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Participatory Modelling of Surface and Groundwater to Support Strategic Planning in the Ganga Basin in India

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Abstract: The Ganga Basin in India experiences problems related to water availability, water quality and ecological degradation because of over-abstraction of surface and groundwater, the presence of various hydraulic infrastructure, discharge of untreated sewage water, and other point and non-point source pollution. The basin is experiencing rapid socio-economic development that will increase both the demand for water and pollution load. Climate change adds to the uncertainty and future variability of water availability. To support strategic planning for the Ganga Basin by the Indian Ministry of Water Resources, River Development and Ganga Rejuvenation and the governments of the concerned Indian states, a river basin model was developed that integrates hydrology, geohydrology, water resources management, water quality and ecology. The model was developed with the involvement of key basin stakeholders across central and state governments. No previous models of the Ganga Basin integrate all these aspects, and this is the first time that a participatory approach was applied for the development of a Ganga Basin model. The model was applied to assess the impact of future socio-economic and climate change scenarios and management strategies. The results suggest that the impact of socio-economic development will far exceed the impacts of climate change. To balance the use of surface and groundwater to support sustained economic growth and an ecologically healthy river, it is necessary to combine investments in wastewater treatment and reservoir capacity with interventions that reduce water demand, especially for irrigation, and that increase dry season river flow. An important option for further investigation is the greater use of alluvial aquifers for temporary water storage.

Keywords: integrated water resources management; river basin planning; Ganga River; India; participatory modelling; conjunctive water use; hydrologic modelling

1. Introduction

The Ganga River Basin (Figure 1) in India stretches over 860,000 km^2 [1] and is home to more than 485 million people (2011 census data [2]). The population is concentrated on the plains that support extensive irrigated agriculture. The plains are of very low slope, falling from 250 m above mean sea level in the west, to approximately 25 m near Farakka at the border with Bangladesh—a distance of over 1500 km. North of the plains the Ganga and its tributaries flow from the Himalaya at elevations over 6000 m. Covered by snow and glaciers, the Himalaya significantly influence the flow regime in the northern tributaries. The mountains and hills to the south are much lower, with an average elevation of around 1000 m. Water availability increases in the plains from west to east. The Himalayan tributaries of the Ganga (the Yamuna, Ghagra, Gandak and Kosi) supply the majority of the water to the plains. Conjunctive irrigation using surface and groundwater in the western part of the plains has led to local decreases in groundwater tables, while in some canal and eastern areas waterlogging is a major problem. In the basin, precipitation increases further to the east, as does mainstem flow as tributaries join. Pre-monsoon water shortage is common in dry years, especially in the western plains.

