial entities that have been defined for the study include:

- the entire Ganges Basin upstream of Farakka
- the Indian portion of the basin upstream of Farakka
- the Nepalese portion of the basin
- the Chinese portion of the basin
- each of the Indian States in the basin.

Temporal Scale include:

Besides assessing the spatial variability of the water resource in the Ganges basin it is equally important to ascertain the temporal variability in each of these spatial units identified above. On the temporal scale, the following information has been found to be useful to be generated.

- at annual and calendar month level for
  - long term annual average (long term basin average)

Scenarios for flow regime change analysis

One of the major issues that is of utmost concern is the ever deteriorating hydrological regime of the river basins because of the over abstraction of groundwater, creation of excessive storages and the diversions and Ganges is no different. Any effort to restore the hydrological status of a basin requires the information on the basin that prevailed before the water resources development, which is usually not available. However, generation of such information is possible only through hydrological simulation and the same has been adopted. The following two scenarios thus have been constructed to represent two distinct flow regimes, representing i) pre-water resources development regime and ii) present flow regime.

Scenario A: Pre-development flow in the absence of water resources infrastructure including water diversions but reflecting catchment hydrology corresponding to the current landuse.

Scenario B: Current regime, representing existing major water resources infrastructure, current management/operation practices, existing crop water demand through irrigation. Current crop management practices differentiating irrigation from Surface and Ground water have been used. Point source input has been taken using average BOD and the average sewage generation per capita and obtaining total load based on subbasin population.

Basin Level Spatial Entities at which Outputs are Consolidated

Flow outputs (Inflow and outflow) in BCM (Billion Cubic Metre) are given, at major subbasins as depicted in Figure 1. Information has been generated for various water balance components such as Water Yield in mm depth, Evapotranspiration in mm depth, and Sediment Yield in Tons and BOD in ppm within these spatial has been aggregated and analysed.
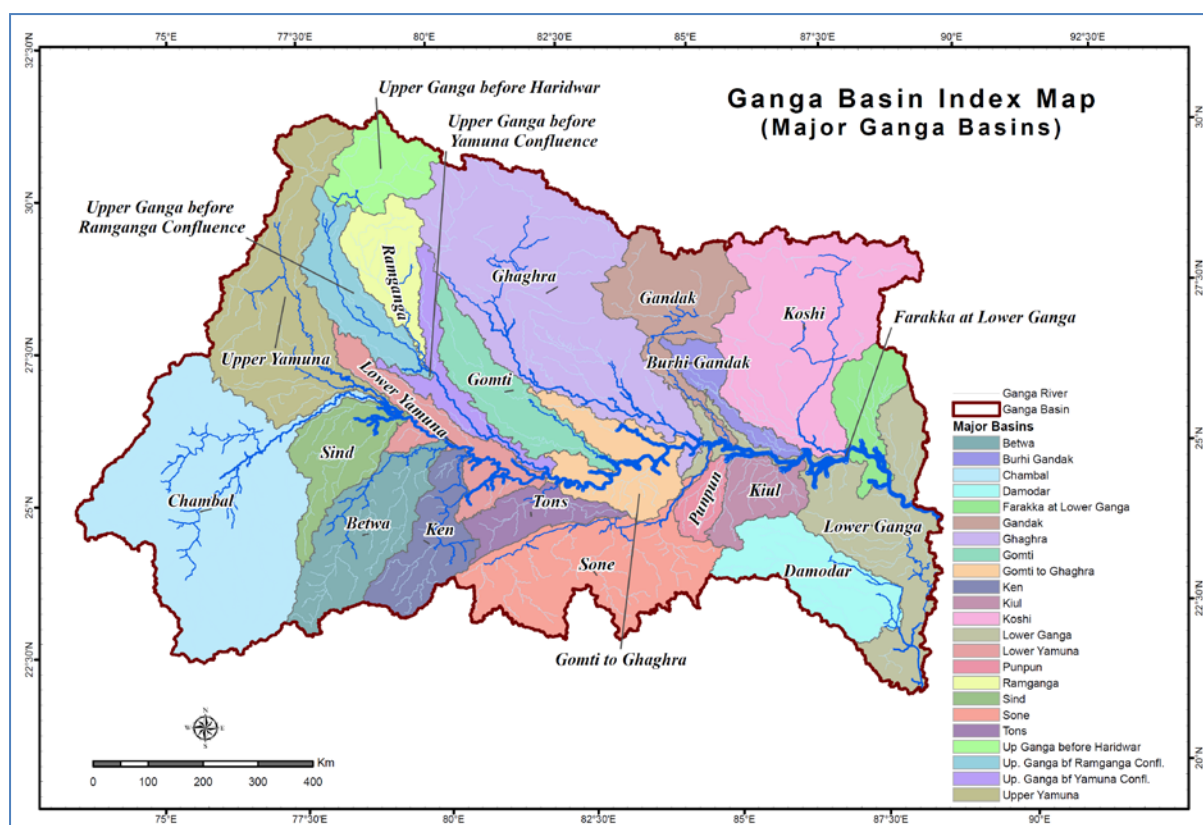
Figure 1: Index map of Ganga Basin - Output 3 at river system for major tributaries of the Ganga river basin

Outputs are presented in graphical and tabular form. Conceptual representation for the basis of graphs for two scenarios is shown in Figure 2.

Table 1: Conceptual representation for the basis of graphs

Parameter	Scenario A (Value)	Scenario B (Value)
Natural Stream Flow	100	100
Irrigation	0	30
Domestic water use (based on population)	5	5
Other Loss (Storage, Conveyance loss)	10	20
Final stream flow	85	45
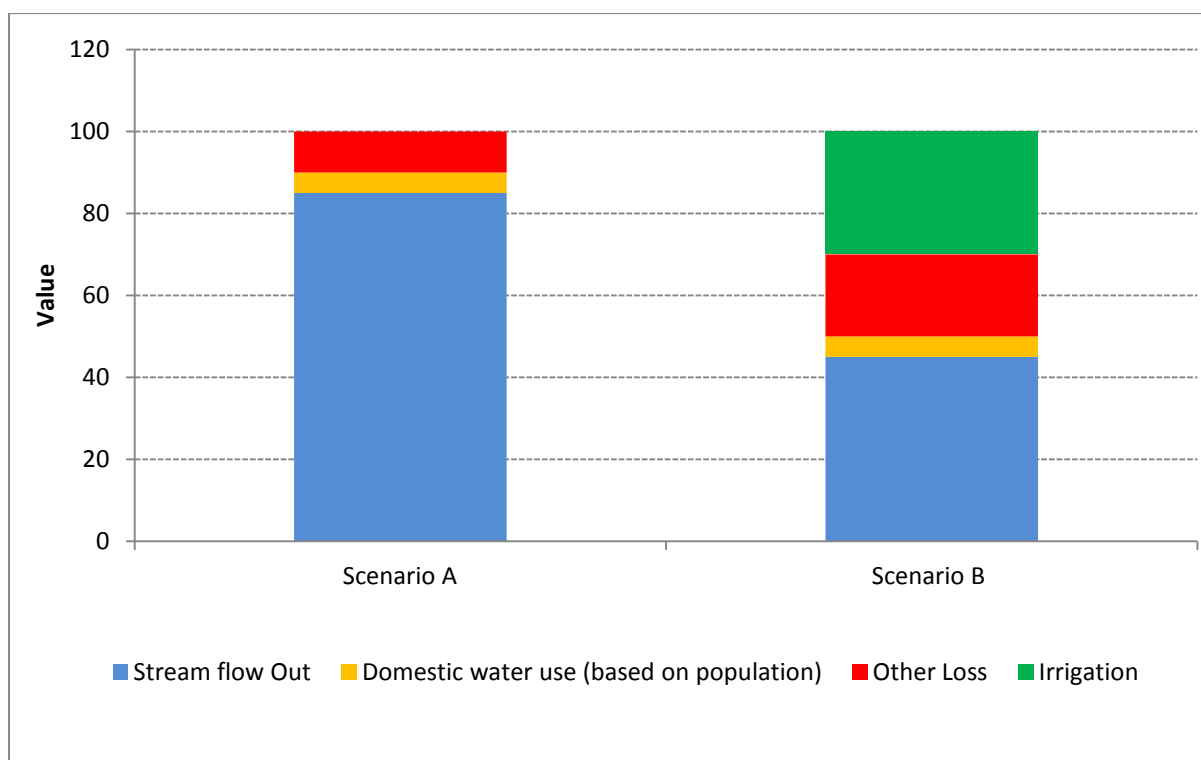
Figure 2: Conceptual representation of Outputs

The overall scheme that has been used to present the results is depicted in Figure 3. This has two distinct segments one depicting the entities in the stream phase such as flow volumes, sediment load, BOD load in river stretches and the other one depicting the entities in the land phase of these sub-areas represented in the form of equivalent depth of water. These quantities are then presented for the Pre-development and Present scenario respectively as shown in Figure 3.
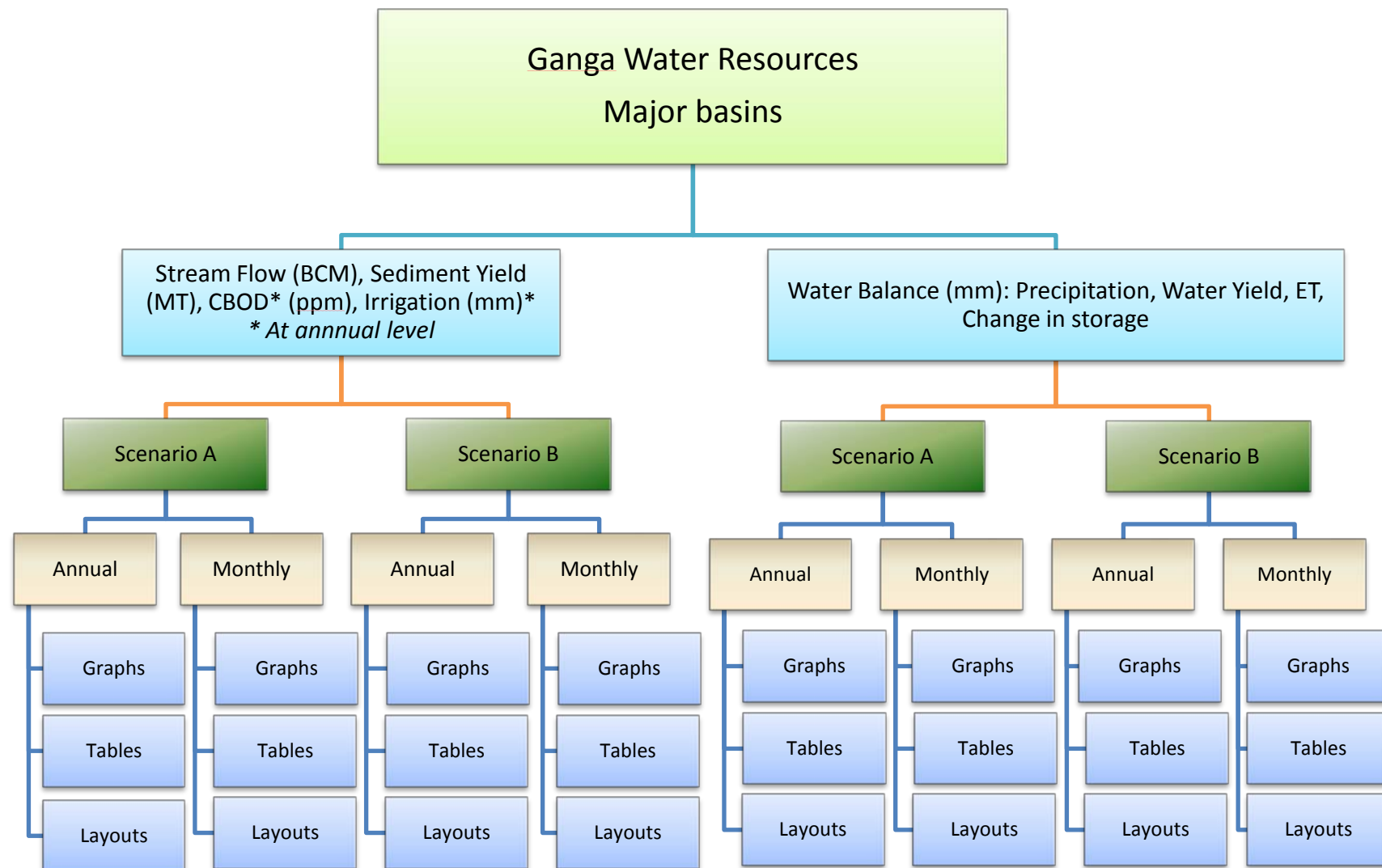
Figure 3: Flow Chart depicting Presentation of Outputs

Chapter 2

Sub-Basin level analysis for Ganga Basin

The first level of analysis has been done using the natural boundaries as per the basic philosophy of hydrology. For the purpose 26 automatically delineated sub-basins as given in Table 2 have been used. The analysis has been performed using the SWAT hydrological model output for 31 years (1975 to 2005) of simulation using landuse, soil characteristics, terrain and daily meteorological data of the basin. The entities used in this analysis are:

- average annual stream flow volumes (BCM) at inlet (if not a head water sub-basin) and outlet of each of the sub-basin,
- average annual equivalent depths in mm of some of the major water balance components for each sub-basin
- average annual sediment load simulated at inlet (if not a head water sub-basin) and outlet of each of the sub-basin.

Stream Flow for Major Ganga Tributaries for Scenario A and B

Pre-development flow (Scenario A) and Post-development flow (Scenario B) series have been generated for major tributaries of the Ganga river by using the SWAT hydrological modeling. Strategic locations on the major tributary basins as well as the locations on the main Ganga used for the purpose are given in Table 2.

Table 2: Major Locations on the Ganga and its Tributaries where Stream Flow is simulated

Sl	Basin	Area, Sqkm
1	Upper Ganga before Haridwar	23,209
2	Upper Ganga (before confluence with Ramganga river)	26,837
3	Ramganga (before confluence with Ganga river) - Left Bank	24,943
4	Upper Ganga (after confluence with Ramganga river)	Not significant
5	Upper Ganga (before confluence with Yamuna river)	18,937
6	Upper Yamuna	80,185
7	Chambal (before confluence with Yamuna river) - Right Bank	141,814
8	Sind (before confluence with Yamuna river) - Right Bank	28,301
9	Betwa (before confluence with Yamuna river) - Right Bank	43,892
10	Ken (before confluence with Yamuna river) - Right Bank	28,665
11	Lower Yamuna (before confluence with Ganga river) - Right Bank	29,639
12	Ganga (after confluence with Yamuna river)	Not significant
13	Tons (before confluence with Ganga river) - Right Bank	17,446
14	Gomti (before confluence with Ganga river) - Left Bank	31,050
15	Ganga (after confluence with Gomti river) - Left Bank	32,213
16	Ghaghra (before confluence with Ganga river) - Left Bank	133,365
17	Ganga (after confluence with Ghaghra river)	NA
18	Sone (before confluence with Ganga river) - Right Bank	67,501
19	Gandak (before confluence with Ganga river) - Left Bank	42,310

20	Punpun (before confluence with Ganga river) - Right Bank	8,900
21	Kiul (before confluence with Ganga river) - Right Bank	17,598
22	Burhi Gandak (before confluence with Ganga river)	12,524
23	Koshi (before confluence with Ganga river)	91,287
24	Farakka at Lower Ganga (before bifurcation to India and Bangladesh)	20,277
25	Damodar (before confluence with Ganga river) - Right Bank	37,568
26	Lower Ganga at Ganga Sagar (India)	70,008

The pre-development flow series have been obtained by performing the simulation after assuming that no storage or diversion projects are in place. However agricultural activity is in place but only rainfed. It is further assumed that the land use during the pre-development situation is the same as the post-development stage. In fact for both the scenarios the same period of 31 years have been used thus the difference is supposed to reflect only the impact on account of anthropogenic activities. The average annual flow in BCM for the major sub-basins of the Ganga basin are shown in Table 3 for both Scenarios A and B.