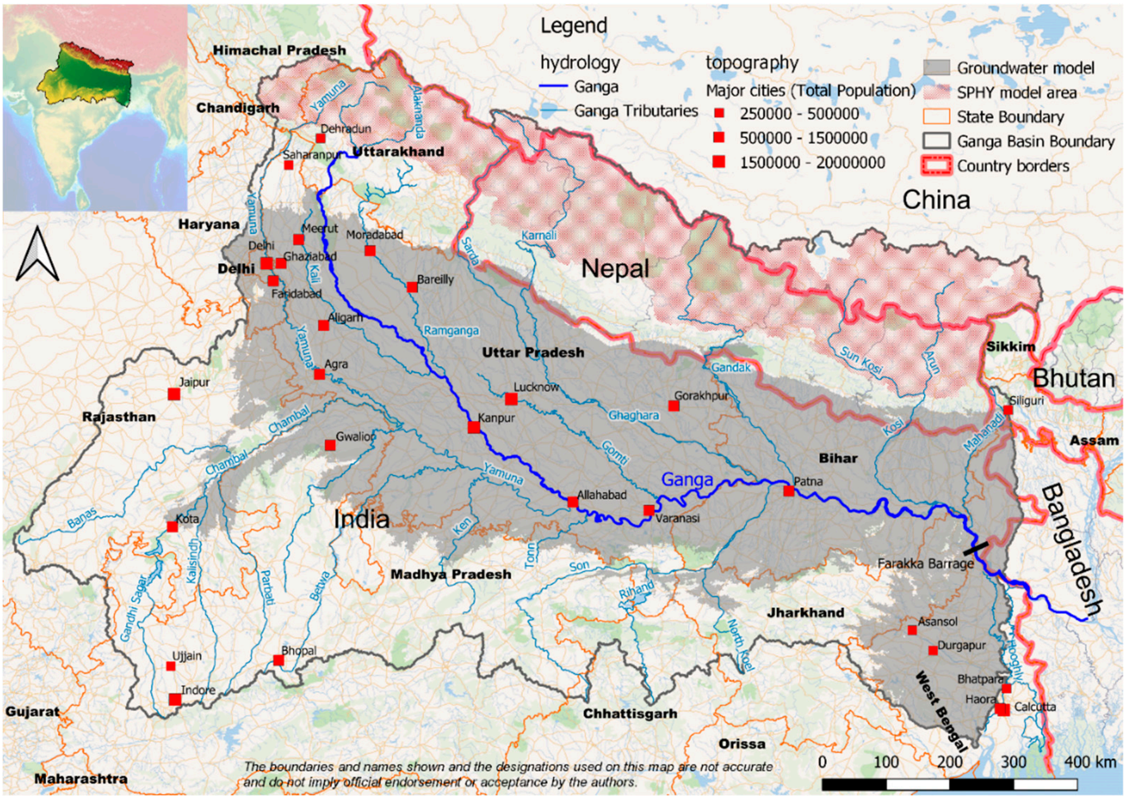

Figure 1. Ganga river basin map. Background based on Wikimedia unlabeled layer.

Water is diverted from rivers through canals and pumped from groundwater. A large fraction of irrigation water is not used for plant transpiration and returns as aquifer recharge or drainage to canals and rivers. There are direct exchanges between the rivers and groundwater. Depending on river and groundwater level, the flow is either from groundwater to river (gaining river) or from rivers/canals to groundwater (losing river). Water quality and riverine ecology depend strongly on the flows resulting from the interaction between geo-hydrology and water resources management.

The ecological health of the Ganga River and some of its tributaries has deteriorated significantly due to high pollution loads from point and non-point sources; river modifications with infrastructure (dams and barrages); flow regime changes caused by high levels of water abstraction, mostly for irrigation, but also for municipal and industrial uses; and hydropower generation [3]. The Government of India has committed to an ambitious goal of rejuvenating the Ganga and has assigned significant funds to address the problem [4]. Since India is a federated country, and responsibility for water resources management is assigned to the states by the Constitution cooperation with and between the national government and those of the 11 Indian states is required for effective basin management.

The Ganga River Basin Model was developed by a collaborative team of national and international scientists with funding from the South Asia Water Initiative (a multi-donor trust fund managed by the World Bank) to support strategic river basin planning. It assesses the impacts of different socio-economic and climate change scenarios combined with different strategies for new infrastructure, management and operation. The objective of applying a participatory approach to model development was to both improve the quality of the model and to increase the commitment and ownership of relevant authorities and agencies. The process of model construction and the assessment of the first scenarios and strategies led by international scientists are intended as the start of a continuous process of model application and improvement led by Indian authorities and agencies. A set of reports provides a description of the set-up and calibration of the Ganga River Basin Model [5], a description of the participatory modelling process [6], and presentation and discussion of the scenario modelling results, environmental flow analysis, and surface-groundwater analysis [7].

2. Materials and Methods

2.1. Participatory Modelling

The technical complexity and scale of the Ganga Basin makes its rejuvenation a problem in which there is a need both for enhanced system understanding and for balancing of a diversity of stakeholder values and perspectives. A participatory modelling approach [8] was applied to facilitate a robust technical analysis to increase existing knowledge on the Ganges River system. Direct interaction with stakeholders facilitated the input of important local knowledge, open discussion of results, interventions, scenarios and strategies. This is the first time a participatory modelling approach has been applied for the Ganga Basin in India.

Participatory modeling refers in this case to the integration of four distinct approaches that can be applied to support strategic basin planning: (i) water resources planning, e.g., the assessment of the impact of different planning alternatives; (ii) the use of scientific knowledge by means of computer-based models to assess impacts; (iii) stakeholder participation in the definition of objectives, indicators, models, interventions, scenarios and strategies; and (iv) collaboration, in the sense of negotiation between stakeholders to reach a decision on the desired plan (Figure 2) [8].

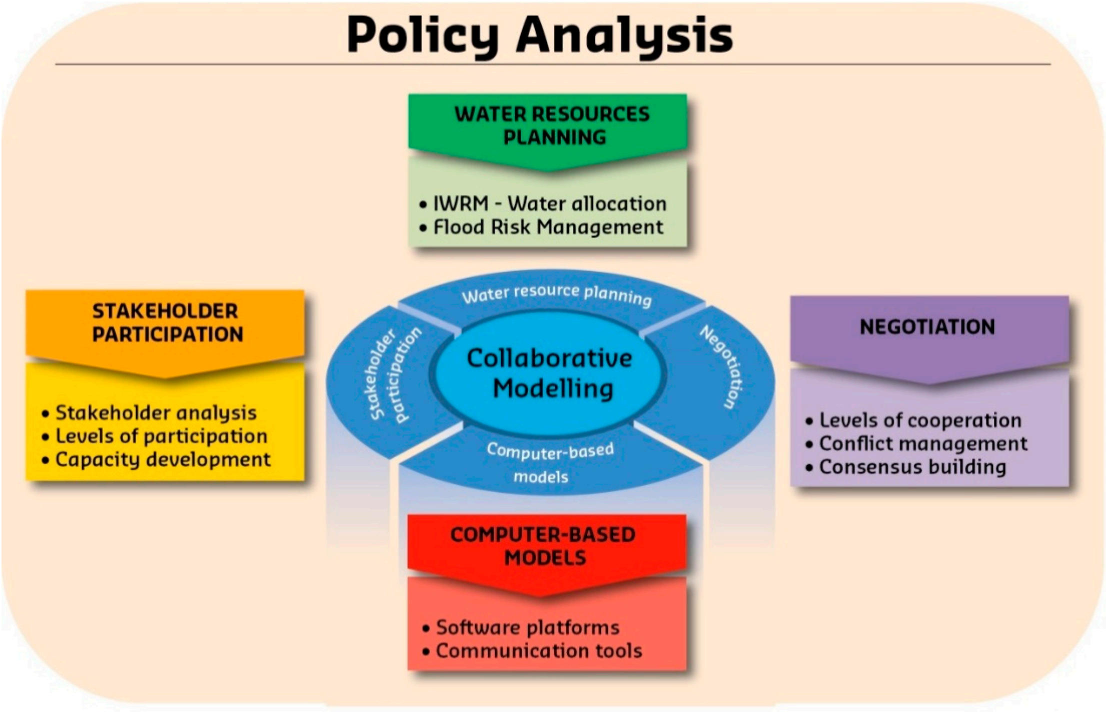

Figure 2. Collaborative modeling for policy analysis.

For system and model definition we adapted and applied a Group Model Building (GMB) approach, a participatory technique to explore constructively and synthesize the multitude of stakeholder perceptions of the interactions in the river system [9,10]. GMB was used particularly for problem and indicator identification and scenario definition, and its results informed the development and application of the computational framework. Further stakeholder engagement was carried out for model validation and strategy development in working groups and workshop settings, where a combination of plenary and focus group discussion techniques were applied.

To effectively involve the range of key technical partners and other stakeholders (both hereafter collectively referred to as 'stakeholders') in the entire Ganga Basin in India, we distinguished different geographical levels (basin and state), and different involvement levels (circles of influence).

2.1.1. Determining Stakeholder Involvement: 'Circles of Influence'

We used a circles of influence approach [11] to structure the participatory planning process for the Strategic Basin Planning in the Ganges River Basin. This approach has been successfully applied in many programs and projects worldwide.

The circles of influence approach engages different stakeholders in various formats and levels of intensity. The generic Circles of Influence framework includes four circles: Circle A—Model Developers, Circle B—Model Users and Validators, Circle C—Interested Parties, and Circle D—Decision Makers (Figure 3). In this project, Circle A stakeholders comprised governmental agencies, such as CWC (Central Water Commission) and CGWB (Central Ground Water Board), and knowledge institutes, such as NIH (National Institute of Hydrology). They were responsible for co-developing the model together with the international technical team. They were trained in hydrologic and river system modelling and were involved in training and capacity building of stakeholders in other circles. Several working groups were organized with Circle B stakeholders—the model validators and users. Circle C stakeholders were consulted at several moments throughout the planning process through multiple consultation meetings conducted in each of the riparian states. Decision makers (Circle D) were also periodically informed and consulted. Stakeholder identification and analysis was conducted during project inception to map stakeholders to their respective circles of influence [11].