Table 3: Stream Flow: Annual Stream flow (BCM/year) - At Major Locations on the Ganga and its Tributaries

	Sub Basin	Scenario A+		Scenario B++	
		Flow In	Flow Out	Flow In	Flow Out
	Long-term Annual Average: Stream Flow (BCM/year)				
1	Upper Ganga before Haridwar	0.0	25.3	0.0	23.4
2	Upper Ganga (before confluence with Ramganga river)	0.0	34.1	0.0	21.7
3	Ramganga (before confluence with Ganga river) - Left Bank	0.0	14.7	0.0	9.2
4	Upper Ganga (after confluence with Ramganga river)	0.0	49.5	0.0	29.2
5	Upper Ganga (before confluence with Yamuna river)	0.0	59.5	0.0	30.6
6	Upper Yamuna	0.0	22.2	0.0	10.9
7	Chambal (before confluence with Yamuna river) - Right Bank	0.0	47.4	0.0	17.3
8	Sind (before confluence with Yamuna river) - Right Bank	0.0	9.1	0.0	1.7
9	Betwa (before confluence with Yamuna river) - Right Bank	0.0	22.6	0.0	9.9
10	Ken (before confluence with Yamuna river) - Right Bank	0.0	17.7	0.0	9.2
11	Lower Yamuna (before confluence with Ganga river) - Right Bank	118.9	130.0	49.0	52.2
12	Ganga (after confluence with Yamuna river)	0.0	189.7	0.0	82.9
13	Tons (before confluence with Ganga river) - Right Bank	0.0	10.0	0.0	5.9
14	Gomti (before confluence with Ganga river) - Left Bank	0.0	13.2	0.0	9.0
15	Ganga (after confluence with Gomti river) - Left Bank	212.9	227.6	97.8	105.4
16	Ghaghra (before confluence with Ganga river) - Left Bank	0.0	112.1	0.0	74.1
17	Ganga (after confluence with Ghaghra river)	0.0	340.5	0.0	178.8
18	Sone (before confluence with Ganga river) - Right Bank	0.0	47.7	0.0	20.2
19	Gandak (before confluence with Ganga river) - Left Bank	0.0	48.5	0.0	32.1

	Sub Basin	Scenario A+		Scenario B++	
		Flow In	Flow Out	Flow In	Flow Out
20	Punpun (before confluence with Ganga river) - Right Bank	0.0	4.4	0.0	2.3
21	Kiul (before confluence with Ganga river) - Right Bank	0.0	10.0	0.0	4.9
22	Burhi Gandak (before confluence with Ganga river)	0.0	7.8	0.0	4.0
23	Koshi (before confluence with Ganga river)	0.0	75.8	0.0	55.6
24	Farakka[*] at Lower Ganga (before bifurcation to India and Bangladesh)	542.3	565.9	299.0	309.6
25	Damodar (before confluence with Ganga river) - Right Bank	0.0	31.3	0.0	11.9
26	Lower Ganga at Ganga Sagar (India)	31.3	66.0	11.9	28.7

* India at Farakka

+ Scenario A: Pre-development flow in the absence of water resources infrastructure and water diversions but reflecting catchment hydrology corresponding to the current landuse

++ Scenario B: Current conditions: Existing major water resources infrastructures, current management/operation practices, existing crop water demand with irrigation wherever applicable.

It may be observed from Table 3 that the average annual yield of the Ganga Basin up to Farakka under the Scenario A was about 566 BCM. If the yield of Damodar and Lower Ganga (66 BCM) is added then the total yield is about 632 BCM. This yield is reduced to 310 BCM and 339 BCM respectively under the Scenario B. This implies that on the average there has been a reduction of about of 256 BCM of water in Ganga Basin up to Farakka and about 37 BCM of water in the Lower Ganga on account of storages, and a range of utilisations such as irrigation, industrial and domestic.

Figure 4 and Figure 5 show the graphical representation of the average annual stream flow entering and leaving each of the identified sub-basins under Scenario A and B respectively. The flow that was generated by the sub-basin under the pre-development situation can be obtained by taking the difference between the outflow and inflow from Scenario A. The impact of water resources development for various purposes including the irrigation (being the major utilisation) from surface and ground water sources has been reflected for each sub basin in Scenario B of Figure 4 and Figure 5.
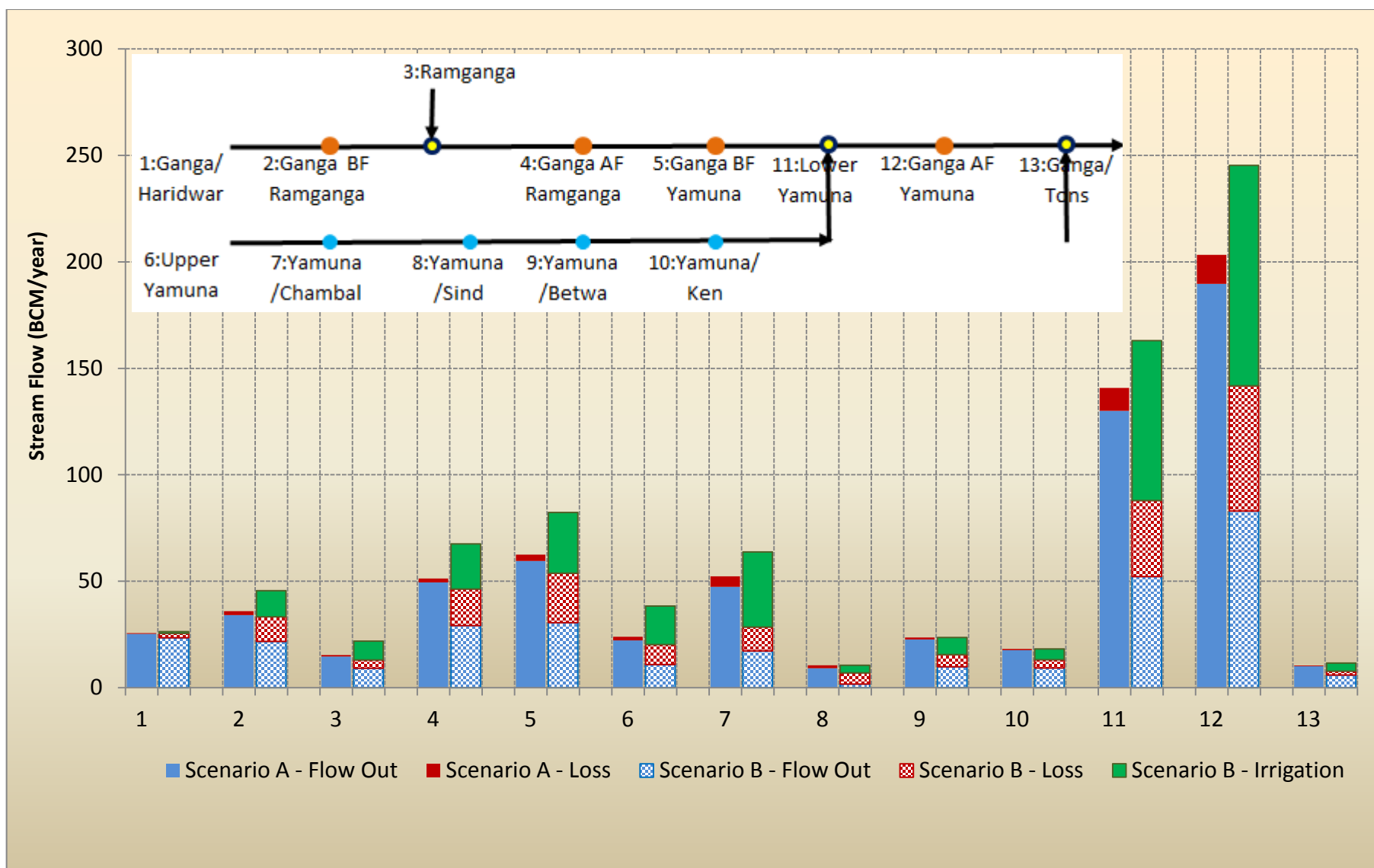
Figure 4: Graph: Annual Stream flow (BCM/year) for Scenario A and Scenario B - Major sub basins Part 1
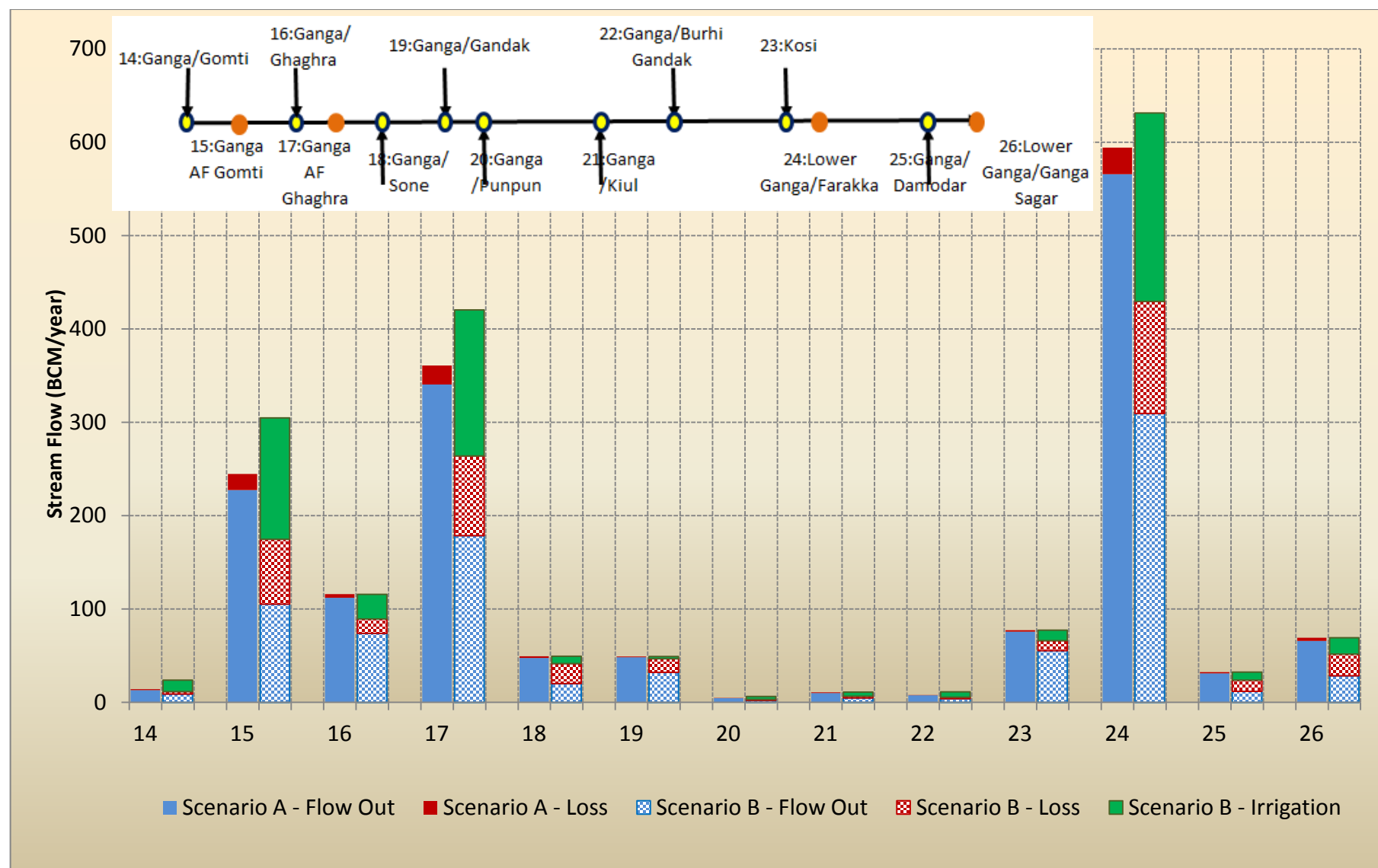
Figure 5: Graph: Annual Stream flow (BCM/year) for Scenario A and Scenario B - Major sub basins Part 2

The sub basin wise reduction of flow from Scenario A (Red bar) and the proportion of flow available under the present Scenario B with respect to Scenario A is shown in Figure 6.
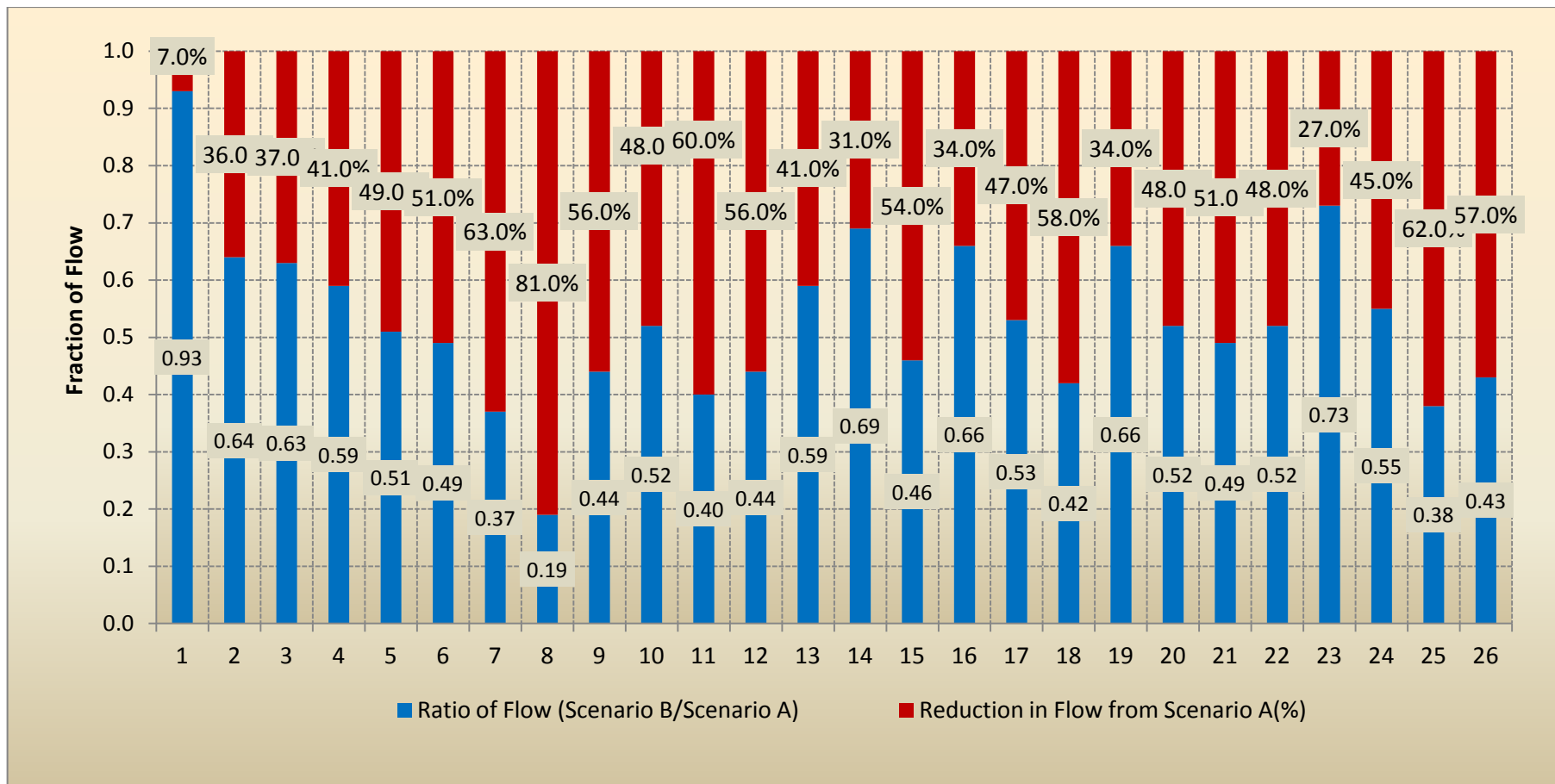

Figure 6: Graph : Change in flow w.r.t. Scenario A and percentage reduction in flow - Major sub basins of Ganga

Another view has been created to depict the reduction by showing the proportion of flow remaining (Scenario B) in comparison to that under Scenario A by using a schematic of the Ganga Basin (Figure 7). The sub basin shown in 'red' i.e., Sind is the one that has experienced maximum reduction to the tune of

81% (0.19 as the ratio of B/A Scenario). On the other extreme the Sub Basin of 'Upper Ganga before Haridwar shown in 'Green' exhibits the minimum reduction of 7% (0.93 as the ratio of B/A Scenario).
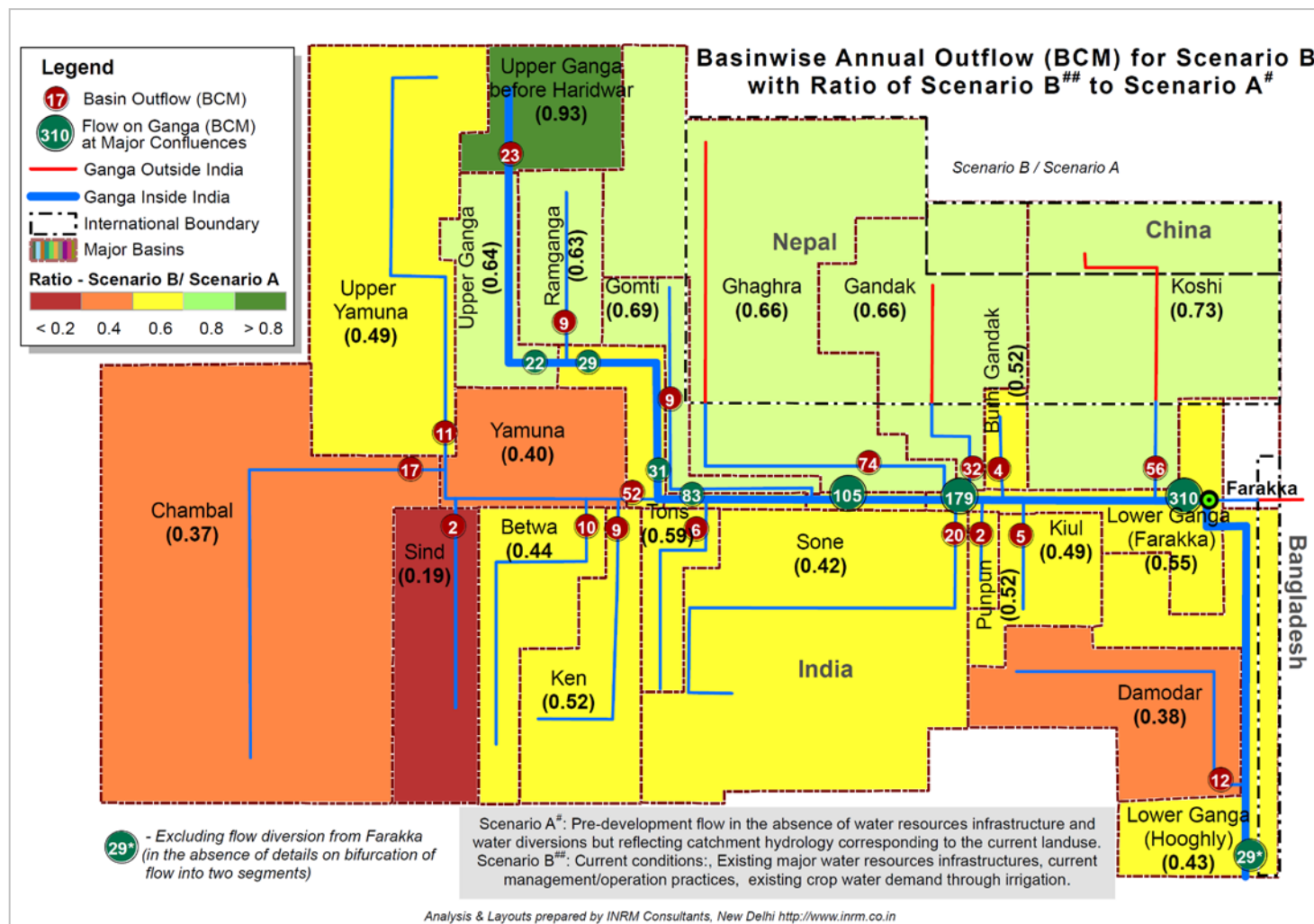