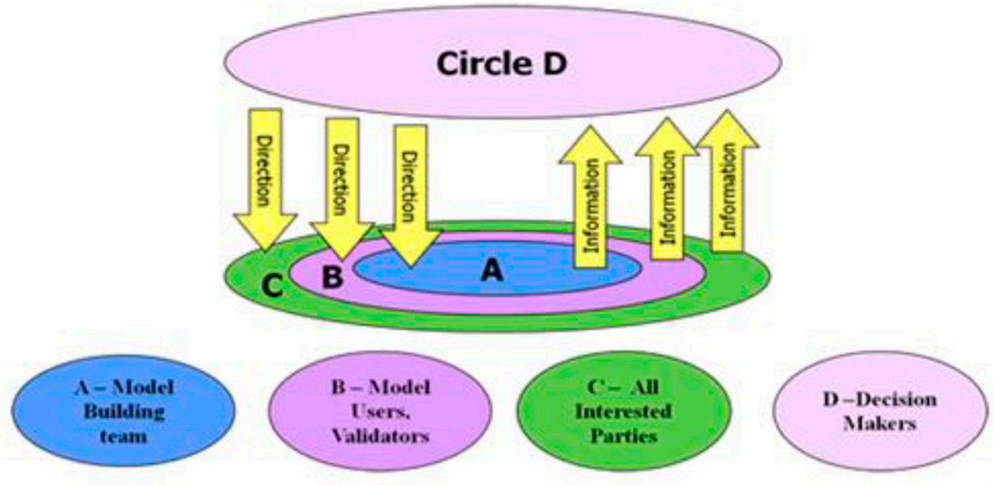

Figure 3. The "circles of influence" process framework [11].

2.1.2. Implementation of the Participation Process

The different stakeholder groups were each engaged in different ways at different stages of the development of the decision-support system (Table 1). The dashboard mentioned in the table is a visualization tool developed to analyze and compare model results (see Section 2.2.6 for details).

Table 1. Summary of steps in stakeholder engagement (A = Model Developers; B = Model Users; C = Interested Parties; D = Decision Makers).

Phase/Step		Stakeholder Groups	Activity
Conceptualization Phase			
1	Definition of methods, models and integration	A, B	Several meetings at Delhi and Roorkee
		A, B, D	29 January 2016, first basin-wide Workshop
2	Data Collection and Analysis	A, B	Small working group meetings per topic
Collaborative Modelling Phase			
3	Identification of indicators	D and partly C	February–May 2016, first series of meetings in all eleven states
		B, D	Questionnaires from stakeholder organizations in the eleven states
4	Model set-up (indicators, schematization, assumptions)	A, B, D	July 2016, second basin-level workshop
		A, B, C, D	July–November 2016, second series of workshops in all eleven states
5	Model calibration	A, B	Small working group meetings by topic
6	Draft version dashboard	A, B	
Scenario Building Phase			
7	Scenario definition	A	Small working group meetings by task
8	Selection of indicators	A	
9	Model application current situation	A	
10	Model application scenarios and strategies	A	
11	Strategy development (packages of measures, dashboard)	A, B, C, D	March 2017, third basin-level workshop
12	Final version dashboard	A, B, C, D	March–June 2017, third series of workshops in all eleven states
Consolidation Phase			
13	Training and dissemination	A, B	Small working group meetings by task
14	Presentation of realistic scenarios and strategies		January 2018, fourth basin-level workshop

In the basin-wide workshops, representatives from national organizations as well as from the eleven States participated. In the different state workshops, participation was limited mostly to representatives from organizations from the hosting state. The first basin-wide workshop (January 2016) and the first series of state meetings in all eleven Ganga Basin States (February–May 2016) were used to introduce project assignments to state-level stakeholders and seek stakeholder responses on the project assignment and circulate stakeholder questionnaires to assess concerns and ideas on water management in the Ganga Basin. The second basin-wide workshop (July 2016) and the second series of state meetings (July–November 2016) were used to validate and further elaborate the findings from the questionnaires for input into the technical modeling process. On average, 25 participants from 10–15 organizations participated in each of the state workshops.