Figure 7: Annual Stream flow (BCM/year) - Major Sub Basins of Ganga - Scenario B and Ratio of Scenario B to Scenario A
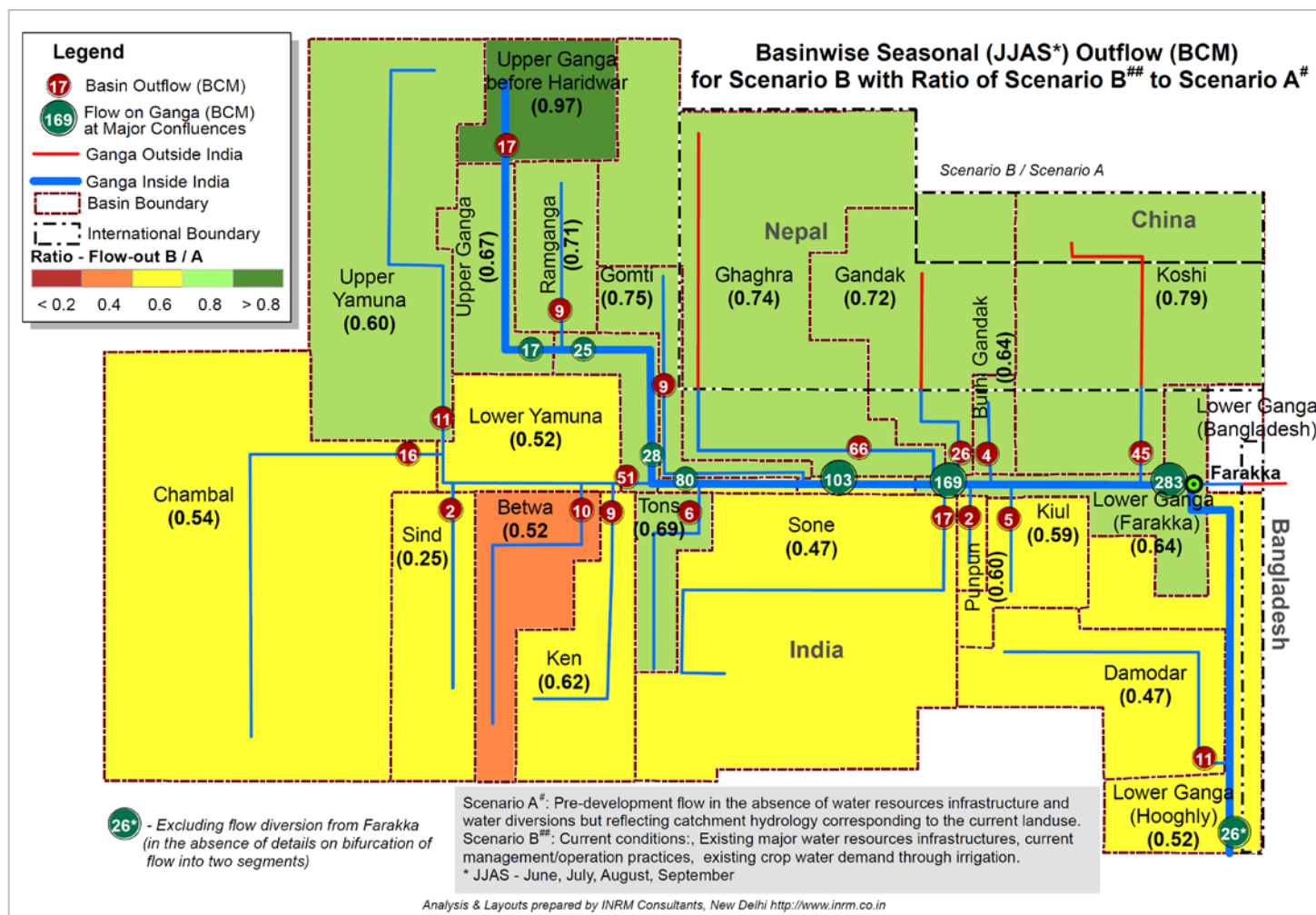
Figure 8: Monsoon (JJAS) Stream flow (BCM) - Major Tributaries of Ganga - Scenario B and Ratio of Scenario B to Scenario A

The impact of the development has not been evenly distributed over the year as well as over the space of the basin. Figure 8 depicts the change in Monsoon (JJAS) flow. It may be observed that the reduction in flow in comparison to the Scenario A is variable over the different sub-basins of Ganga. The reduction in the sub-basins joining Ganga river from South have higher reduction (maximum being Sind with 75% reduction) in comparison to those joining

Ganga river from North side (with maximum reduction of 40% for Upper Yamuna). However, the situation is drastically different during the Non-monsoon (OND) period. There is a very small fraction of flow left during the non-monsoon period specially in the sub-basins joining Ganga river from southern side as shown in Figure 9. Reduction is also considerable even in the flows of the sub-basins joing Ganga River from the northern side ranging from 44% to 94%.
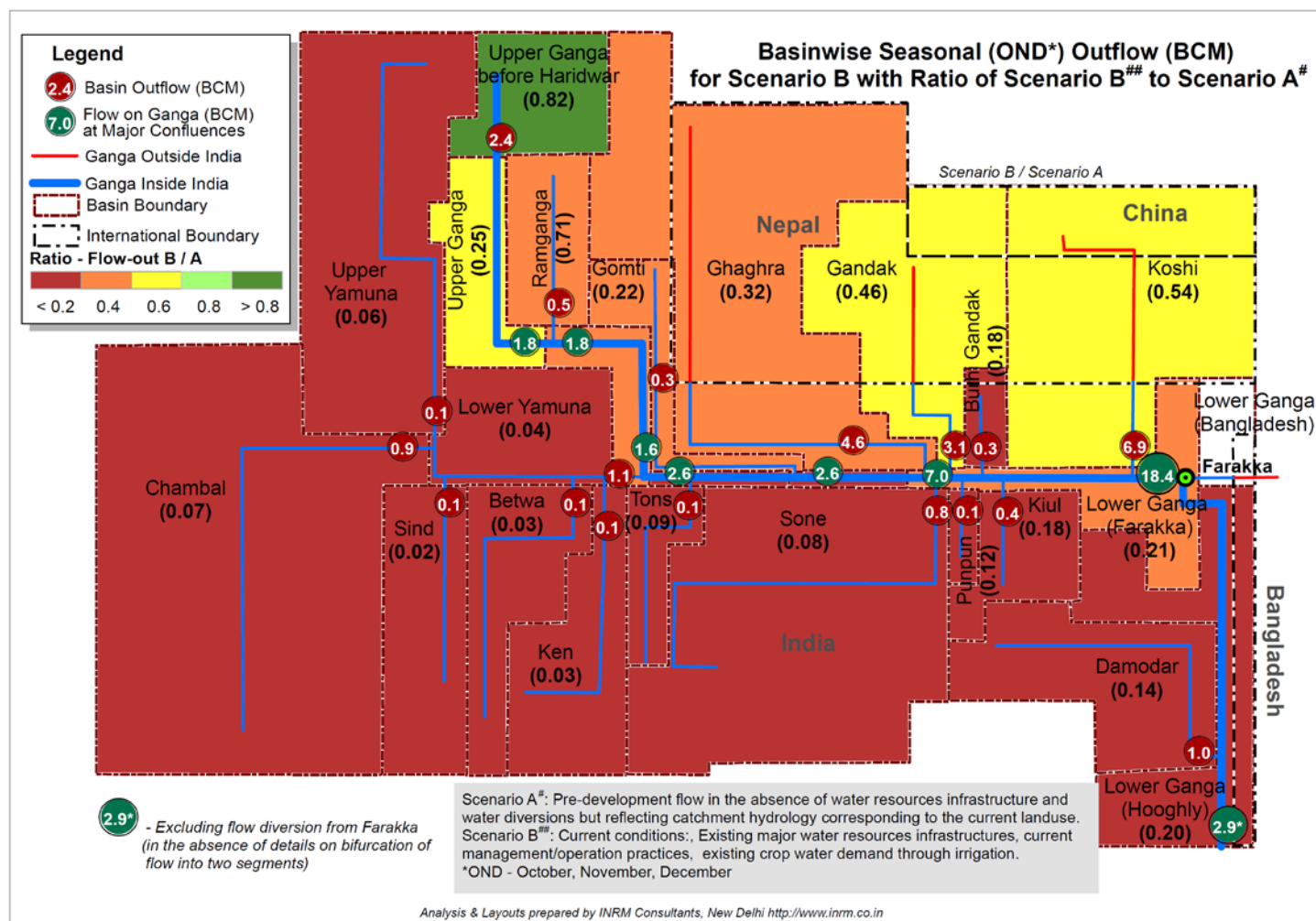

Figure 9: Non monsoon (OND) Stream flow (BCM) - Major Tributaries of Ganga - Scenario B and Ratio of Scenario B to Scenario A

Monthly Stream Flow in BCM/month - Scenario A - Major sub basins Level

Analysis has also been performed in the similar manner at the monthly level so as to ascertain the resource availability and its variability at the monthly level using the simulation outputs of 31 years. Impact of the water resources development has been depicted by incorporating all the major water resources projects in the hydrological simulation and depicting the same on average monthly basis under the Scenario B. Details of these outputs have been provided in Annexure I.

Annual Water Balance BCM/year - Scenario A and Scenario B - Major sub basins Level

Average annual water balance components are provided by the SWAT hydrological model at the sub basin level in the form of equivalent depth of water. Some of the prominent water balance components namely water yield and evapotranspiration in mm/year have been presented for sub basin of Ganga for Scenario A and Scenario B (Table 4).

Table 4: Long term Average Annual Water Balance components (mm) for sub basins of Ganga

Sl	Sub Basins	Precipitation	Scenario A+			Scenario B++		
			Water Yield	Evapo-transpiration	Change in Storage	Water Yield	Evapo-transpiration	Change in Storage
	Annual Average : Water Balance (mm/year)							
1	Upper Ganga before Haridwar	1225.8	1101.7	310.7	-186.6	1100.4	323.2	-197.8
2	Upper Ganga (before confluence with Ramganga river)	910.3	385.7	518.0	6.6	288.8	570.5	51.0
3	Ramganga (before confluence with Ganga river) - Left Bank	1116.5	613.8	507.2	-4.5	525.2	537.6	53.7
5	Upper Ganga (before confluence with Yamuna river)	1054.0	593.6	471.6	-11.2	393.4	537.1	123.5
6	Upper Yamuna - Right Bank	717.7	298.8	405.9	13.0	253.3	433.1	31.3
7	Chambal (before confluence with Yamuna river) - Right Bank	757.8	368.8	401.7	-12.7	200.8	421.5	135.5
8	Sind (before confluence with Yamuna river) - Right Bank	774.9	371.7	388.0	15.2	153.4	406.7	214.8
9	Betwa (before confluence with Yamuna river) - Right Bank	975.3	536.3	427.0	12.0	334.0	445.6	195.7
10	Ken (before confluence with Yamuna river) - Right Bank	1087.4	634.6	426.0	26.8	432.2	444.8	210.4
11	Lower Yamuna (before confluence with Ganga river) - Right Bank	852.6	414.0	433.6	5.0	261.5	449.1	142.0
13	Tons (before confluence with Ganga	1067.9	595.0	451.7	21.2	444.2	470.0	153.7

SI	Sub Basins	Precipitation	Scenario A+			Scenario B++		
			Water Yield	Evapo-transpiration	Change in Storage	Water Yield	Evapo-transpiration	Change in Storage
	river) - Right Bank							
14	Gomti (before confluence with Ganga river) - Left Bank	940.4	458.6	477.3	4.5	373.9	490.2	76.3
15	Ganga (after confluence with Gomti river) - Left Bank	1032.5	526.5	500.1	5.9	424.1	532.4	76.0
16	Ghaghra (before confluence with Ganga river) - Left Bank2	1264.0	870.7	450.4	-57.1	670.2	473.8	120.0
18	Sone (before confluence with Ganga river) - Right Bank	1180.3	731.3	447.1	1.9	437.9	466.7	275.7
19	Gandak (before confluence with Ganga river) - Left Bank	1436.1	1163.8	378.2	-105.9	862.9	393.8	179.4
20	Punpun (before confluence with Ganga river) - Right Bank	1005.7	521.4	466.3	18.0	356.2	483.2	166.3
21	Kiul (before confluence with Ganga river) - Right Bank	1104.1	616.5	479.0	8.6	384.7	498.9	220.5
22	Burhi Gandak (before confluence with Ganga river)	1312.7	635.6	562.1	115.0	441.6	689.9	181.2
23	Koshi (before confluence with Ganga river)	1121.0	847.1	369.4	-95.5	682.1	381.4	57.5
24	Farakka at Lower Ganga (before bifurcation to India and Bangladesh)	1814.9	1225.1	602.2	-12.4	731.4	631.3	452.2
25	Damodar (before confluence with Ganga river) - Right Bank	1438.4	867.5	562.7	8.2	460.0	582.7	395.7
26	Lower Ganga at Ganga Sagar (India)	1245.0	776.9	519.7	-51.6	529.8	546.1	169.1

* India at Farakka

Change in Storage = Change in Snowpack (snowfall-snowmelt) + Change in Shallow ground water storage + Change in Deep ground water storage

+ Scenario A: Pre-development flow in the absence of water resources infrastructure and water diversions but reflecting catchment hydrology

Sl	Sub Basins	Precipitation	Scenario A+			Scenario B++		
			Water Yield	Evapo-transpiration	Change in Storage	Water Yield	Evapo-transpiration	Change in Storage
corresponding to the current landuse.								
++ **Scenario B:** Current conditions: Existing major water resources infrastructures, current management/operation practices, existing crop water demand with irrigation wherever applicable.								

It may be observed from the Table 4 that for the sub basins having contribution from snow and glacial melt there is surplus storage in the water balance which in all probability is contributed by the melt. The other obvious inference that can be drawn is that invariably in all the sub basins there has been some level of reduction in the water yield on account of the water resources development. The storage that has been depicted under the Scenario B can be higher than the storage created since the simultaneous use of the storage can lead to the additional entrapment beyond the capacity. An increase in evapotranspiration in the Scenario B is also evident which is on account of the irrigation deployed in the sub basins.

Spatial variation of the annual water balance components for Scenario A and Scenario B for sub basins of Ganga is shown in Figure 14.

Figure 10: Spatial Depiction: Annual Water Balance Components (mm/year) - Major sub basins Level

Annual Average Water Balance Components for Major Ganga Basins

Scenario A*

Scenario B**

Precipitation (mm)
< 800   1000   1200   1400   >1400

Water Yield (mm)
< 250   500   750   1000   > 1000

Evapotranspiration (mm)
< 400   425   450   500   > 500

Scenario A#: Pre-development flow in the absence of water resources infrastructure and water diversions but reflecting catchment hydrology corresponding to the current landuse.

Scenario B**: Current conditions:, Existing major water resources infrastructures, current management/operation practices, existing crop water demand through irrigation.

Monthly Water Balance mm/month - Scenario A and Scenario B

Average long term monthly water balance components namely water yield and evapotranspiration in mm/month have been made available for sub basins of Ganga for Scenario A and Scenario B at Annexure I.

Flow Duration Curve (FDC) at Major sub basins Level

Assessment of dependability of flows in time is essential for planning and development of water resources projects of various kind. The dependability of the water yield of various sub basins of Ganga has been analyzed with respect to three levels of 50, 75 and 90% dependability for Scenarios A and B. The Flow Duration Curves for Scenarios A and B for every sub basin of Ganga have been provided in Figure 11.

The extent of change in flow at a particular point on a drainage system is not only influenced by the storages or utilization in the sub basin in question but also due to the interventions in the sub basin up-stream.

Flow Duration Curve and Flow Dependability

Figure 11: Flow Duration Curves Major sub basins Level
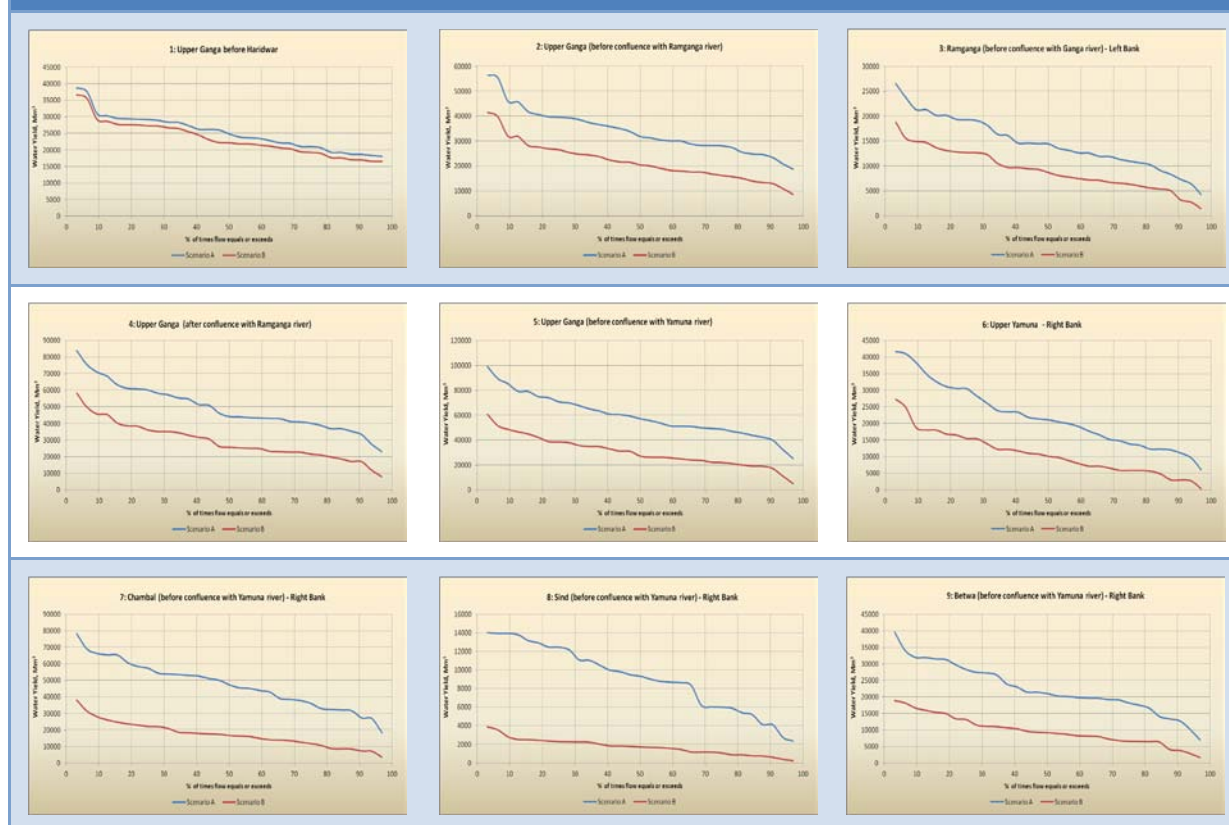
Figure 11: Flow Duration Curves Major sub basins Level
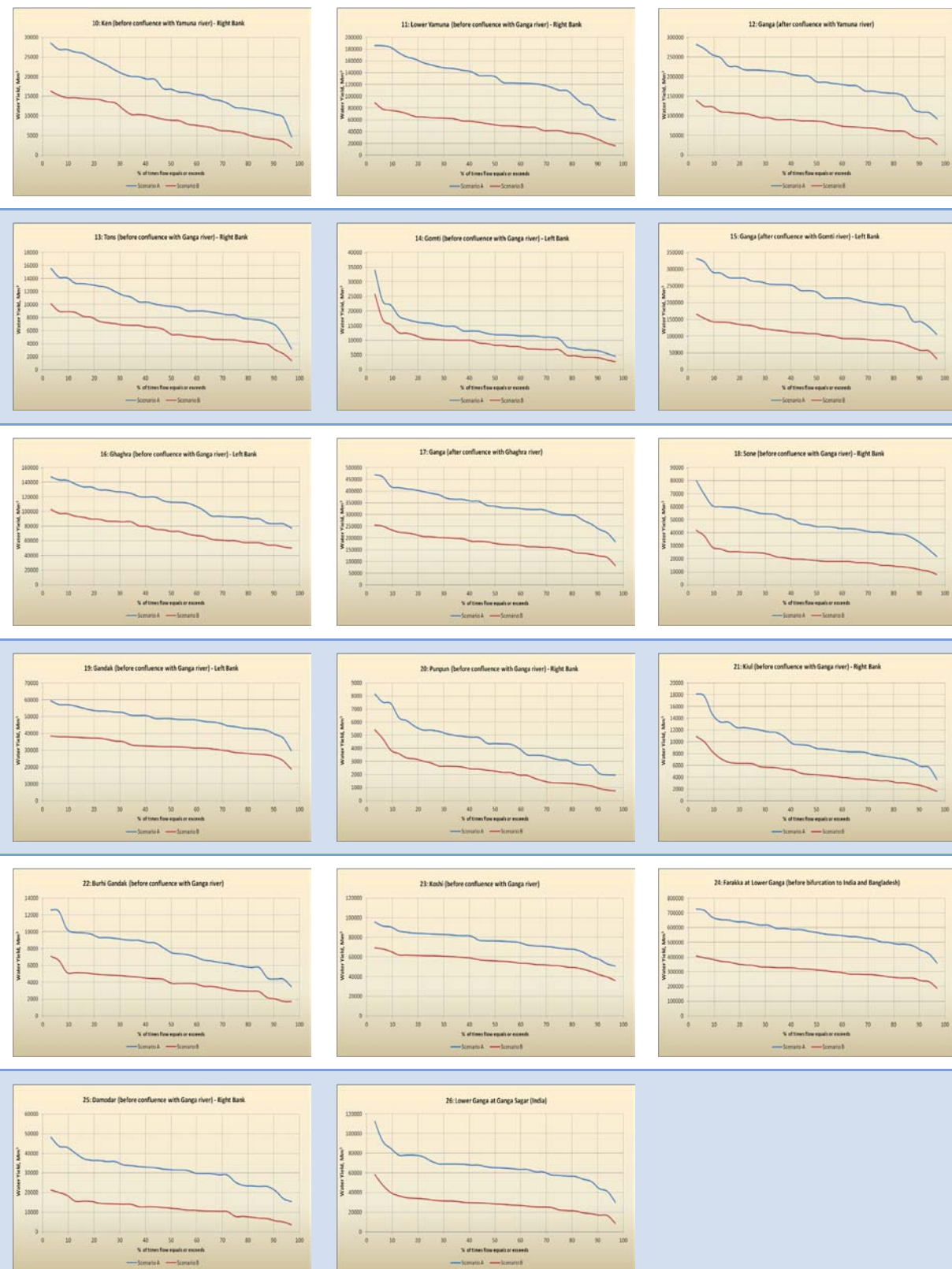
Figure 11: Flow Duration Curves Major sub basins Level
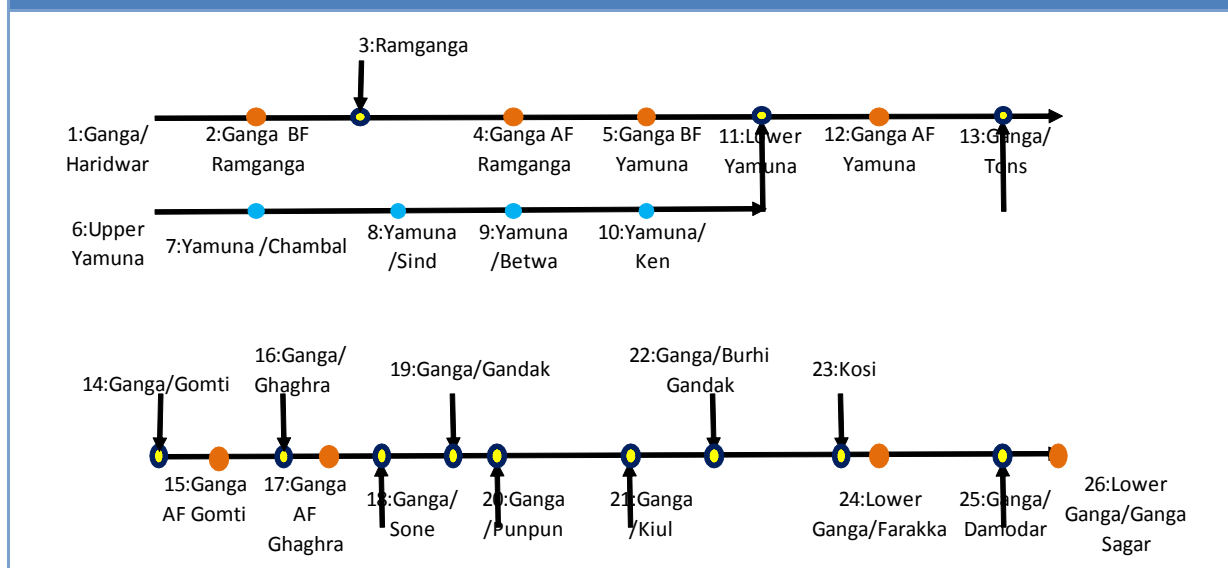
Sediment Flow at Major sub basins Level

One of the important outputs available from SWAT simulation is sediment load that gets generated from land mass and subsequently flow through various drainage networks. This is an important output from the view point of the impacts of water resources development on sediment transport in the sub basins of Ganga. Average annual sediment flow in million metric tons per year has been reported for various sub basins of Ganga for scenario A and scenario B.

Annual Sediment Flow for Sub basins of Ganga for Scenarios A and B

Average annual sediment load at inflow point (in case of intervening sub basins) and flow point for each of the sub basins of Ganga are given in Table 5.

Table 5: Annual Sediment flow (Million metric tons (MT)/year) - Major sub basins Level

SI	Sub Basin	Scenario A+		Scenario B++	
		Sediment In	Sediment Out	Sediment In	Sediment Out
Average Annual Sediment Flow (MT/year)					
1	Upper Ganga before Haridwar	0.0	61.1	0.0	76.1
2	Upper Ganga (before confluence with Ramganga river)	0.0	54.1	0.0	49.8
3	Ramganga (before confluence with Ganga river) - Left Bank	0.0	28.3	0.0	8.0
4	Upper Ganga (after confluence with Ramganga river)	83.7	83.7	56.6	56.6
5	Upper Ganga (before confluence with Yamuna river)	0.0	81.6	0.0	43.1
6	Upper Yamuna - Right Bank	0.0	32.4	0.0	19.1
7	Chambal (before confluence with Yamuna river) - Right Bank	0.0	39.4	0.0	17.4
8	Sind (before confluence with Yamuna river) - Right Bank	0.0	6.8	0.0	1.9
9	Betwa (before confluence with Yamuna river) - Right Bank	0.0	28.2	0.0	24.8
10	Ken (before confluence with Yamuna river) - Right Bank	0.0	18.5	0.0	9.8
11	Lower Yamuna (before confluence with Ganga river) - Right Bank	125.3	130.4	73.1	69.7
12	Ganga (after confluence with Yamuna river)	212.5	212.5	113.1	113.1
13	Tons (before confluence with Ganga river) - Right Bank	0.0	14.1	0.0	10.3
14	Gomti (before confluence with Ganga river) - Left Bank	0.0	14.5	0.0	6.7
15	Ganga (after confluence with Gomti river) - Left Bank	241.2	265.1	130.1	87.8
16	Ghaghra (before confluence with Ganga river) - Left Bank	0.0	156.0	0.0	76.2
17	Ganga (after confluence with Ghaghra river)	422.2	422.2	161.5	161.5
18	Sone (before confluence with Ganga river) -	0.0	46.6	0.0	19.3

Sl	Sub Basin	Scenario A+		Scenario B++	
		Sediment In	Sediment Out	Sediment In	Sediment Out
	Right Bank				
19	Gandak (before confluence with Ganga river) - Left Bank	0.0	84.6	0.0	80.3
20	Punpun (before confluence with Ganga river) - Right Bank	0.0	4.4	0.0	2.1
21	Kiul (before confluence with Ganga river) - Right Bank	0.0	7.9	0.0	4.2
22	Burhi Gandak (before confluence with Ganga river)	0.0	7.8	0.0	2.3
23	Koshi (before confluence with Ganga river)	0.0	131.5	0.0	108.1
24	Farakka *at Lower Ganga (before bifurcation to India and Bangladesh)	641.1	634.2	266.4	235.5
25	Damodar (before confluence with Ganga river) - Right Bank	0.0	34.9	0.0	13.4
26	Lower Ganga at Ganga Sagar (India)	34.9	56.3	13.4	23.0
* India at Farakka					
+ Scenario A: Pre-development flow in the absence of water resources infrastructure and water diversionsbut reflecting catchment hydrology corresponding to the current landuse					
++ Scenario B: Current conditions: Existing major water resources infrastructures, current management/operation practices, existing crop water demand with irrigation wherever applicable.					

Figure 12 and Figure 13 show the graphical representation of the sediment load at inflow and outflow points for sub basins of Ganga for Scenario A and Scenario B respectively. The SWAT model performs the sediment erosion and transport routing on landmass as well as through river channel systems to arrive at the sediment flow at a specific location. One can observe the reductions of sediment load in many of the sub basins on account of water resources development through creation of storages as well as diversions.
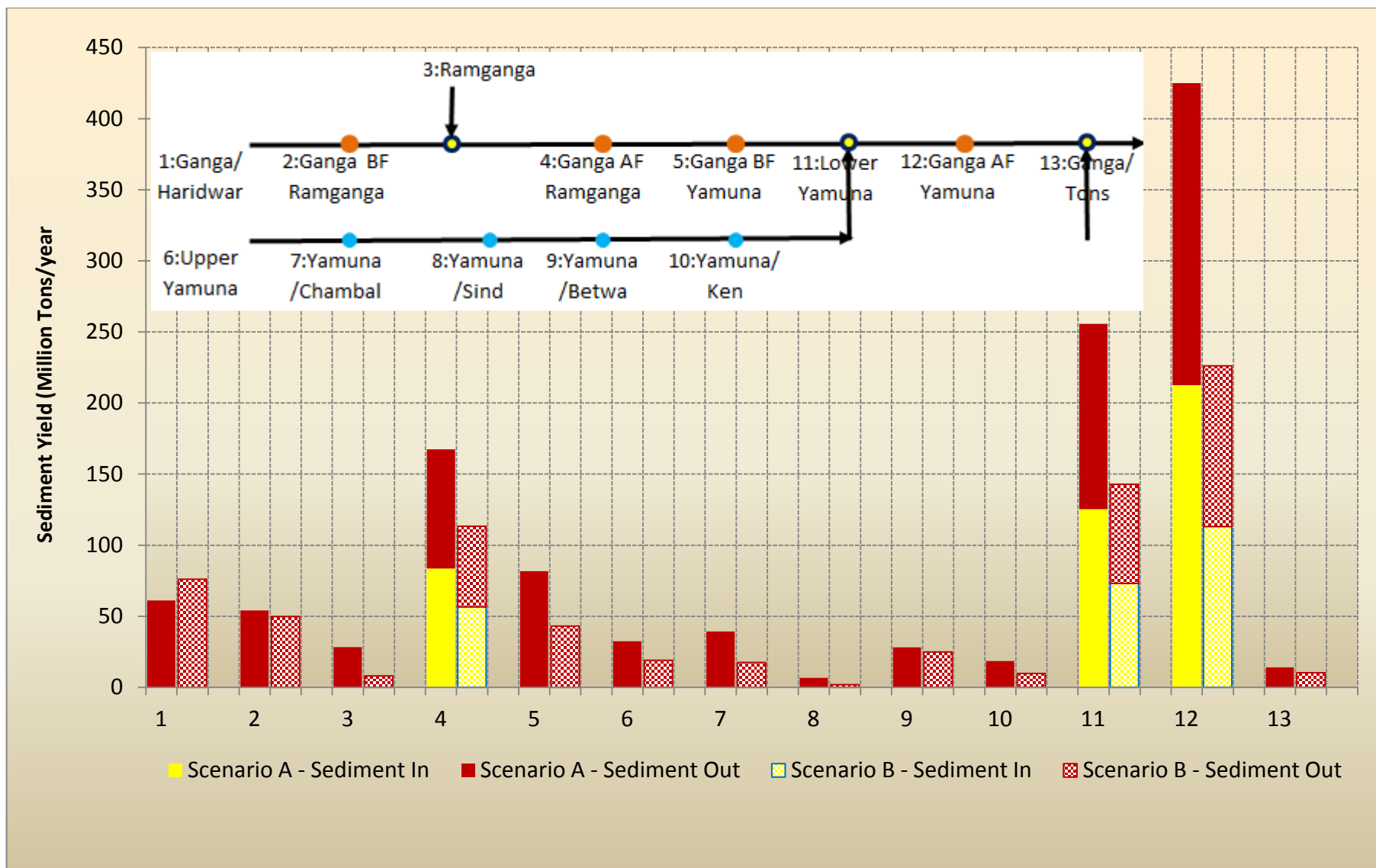
Figure 12: Annual Sediment flow (MT/year) for Sub basins of Ganga, Scenario A and Scenario B - Part 1
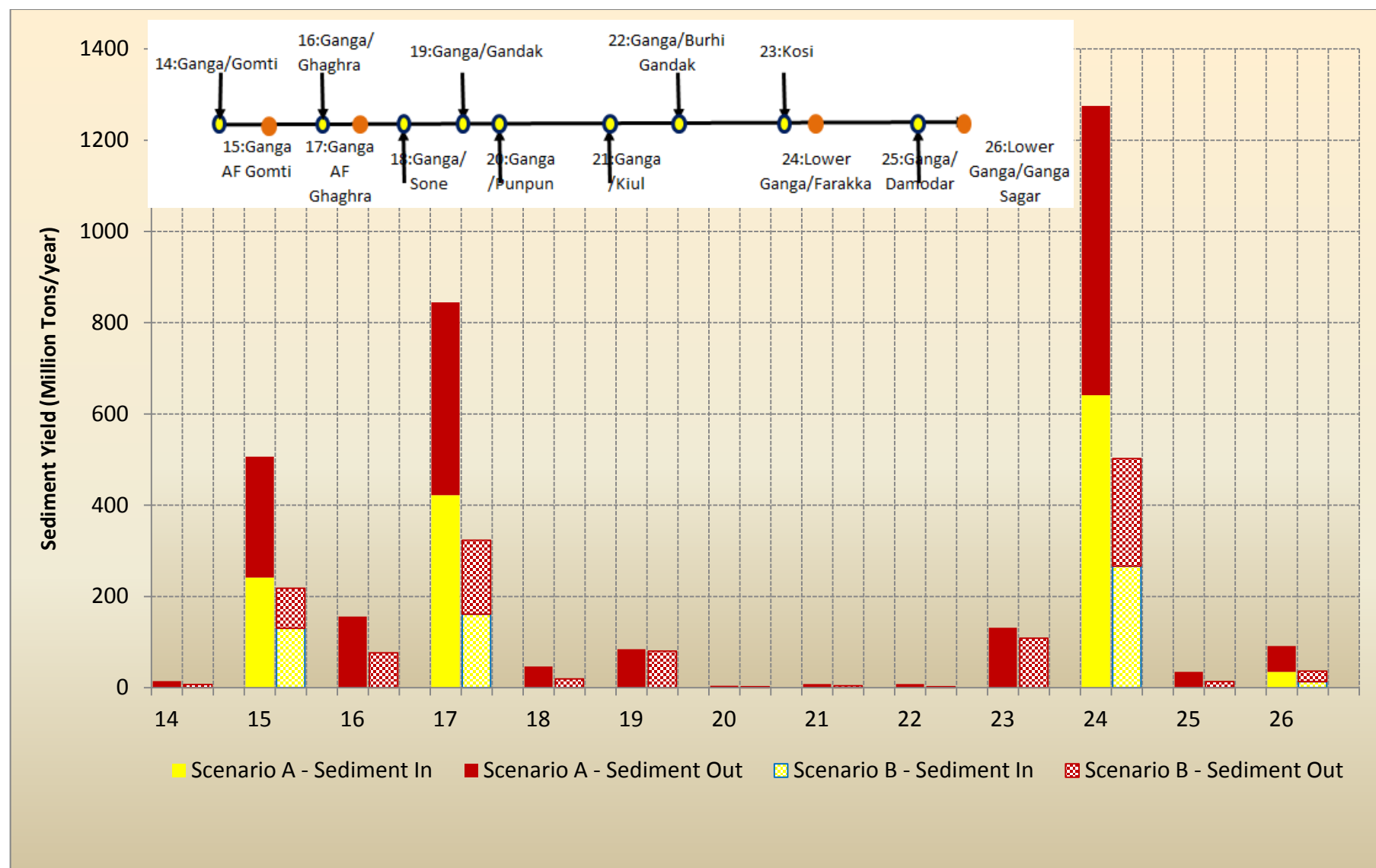
Figure 13: Annual Sediment flow (MT/year) for Sub basins of Ganga, Scenario A and Scenario B - Part 2