The results of the second series of consultations was used to improve the Ganga River Basin Model and the dashboard developed to present its results. The third basin-wide workshop (March

2017) and the third series of state meetings (March–June 2017) focused on the validation of the model results for the present situation and for the development of scenarios and strategies.

2.2. Computational Framework

A model to support strategic planning should include all essential components of the system and their interactions in order to be able to assess the impact of scenarios and strategies. However, the amount of detail that can be included in the model is limited. The value of the model is in its schematic representation of reality. Previous modelling exercises for the Ganga Basin include:

1. Water systems modelling for Ganga Basin by INRM Consultants Pvt. Ltd. [12], which applied the SWAT model;
2. Ganges river basin modelling by Institute of Water Modelling [13], which applied the MIKE BASIN model; and
3. Surface and groundwater modelling of the Ganga River Basin by IIT (Indian Institutes of Technology) [14], which applied SWAT and MODFLOW.

All three reports mention issues regarding lack of data for model input as well as calibration, and all three show calibration results with varying degrees of acceptability, as well as results from limited scenario analysis. Ref. [12,13] are limited to surface water hydrology. Ref. [14] combines modeling of surface and groundwater, but the interaction between the two systems is not modelled dynamically. Only [12] includes water quality modeling, but no calibration is included. None of these modelling exercises includes impacts on ecology and the results. The recommendations of these studies have had little impact on management and planning for the Ganga Basin [15]. Model input and output generated as part of these three studies have not been made available publicly and can therefore not be used as a starting point for new modeling.

The Ganga River Basin Model presented in this paper has a very wide scope allowing for an integrated assessment of impacts related to hydrology, geohydrology, water resources management, water quality and ecology. This is the first time that all these aspects have been integrated into one modelling approach. The level of detail included is limited to keep the model manageable and the complexity understandable.

The model components and their interactions (Figure 4) are described in the remainder of this Section, focusing on the input data and the interaction between the model components with references provided for detailed descriptions of the individual components.

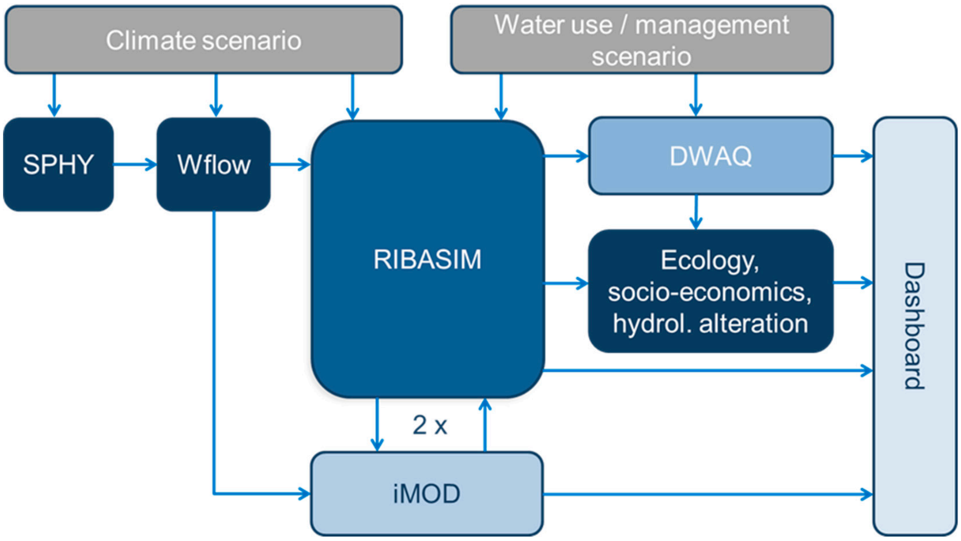

Figure 4. Schematic representation of the workflow of the different model components of the Ganga River Basin Model.