Spatial depiction of annual sediment load (MT/year) for tributaries of sub basins of Ganga is shown in Figure 14 for Scenario B. Reduction of sediment load on account of water resources development has been depicted using the ratio of sediment flow of Scenario B to Scenario A. The lower this ratio, the higher is the entrapment of sediment in the sub basin
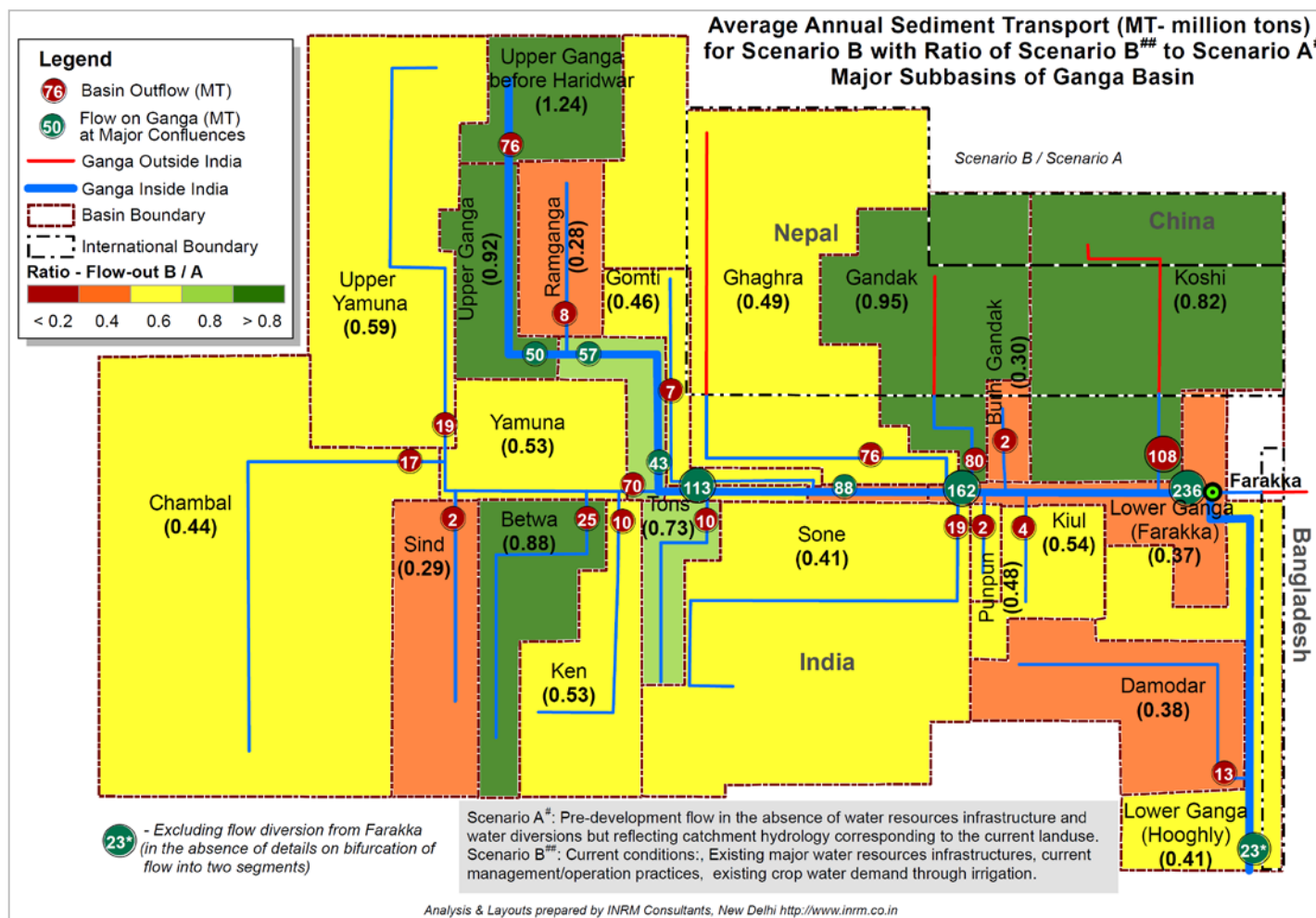
Figure 14: Annual Sediment Flow (MT/year) for Sub basins of Ganga

Monthly Sediment Flow in MT/month - Scenario A - Major sub basins level

The temporal variation of sediment transport in the sub basins of Ganga has been provided for Scenarios A and B in Annexure I as average monthly sediment inflow and outflow for sub basins of Ganga.

CBOD at Major sub basins Level

Biochemical oxygen demand (BOD) is a measure of the dissolved oxygen consumed by microorganisms during the oxidation of reduced substances in waters and wastes. Typical sources of BOD are readily biodegradable organic carbon (carbonaceous, CBOD) and ammonia (nitrogenous, NBOD). These compounds are common constituents or metabolic by-products of plant and animal wastes and human activities (domestic and industrial wastewaters). The increased organic loading stimulated microbial decomposition that utilized dissolved oxygen (DO) in the surface water. Greater the BOD, more rapid will be oxygen depletion resulting in less oxygen available to aquatic life.

Average CBOD in ppm has been simulated by the SWAT model for sub basins of Ganga for scenario B. Permissible Permissible limit of Biochemical Oxygen Demand 5 days at 20°C is 3mg/l or less[1].

Average CBOD ppm for Scenario A and Scenario B - Major sub basins level

Table 6 shows the average annual CBOD for each major sub basins.

Table 6: Average CBOD (ppm) - Major sub basins Level

Sl	Sub Basin	Scenario B++	
		CBOD In	CBOD Out
1	Upper Ganga before Haridwar	0.0	6.6
2	Upper Ganga (before confluence with Ramganga river)	0.0	1.4
3	Ramganga (before confluence with Ganga river) - Left Bank	0.0	1.5
4	Upper Ganga (after confluence with Ramganga river)	4.1	4.1
5	Upper Ganga (before confluence with Yamuna river)	0.0	0.5
6	Upper Yamuna	0.0	0.2
7	Chambal (before confluence with Yamuna river) - Right Bank	0.0	0.5
8	Sind (before confluence with Yamuna river) - Right Bank	0.0	3.1
9	Betwa (before confluence with Yamuna river) - Right Bank	0.0	0.8
10	Ken (before confluence with Yamuna river) - Right Bank	0.0	0.8
11	Lower Yamuna (before confluence with Ganga river) - Right Bank	0.7	1.2
12	Ganga (after confluence with Yamuna river)	1.2	1.2
13	Tons (before confluence with Ganga river) - Right Bank	0.0	4.6
14	Gomti (before confluence with Ganga river) - Left Bank	0.0	1.8
15	Ganga (after confluence with Gomti river) - Left Bank	1.5	0.7
16	Ghaghra (before confluence with Ganga river) - Left Bank	0.0	3.7
17	Ganga (after confluence with Ghaghra river)	0.0	1.1

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[1] http://www.cpcb.nic.in/Water_Quality_Criteria.php

Sl	Sub Basin	Scenario B++	
		CBOD In	CBOD Out
18	Sone (before confluence with Ganga river) - Right Bank	0.0	1.6
19	Gandak (before confluence with Ganga river) - Left Bank	0.0	4.4
20	Punpun (before confluence with Ganga river) - Right Bank	0.0	8.5
21	Kiul (before confluence with Ganga river) - Right Bank	0.0	17.6
22	Burhi Gandak (before confluence with Ganga river)	0.0	2.0
23	Koshi (before confluence with Ganga river)	0.0	2.2
24	Farakka[*] at Lower Ganga (before bifurcation to India and Bangladesh)	1.0	0.9
25	Damodar (before confluence with Ganga river) - Right Bank	0.0	6.3
26	Lower Ganga at Ganga Sagar (India)	0.0	0.4

Figure 15 shows the spatial depiction of annual CBOD concentration for Scenario B.
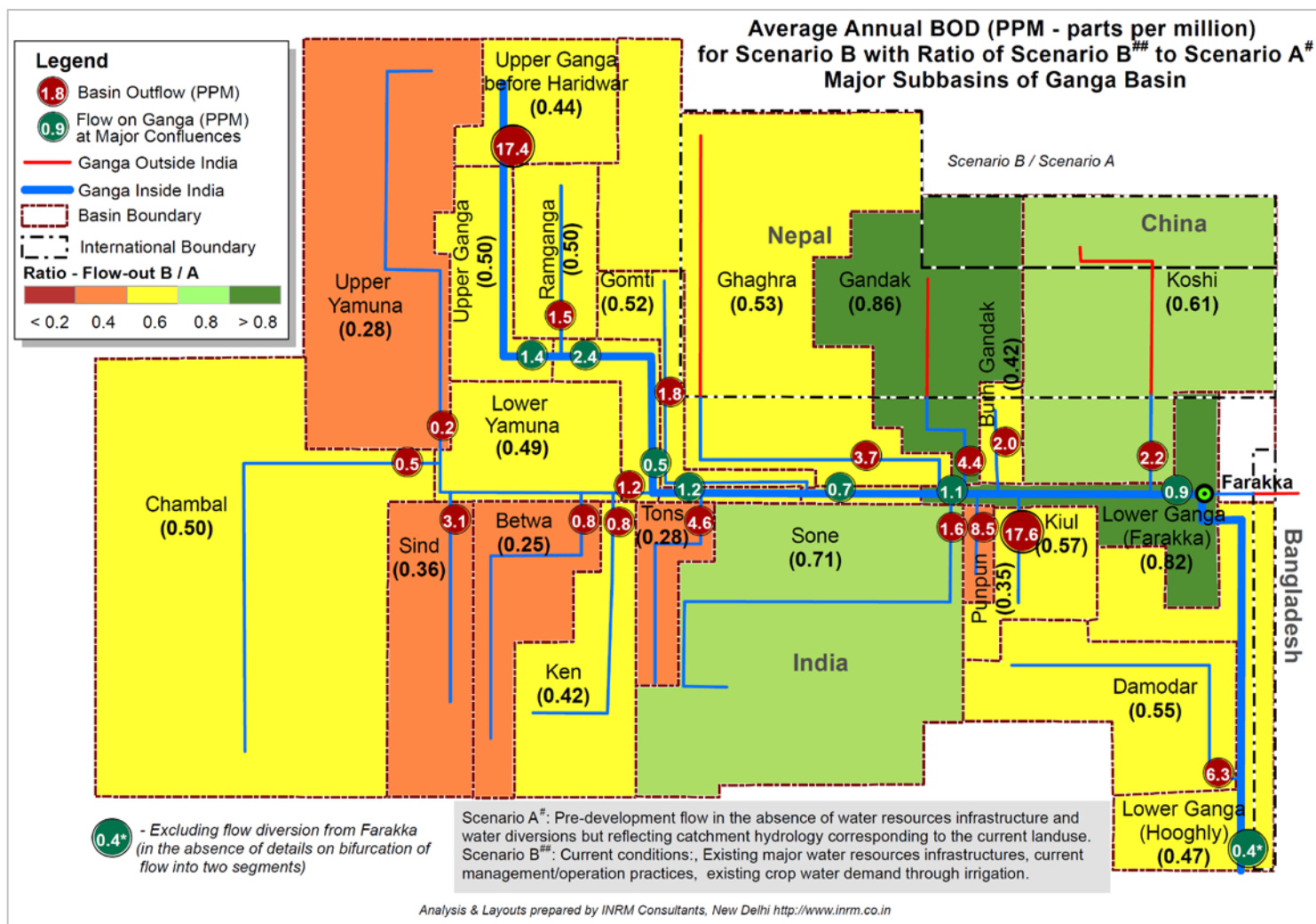
Figure 15: Annual CBOD (ppm) for Sub basins of Ganga

Irrigation Applied for Major crops at Major sub basins Level

There has been considerable change within the agricultural area in the Ganga basin that is having significant impact on the hydrological regime of the Ganga basin. Secondary data on cropping patterns and the irrigation sources has been analysed for 42 years (1966 – 2007) and trend analysis has been performed to detect change in crop and the source of irrigation.

Trend in change of cropped area for major crops of rice, wheat, sugarcane, maize, millets and pulses. Results of the trend analysis are presented in Figure 16 and it show that there is a significant reducing trend in the area under sugarcane, maize millets and pulses though spread over various sub basins of Ganga basin. However there is a significant positive trend in the areas under rice, wheat and pulses crops. Similar analysis has been performed on the trend in the total area irrigated under rice and wheatand also in the trend in the source of irrigation. There is a positive trend in the total area under irrigation in the Ganga basin as shown in Figure 16. It can also be observed that the area under surface irrigation is reducing and the area with grounwater as the source of irrigation is increasing. There is positive trend in irrigated area under wheat and rice for majority of the sub basins but for a few areas which show negative trend. However the crop intensity has increased in majority of the sub basins of Ganga.

Figure 16:Trend in Agriculture in the Ganga Basin

Trend in Percentage of Cropped Area with respect to Gross Cropped Area for Ganga Basin

Source : *District level data from International Crops Research Institute for the Semi Arid Tropics (ICRISAT)for the period 1966-2007 (42 years)

Analysis & Layouts prepared by INRM Consultants, New Delhi
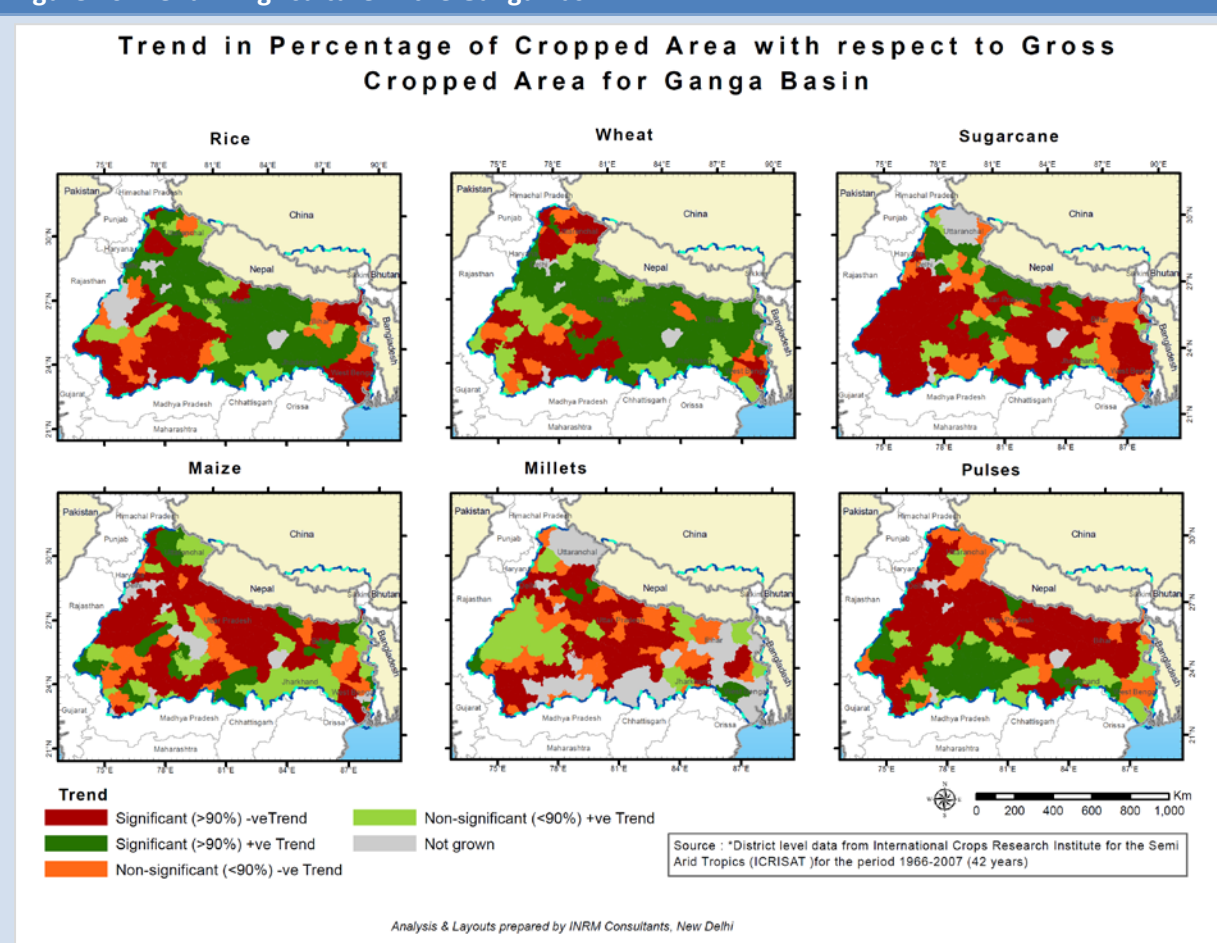
Figure 16:Trend in Agriculture in the Ganga Basin
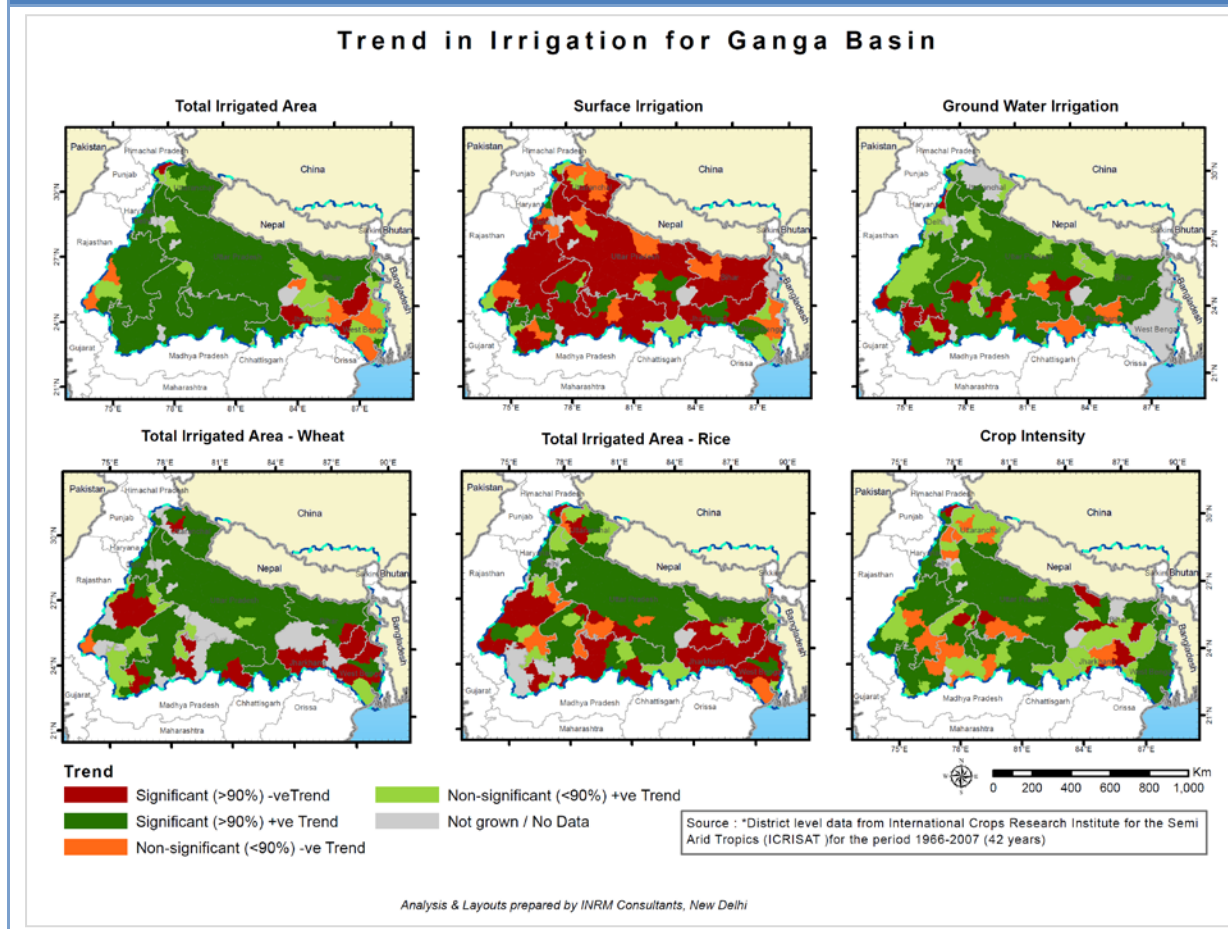
Analysis has also been made on the average seasonal irrigation water used for crops in various sub basins of Ganga and the same has been shown in Figure 17 for Kharif and Rabi seasons. It may be observed that the extent of irrigation in Rabi season (non-monsoon season) is almost double of the irrigation requirement of the Kharif being the monsoon period season. This is one of the reason for deterioration of the hydrological health of the Ganga basin that has been assessed in the next section.

Figure 17:Seasonal Average Irrigation water use for Rice and Wheat Major sub basins of Ganga
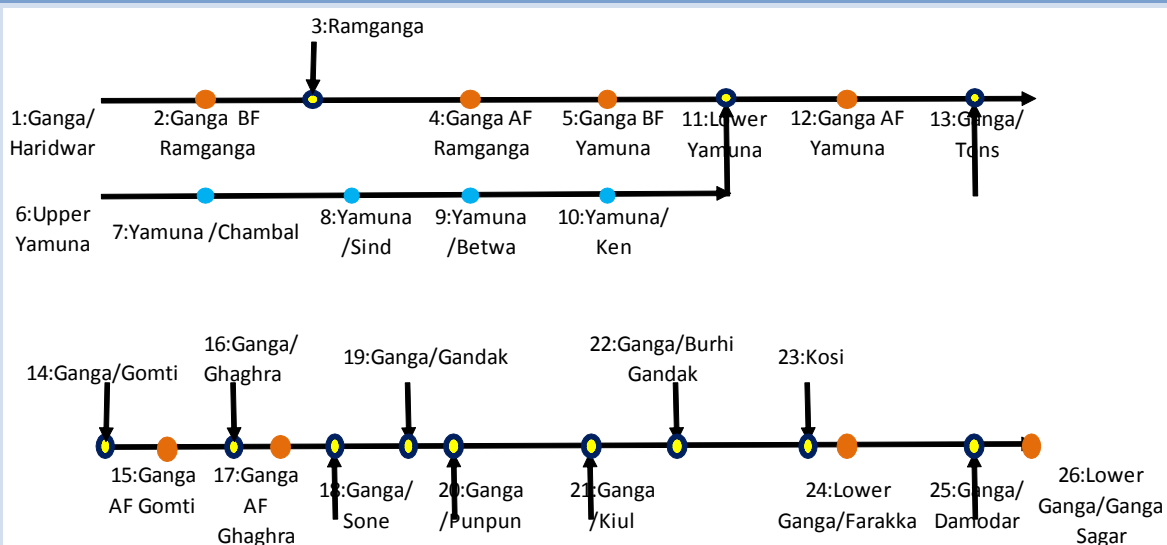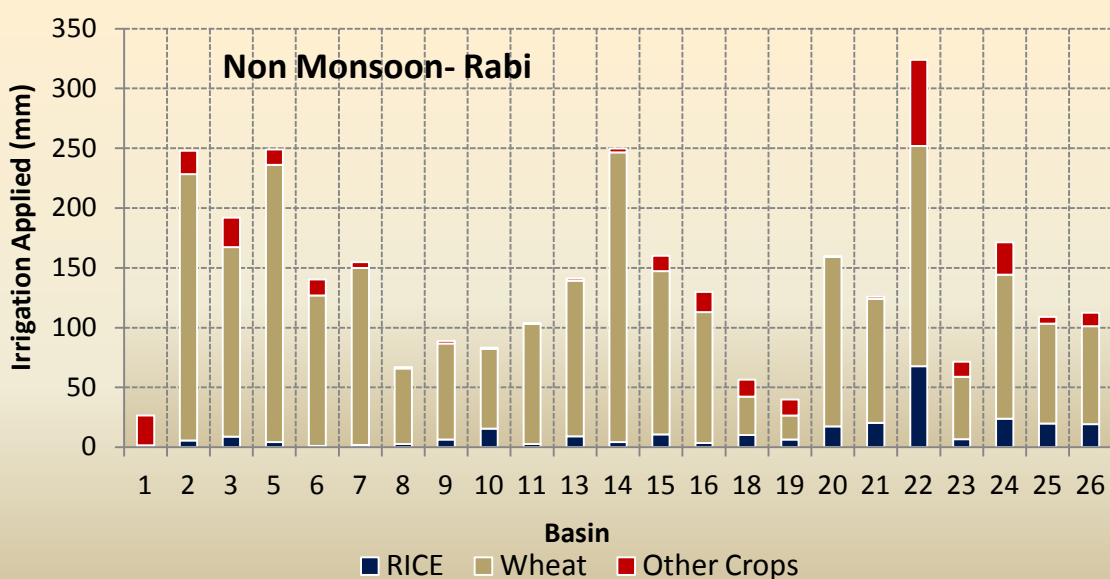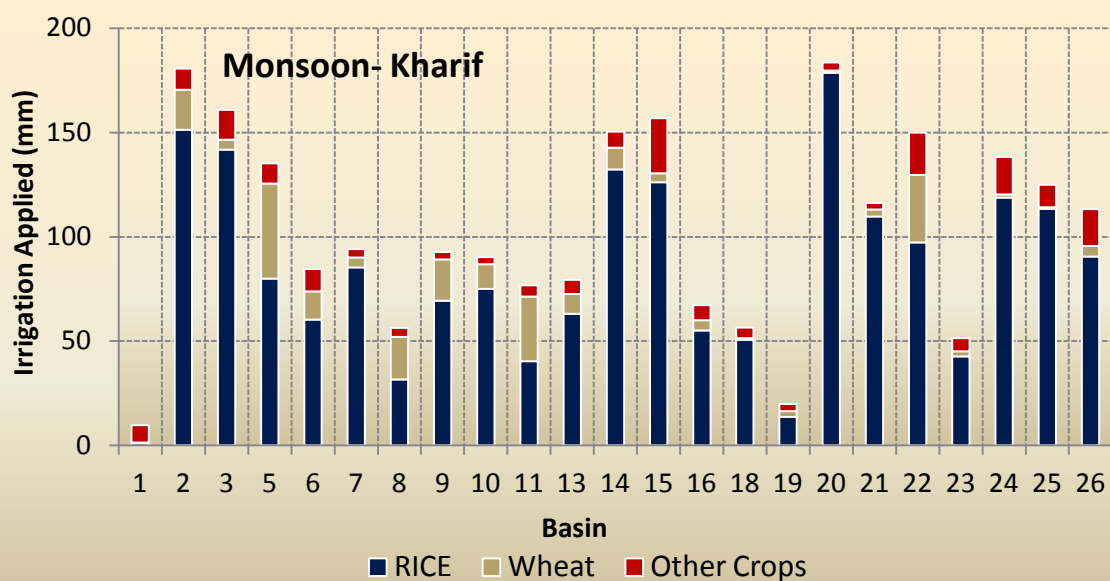
River Health Assessment

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[2]). 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.

Flow health was used for analysis of river health in different rivers of China by a project undertaken by International water centre. The indicators identified to assess the river flow regime are shown in Figure 18. The flow regime was analyzed and the parametric variations contributing to the Flow health score formulation was analyzed in the study. (Zhang Yuan, 2007)

Figure 18: Indicators of river flow regime contributing to river flow health
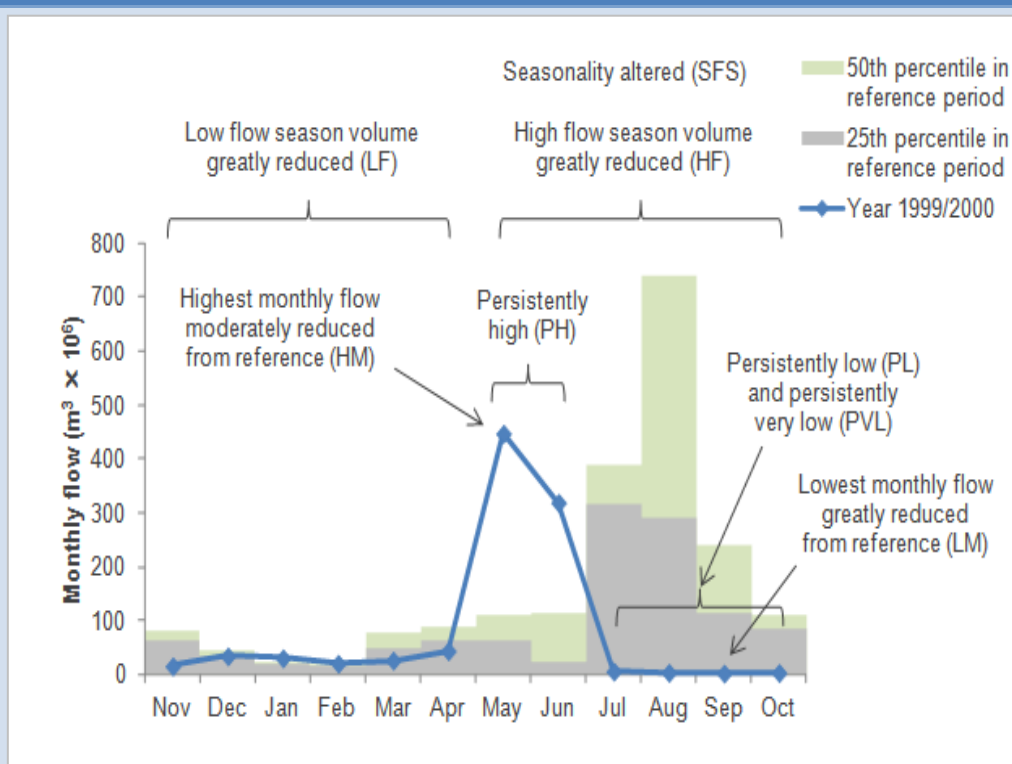
Source: Gippel, C.J., Marsh, N. and Grice, T. 2012, Flow Health - Software to assess the deviation of river flows from reference and to design a monthly environmental flow regime. Technical Manual and User Guide, Version 2.0.

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

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[2] Bond, Nick, Chris Gippel, Jane Catford, Liu Lishi, Lian Hao, Liu Bin, and Huang Yuming (2012) River Health And Environmental Flow In China Project: Preliminary Environmental Flows Assessment In The Li River, International Water Centre, Brisbane

are closely related to the basic flow components of a natural flow regime (Figure 19). The Flow Health Index combines the scores of the nine sub-indicators.