The hydrological models cover the entire Ganga Basin upstream of Farakka Barrage including those parts of the upstream basin located in Nepal and China. This permits robust assessment of the upstream flows. On request of the state of West Bengal, the part of the catchment west of the Hooghly branch below Farakka was also been included in the model area. The remainder of the analysis focuses on the Indian part of the basin upstream of Farakka Barrage.

2.2.1. Hydrological Models

The description of basin hydrology uses the SPHY [16,17] and Wflow [18] models. These are fully distributed models implemented on a 1 km by 1 km grid. SPHY describes the hydrological process in the mountainous areas of the Himalaya and was selected as it is specifically designed for glacier and snow hydrology and it has previously been successfully applied to the Himalaya [19]. Rainfall-runoff for the non-mountainous part of the Ganga Basin were simulated with Wflow—a general-purpose hydrological model. River discharges from SPHY provide inputs to Wflow. Both models use the following static input data:

- A digital elevation model (DEM) derived from the HydroSheds SRTM DEM [20]
- A shapefile of the main rivers derived from Open Street Map [21]
- Land use/land cover map for the Indian part of the model area from the Indian Institutes of Technology (IIT), based on data from the National Remote Sensing Centre (NRSC) [22]) and the GlobCover map [23] for the parts in Nepal and China
- A soil map based on FAO's Soil Map of the World [24] and a soil map with quantitative soil properties for the topsoil and subsoil [25]

SPHY also uses a map of glacier outlines and distinction between debris-covered and debris-free glacier surfaces from [26].

Both models use the following distributed meteorological data:

- Precipitation inside India for the period 1959–2012 from the Indian Meteorological Department (IMD) [27] and for the years 2013 and 2014 data from the WFDEI data set [28]. Outside India the EUWATCH dataset [29] were used for the period 1959–1978 and WFDEI for 1979–2014.
- For temperature and potential evapotranspiration, the IMD data could not be used due to an issue with the interpolation in the Himalayas [30]. Therefore, the global data sets from EUWATCH, for 1959–1978, and WFDEI, for 1979–2014, were used for the entire model domain.

The concepts used by SPHY and Wflow to simulate river flow are described in [16,17] and [18] respectively. They produce gridded, daily flows across the entire model domain, which are input to the water resources model (see Section 2.2.2), and gridded, daily infiltration rates, which are input to the groundwater model (see Section 2.2.4).

2.2.2. Water Resources Model

RIBASIM [31,32] simulates the use and distribution of water using river discharges from Wflow as input. It uses a schematization of links and nodes (Figure 5) to describe the flow of water in the rivers, storage in reservoirs, diversions into canals, and consumptive use and return flows across the basin. Water can be used from precipitation, rivers, canals, or from groundwater. Conjunctive use of surface and groundwater is included. Return flows can be divided between rivers, canals and groundwater. This is important for the Ganga plains, where extensive leakage from irrigation canals recharges groundwater aquifers. RIBASIM was linked to the groundwater model by simulation of extraction and infiltration rates and by the flux between the river and the groundwater, as simulated by the groundwater model.