Figure 19: Basic flow components of natural flow regime
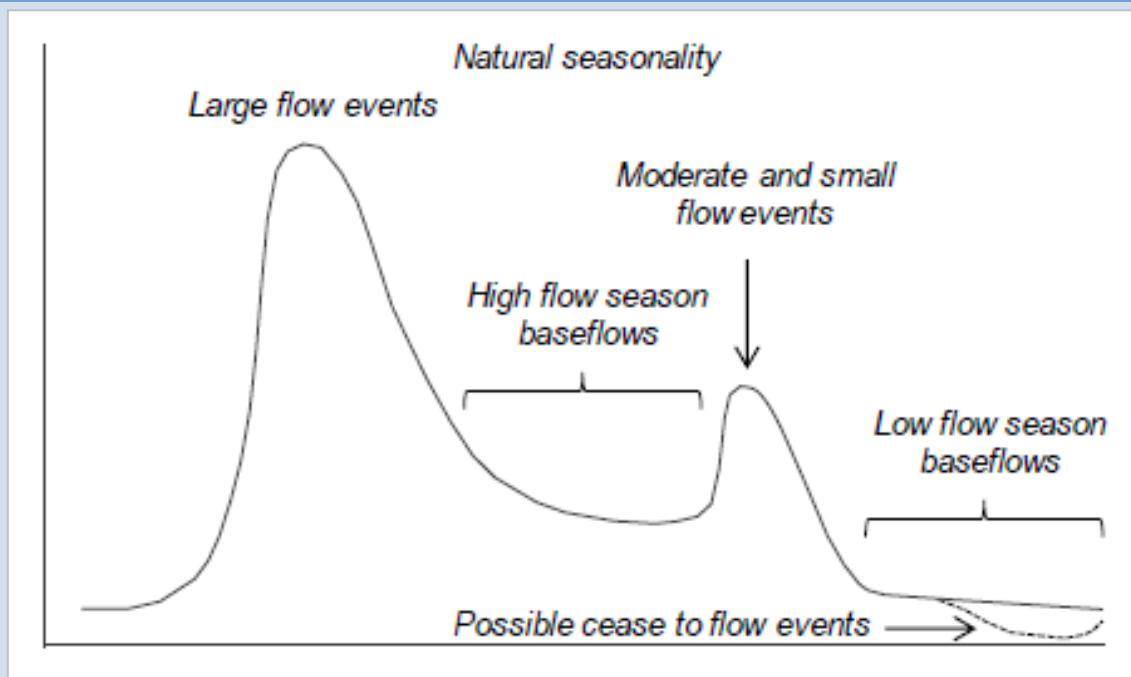
Source: Gippel, C.J., Marsh, N. and Grice, T. 2012, Flow Health - Software to assess the deviation of river flows from reference and to design a monthly environmental flow regime. Technical Manual and User Guide, Version 2.0.

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 four main functions(Gippel et al, 2012).:

- To provide an annual score for the hydrology indicator in river health assessment
- To recommend a minimum monthly environmental flow regime
- To test the hydrological health of any monthly environmental flow regime
- To generate a synthetic monthly flow time series based on the designed environmental flow regime

For the major tributaries of the Ganga River, flow health analysis has been carried out to provide an annual score for the hydrology indicator in river health assessment.

The assessment of flow health has been carried out by considering natural low-flow and natural high-flow periods based on the flows from Scenario A (Reference period). The percentile ranking of different flow metrics has been obtained by comparing the Scenario B flow with the reference period to arrive at non-dimensional scoring system of different flow indices.

Ecosystem Significance of Flow health parameters

- Highest Monthly Flow (HMF)
    - o Magnitude of flood flows which are critical for inundating wetlands, cuing fish spawning behaviour, facilitating fish migration and mobilising sediment for creation of physical habitat.
- Lowest Monthly Flow (LMF)
    - o Magnitude of the lowest flow of the year, when minimum flows are required for survival
    - o HMF and LMF are not determined for the high flow and low flow seasons respectively, but for the entire year.
- Highest and Lowest flow Volume (HF& LF)
    - o Total seasonal volume will reflect the prevailing natural hydrological conditions (in particular, highlighting dry years) and also indicate any major reductions in total flow volume (and hence gross habitat area availability) due to flow regulation
    - o Significant regulation impacts would tend to be characterised by a sustained reduction in HFV, perhaps also with a sustained reduction in LFV.
- Persistently Higher flow (PHF)
    - o Intended to relate to the situation of flows being artificially regulated at significantly higher than reference magnitude for long periods through the low flow period.
    - o This can reduce light penetration to the bed, and hence reduce primary production of benthic algae
    - o Persistently elevated low flows might also mean that invertebrates are not seasonally stressed, which could be a natural disturbance process that plays a role in maintaining diversity
    - o Higher than normal flows in the low flow period can also stress riparian vegetation by waterlogging root zones, or preventing recruitment in exposed soils.
- Persistently Lower flow (PLF)
    - o Intended to relate to the situation of flows, either in the low or high flow season, being depressed for long periods.
    - o This indicator would usually indicate persistently depressed low flow season flows, which would have implications for gross habitat area availability for fish and macroinvertebrates.
    - o This flow condition would potentially allow colonisation of the stream bed by invasive vegetation, or accumulation of fine sediments that settle out during periods of low flow. In a river with a high level of flow diversion, a high proportion of the year could have markedly depressed flows, which could impact the entire life cycles of many aquatic organisms.
- Persistently very Low (PVL):
    - o Relates to the situation of flows being artificially regulated at very low levels for long periods through the low flow period.
    - o The consequences of this drying or near-drying of the channel can be critical for all organisms in the stream.

- o Very low flows are often associated with the loss of riffle habitats, crowding in pools and degraded water quality, such as temperature extremes and increased risk of hypoxia and high salinity.
- Seasonal flow shift (SFS) :
  - o relates to the situation of the seasonal pattern of flows being reversed, or partly reversed, due to storage of flows in the natural high flow season, and release of flows for downstream supply in the natural low flow season.
  - o The consequences of this can be disruption of the natural timing of flow pulses and baseflows that stimulate the behaviour of aquatic organisms whose life cycle has adapted to a particular seasonal pattern of flow.

Flow health graphical outputs for major tributary basins of the Ganga river is presented in Figure 20.

Figure 20: Flow Health Score at Major sub basins of the Ganga River Basin
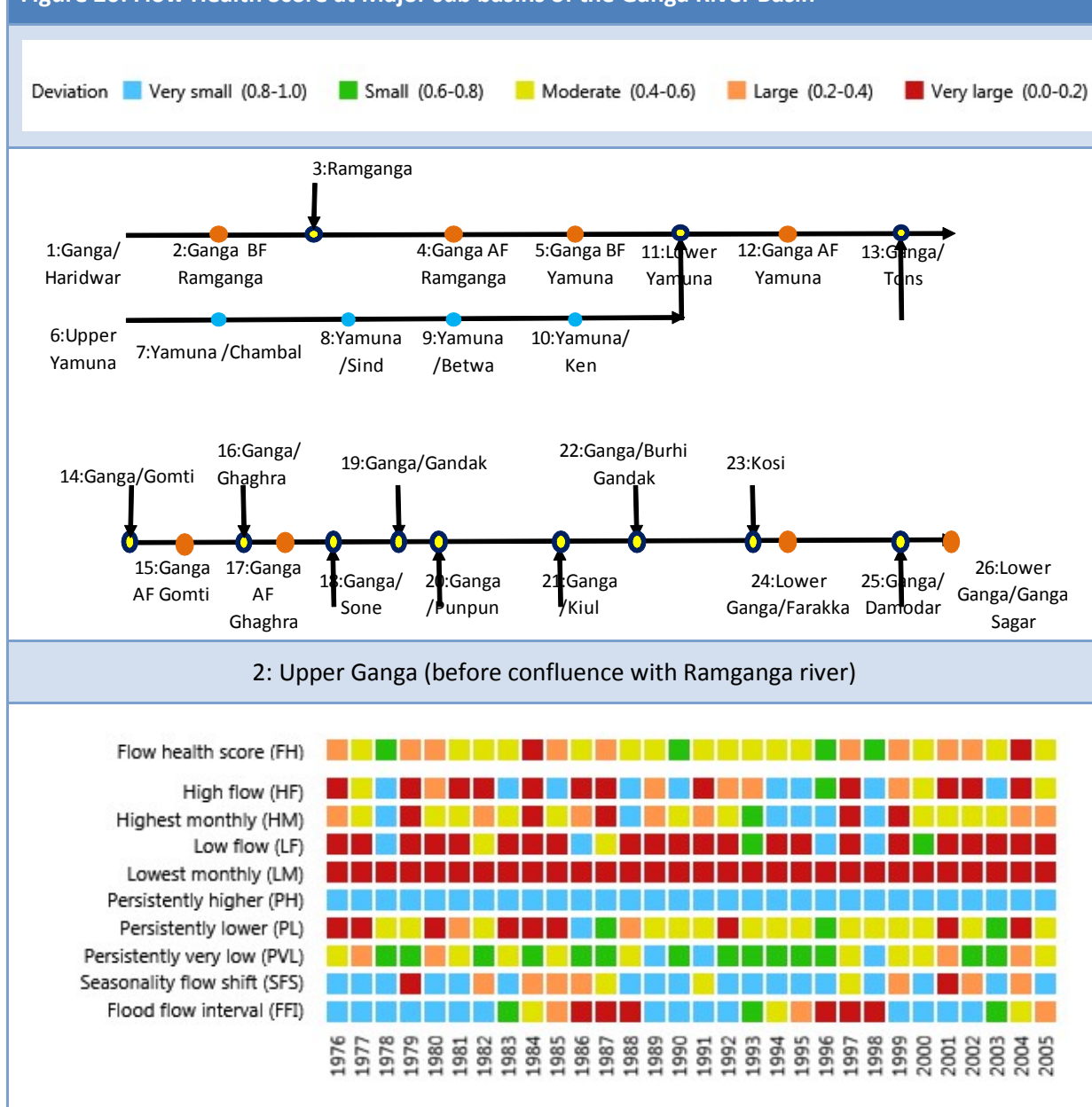
Figure 20: Flow Health Score at Major sub basins of the Ganga River Basin

3: Ramganga (before confluence with Ganga river) - Left Bank
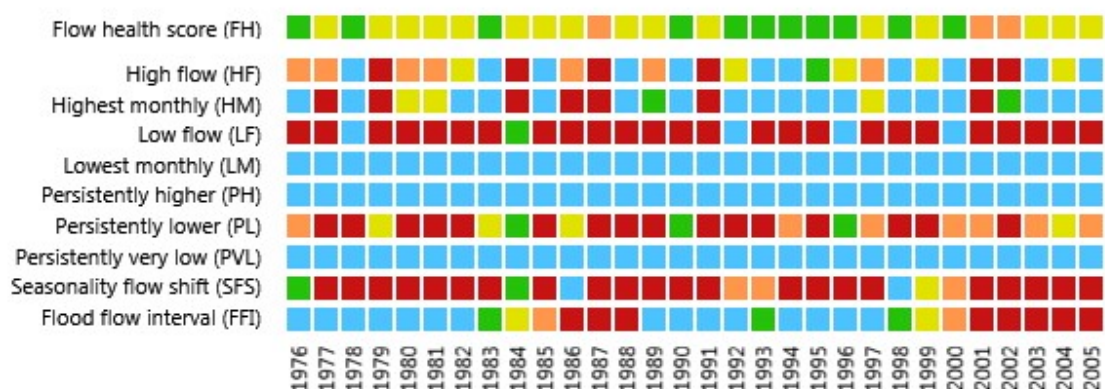
4: Upper Ganga (after confluence with Ramganga river)

5: Upper Ganga (before confluence with Yamuna river)

Figure 20: Flow Health Score at Major sub basins of the Ganga River Basin
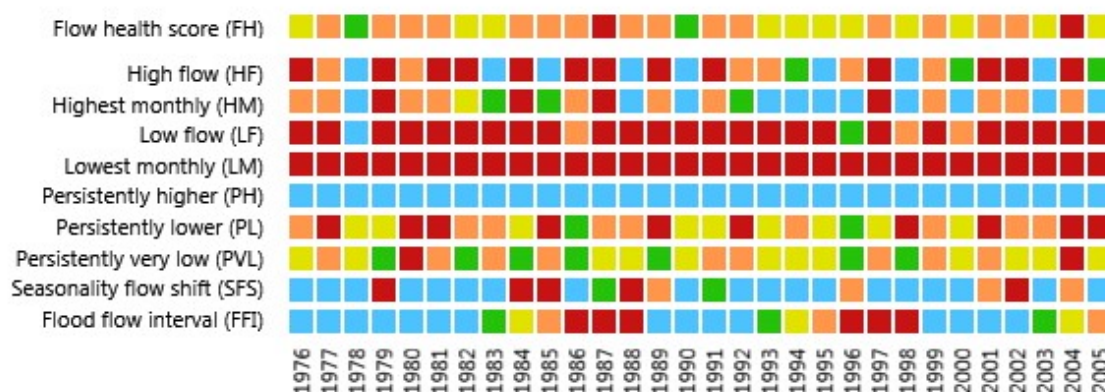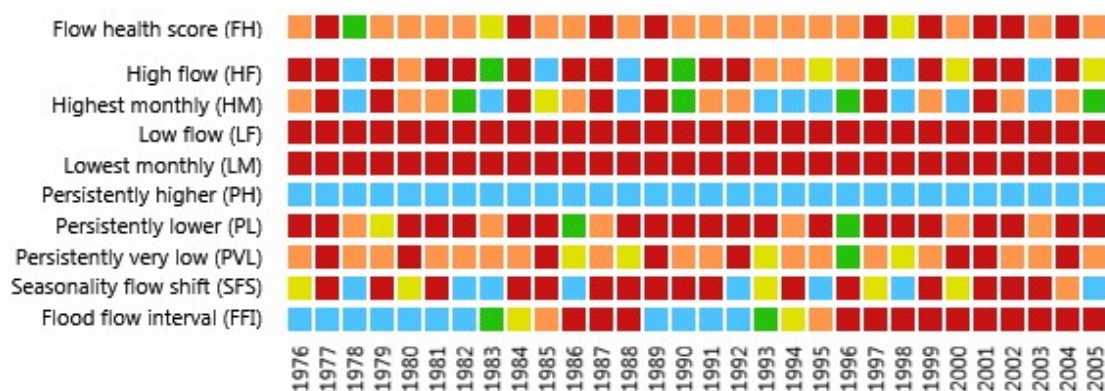
6: Upper Yamuna
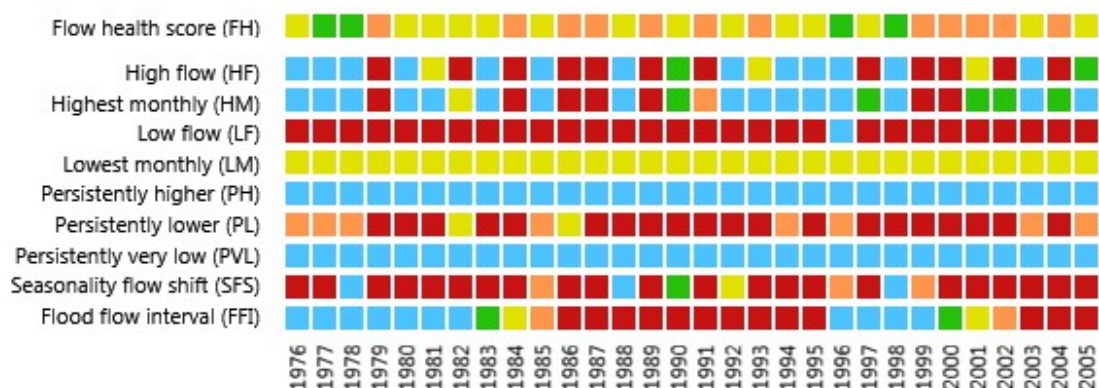
7: Chambal (before confluence with Yamuna river) - Right Bank
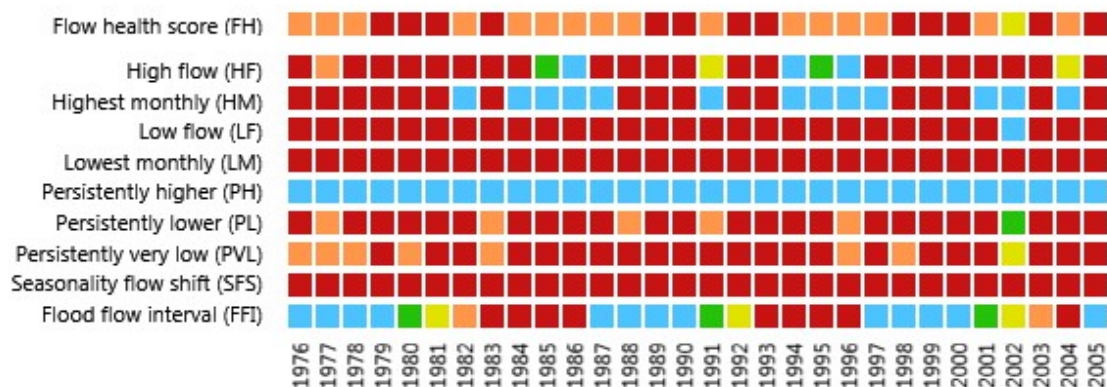
8: Sind (before confluence with Yamuna river) - Right Bank
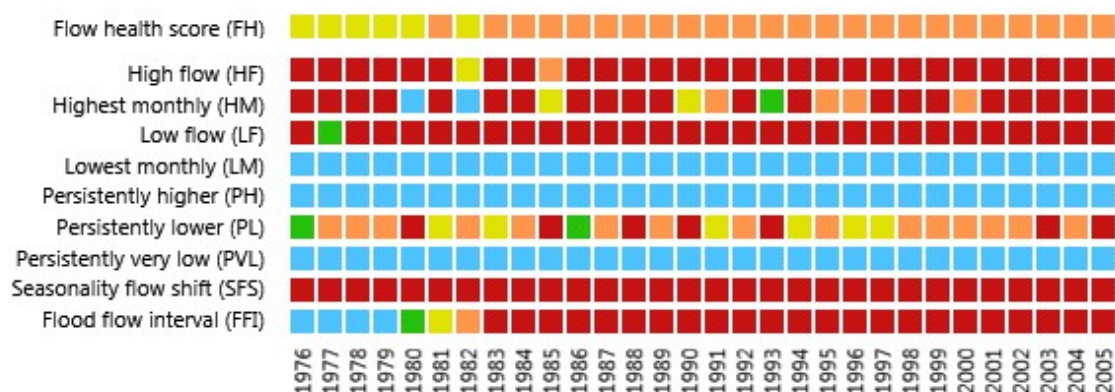
Figure 20: Flow Health Score at Major sub basins of the Ganga River Basin