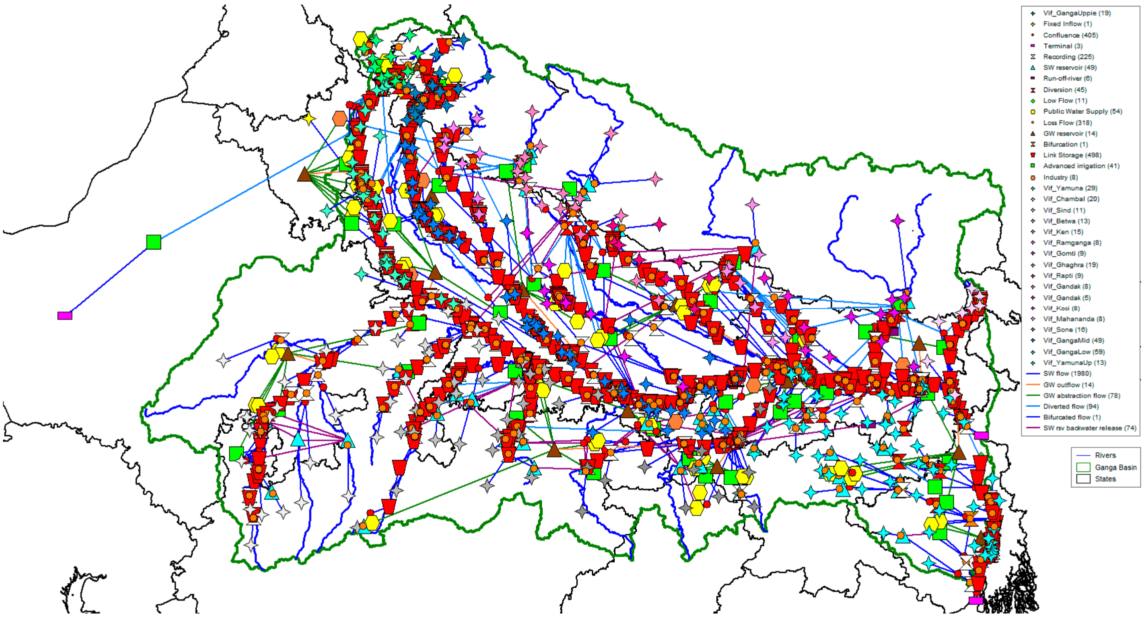

Figure 5. Schematization of the Ganga River Basin in RIBASIM.

Data for water infrastructure such as barrages, dams and canals were mainly been derived from the Ganga Basin Report [33] and the India-WRIS (Water Resources Information System [34]). The schematization was adapted with input from the first round of state and basin-wide workshops, including on the location of existing and planned reservoirs and canals, the compartmentalization of irrigated areas in command areas, and the main abstractions of surface and groundwater.

Information on irrigated crop areas was derived from the Land Use Statistics Information System of the Ministry of Agriculture and Farmers Welfare [35]. Data for 246 districts was aggregated to data for 41 irrigation nodes. The cropping calendar, describing when which crop is planted, was derived from information provided by the Crop Science Division of the Indian Council of Agricultural Research [36]. Estimates for irrigation efficiencies and return flow fractions from [37] and monthly average reference evapotranspiration data per state from [38] were used. Monthly crop transpiration coefficients for most crops are India specific values from [39], but for maize and rapeseed coefficients from [40] were used. For sugarcane, tobacco and fodder crops no information specific for India could be found, and values from FAO [41] were used.

District-level population data from the 2011 census data [2] were used to assess domestic water demands and extrapolated to 2015 based on projections for 2001 to 2026 [42] and on urbanization rates for the period 2001–2011. District data were aggregated to correspond with the 55 public water supply nodes for domestic demand. Data on water sources, leakage and return flow for major cities from [43] and data on industrial water demand from [44] were also used.

The water demand of public water supply and irrigation nodes can be fulfilled by water from surface and groundwater resources to simulate conjunctive use. The capacity of the surface water supply for irrigation is determined by the canal capacity, mostly obtained from India-WRIS, and for public water supply from [43]. The capacity of groundwater supply for both has been tuned to yield results that are comparable to the estimates presented in [45].

During periods of water shortage, RIBASIM allocates water based on priorities. The following ranking of priorities was used in the Ganga Basin Model:

1. Drinking water supply;
2. Industrial water supply;
3. Irrigation water supply;
4. Low flow requirements for spiritual use, bathing and environmental flows.

The concepts used by RIBASIM to simulate water demand and allocation, and the operation of infrastructure, are described in [31,32]. RIBASIM results include monthly flows in rivers and canals, groundwater abstraction rates, and the water supplied to fulfil each water demand. The simulated groundwater abstraction rates are used as input to groundwater model. Simulated river flows are used in the groundwater model to assess the water level that determines the exchange between the river and the groundwater. In the workflow (Figure 4) the water resources model is run twice: once before the groundwater simulation with zero exchange between rivers and groundwater, and once after the completion of the groundwater simulation with the exchanges as calculated by the groundwater model. The simulated flows in the rivers are used as input to the water-quality model, the ecological assessment module, and the dashboard.