9: Betwa (before confluence with Yamuna river) - Right Bank

10: Ken (before confluence with Yamuna river) - Right Bank

11: Lower Yamuna (before confluence with Ganga river) - Right Bank
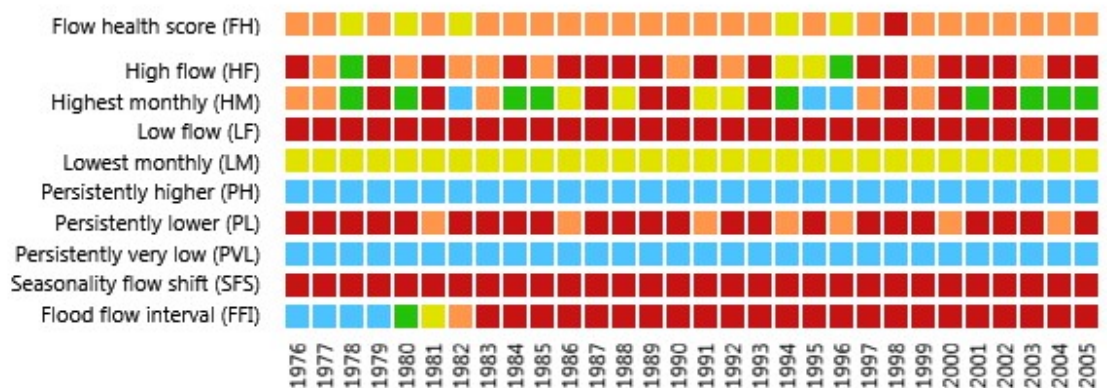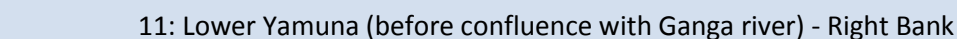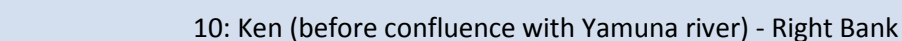
Figure 20: Flow Health Score at Major sub basins of the Ganga River Basin

12: Ganga (after confluence with Yamuna river)
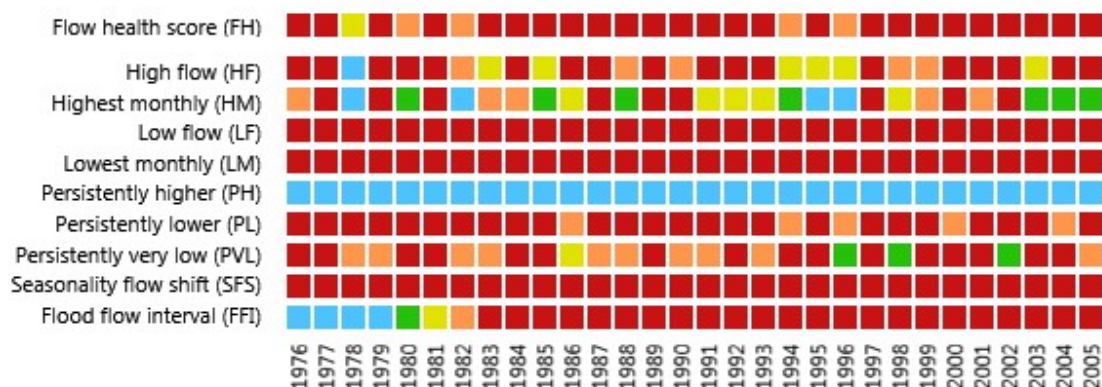
13: Tons (before confluence with Ganga river) - Right Bank
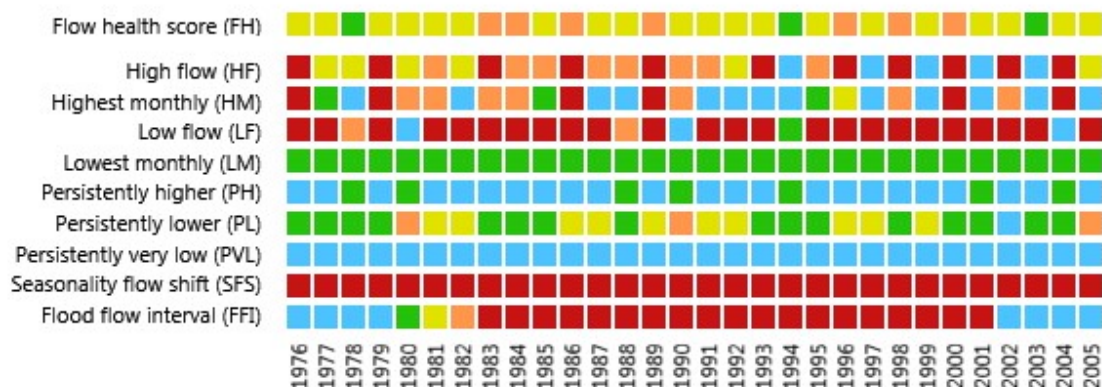
14: Gomti (before confluence with Ganga river) - Left Bank
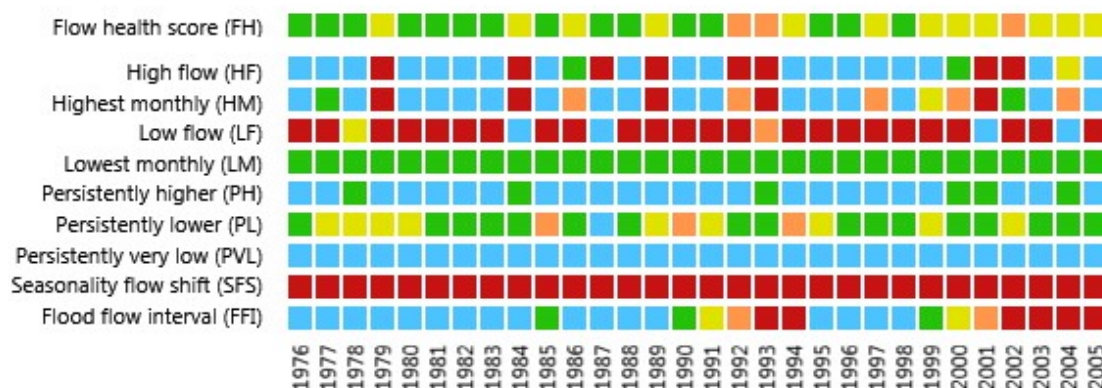
Figure 20: Flow Health Score at Major sub basins of the Ganga River Basin

15: Ganga (after confluence with Gomti river) - Left Bank
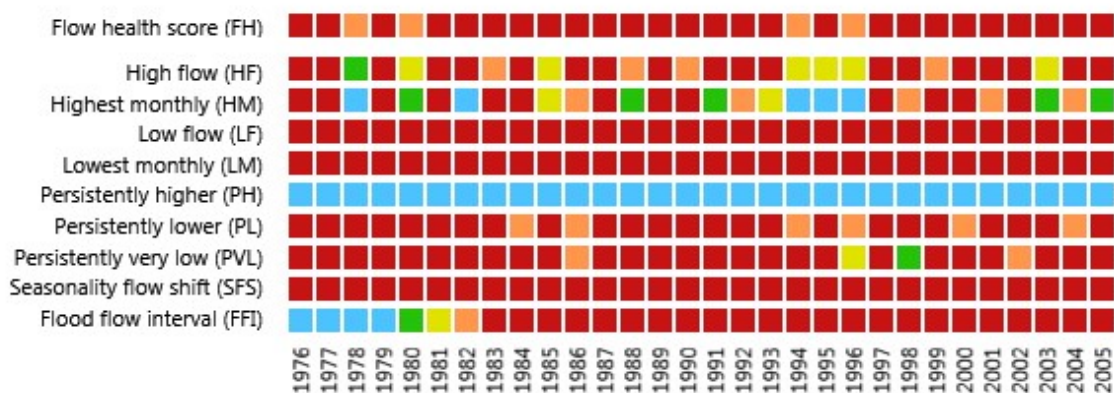
16: Ghaghra (before confluence with Ganga river) - Left Bank

17: Ganga (after confluence with Ghaghra river)

Figure 20: Flow Health Score at Major sub basins of the Ganga River Basin

18: Sone (before confluence with Ganga river) - Right Bank

19: Gandak (before confluence with Ganga river) - Left Bank

20: Punpun (before confluence with Ganga river) - Right Bank

Figure 20: Flow Health Score at Major sub basins of the Ganga River Basin

21: Kiul (before confluence with Ganga river) - Right Bank

22: Burhi Gandak (before confluence with Ganga river)

23: Koshi (before confluence with Ganga river)

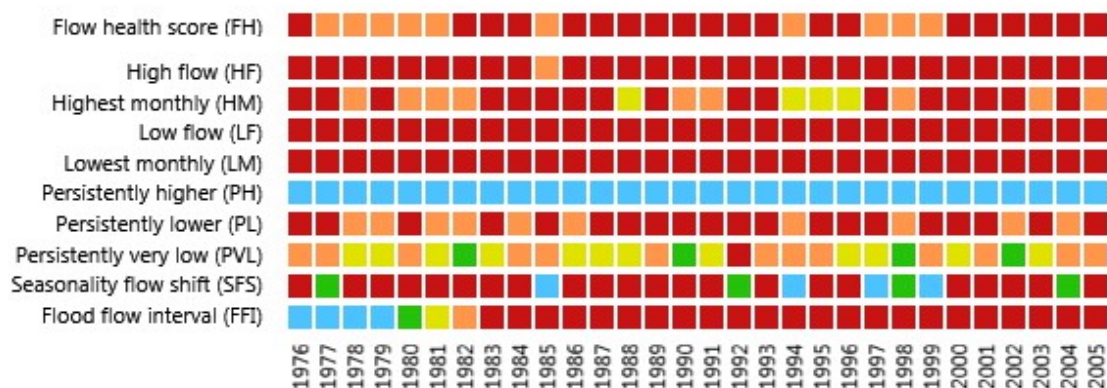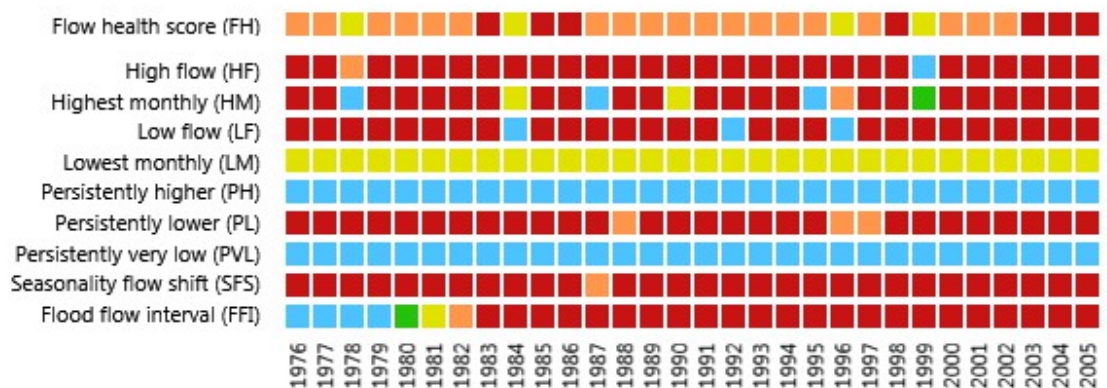**Figure 20: Flow Health Score at Major sub basins of the Ganga River Basin**

24: Farakka at Lower Ganga (before bifurcation to India and Bangladesh)

25: Damodar (before confluence with Ganga river) - Right Bank

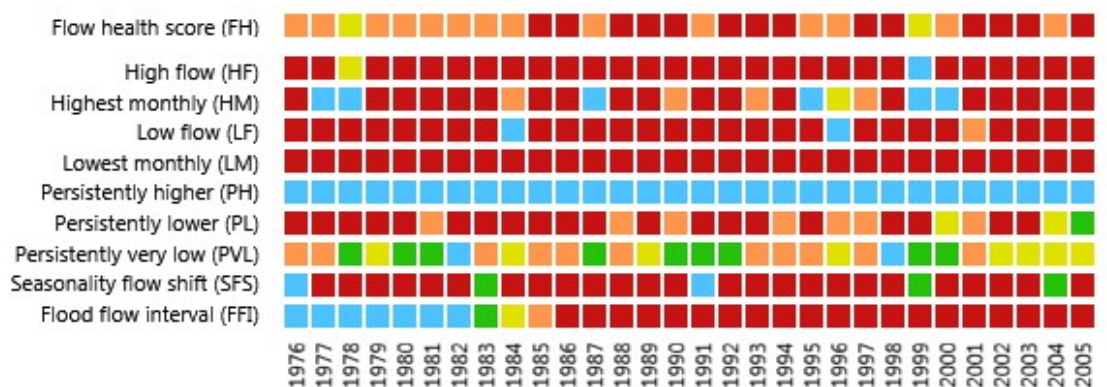26: Lower Ganga at Ganga Sagar (India)

Figure 21 presents the flow health score for all the sub basins of the Ganga basin. It can be observed that Chambal, Lower Ganga (Farakka) and Lower Ganga (Hooghly) perform the poorest on the flow health score.
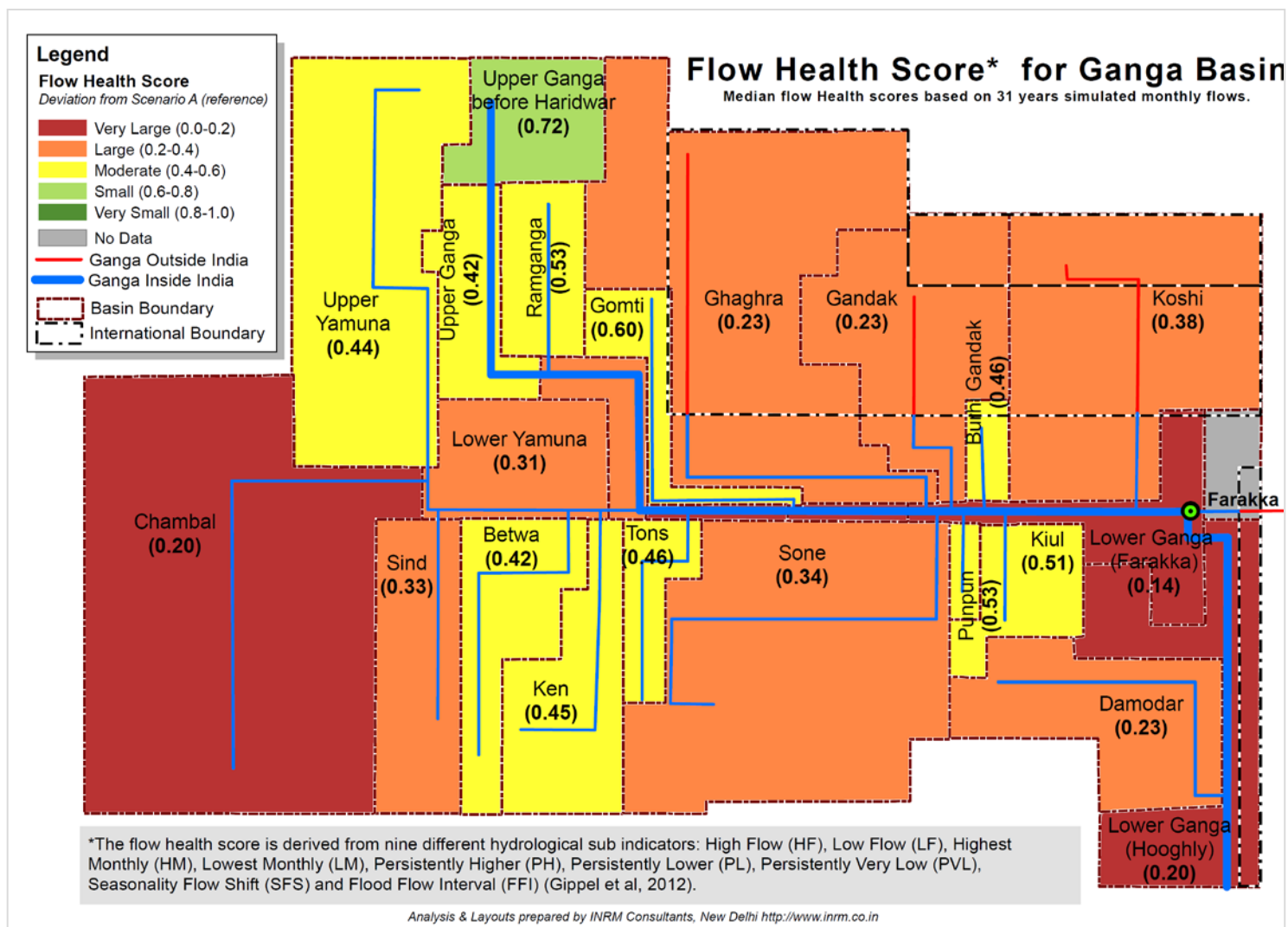
Figure 21: Flow Health Score - Major sub basins Level