2.2.3. Water-Quality Model

Water quality is assessed using DWAQ [46,47] by combining RIBASIM discharges with pollutant load estimates. DWAQ applies the advection-diffusion equation using a numerical solution based on finite volumes derived from the RIBASIM calculation grid to obtain pollutant concentrations of, among others, BOD5 (Biological Oxygen Demand in 5 days) and coliform bacteria. For RIBASIM, links representing schematized canals without flow volumes are estimated based on length of the link and estimated maximum flow velocity in the link. Decay of BOD5 and coliforms in the Ganges and Yamuna depends on simulated residence time and kinetic rate constants adapted from [48] and adjusted by calibration against surface water quality measurements obtained by CWC and CPCB (Central Pollution Control Board) for the period 1999–2014. In DWAQ, pollutants enter surface water as net emissions representing the non-treated fraction of the total waste load generated at RIBASIM nodes. Gross emissions are the product of emission variables and specific emission factors as follows:

- number of rural and urban population multiplied by waste production per capita [44,49,50];
- industrial effluent [44] multiplied by the typical effluent concentrations for chemicals [49,51], distilleries [52], dying textile and bleaching [49,51], food, dairy and beverages [53,54], pulp and paper [55,56], sugar [57] and for tanneries and others [51,58,59]; and
- cropping pattern area (Section 2.2.2) multiplied by specific emission factors to represent irrigation losses by leaching from soil [59].

Sewage effluent and treatment is modelled separately, considering volumetric treatment capacity based predominantly on [40] and removal efficiency by contaminant from [60,61].

2.2.4. Groundwater Model

Groundwater movement is simulated by iMOD [62], the Deltares extension of the well-known MODFLOW code [63] for solving the groundwater flow equation. iMOD uses the same calculation grid as Wflow, but is applied only to the alluvial area of the basin. It was not possible to model groundwater in the hard-rock areas because of a lack of data on surface-groundwater connectivity. iMOD simulations are transient, while recharge, abstraction and surface water level data inputs are time-dependent.

iMOD describes the alluvial aquifers using geological information. Fence diagrams were available from CGWB as well as MAP files describing the thickness of geologic layers. The result is a three-layer aquifer conceptualization of variable thickness. In the mountainous areas to the south, the shallow aquifer thins; it is thickest in the central basin with a maximum depth of approximately 400 m below sea level. Aquifer parameters (permeability, storage coefficient) were provided by CGWB based on modelling studies by Indian Institutes of Technology [14]. Groundwater recharge was obtained from Wflow (grid-based) for non-irrigated areas and from RIBASIM (lumped) for irrigated areas.

Based on RIBASIM river discharge, river water levels are derived on a 1 km scale and used to calculate fluxes between the river and groundwater. This approach was applied to the Ganga and its main tributaries. For the intermediary areas the surface water system, represented by minor streams and local drainage, is modelled using the MODFLOW Drain Package [63]. This simulates head-dependent flux boundaries, such as the exchange between the groundwater and local surface water.

For each RIBASIM node, groundwater demand for irrigation, industry and public water supply is estimated. For iMOD, all demands besides irrigation are equally distributed as abstraction wells on a 1 km scale over each node area. Irrigation abstraction is spatially distributed using additional information from the irrigation map developed by the International Water Management Institute [64] that indicates irrigation areas and irrigation source. Abstraction wells are only located in cells indicated with irrigation from groundwater.

The CGWB manages a widely-distributed network of nearly 9000 groundwater monitoring locations. Data from this network was made available for calibration. A selection of 1800 locations was used to adjust the model parameters.

2.2.5. Ecological Assessment Module

The ecological assessment module translates the simulated impact of scenarios and interventions on hydrology and water quality into impacts on ecology and ecosystem services. To calculate the overall hydrological indicator, ten ecologically-relevant hydrological sub-indicators were identified to give an indication of changes in magnitude, duration, timing and frequency of both low and high discharge events compared to the pristine condition.

Ecological sub-indicators are expressed as changes in habitat suitability compared to the pristine situation for several fish species, the Ganga river dolphin, the Gharial and the Indian Flapshell turtle. Habitat suitability was calculated with response curves containing environmental thresholds for water quality and water depth.

For socio-economics, the sub-indicators are fisheries, ritual bathing and floodplain agriculture. The fisheries score depends on habitat suitability for the commercially valuable fish species; the religious bathing scope depends on water depth and BOD, coliform bacteria are less important due to the lower risk of contamination during religious bathing when compared to swimming; and the floodplain agriculture score depends on previously flooded bare areas that becomes available during the dry season.

Since the Ganga River and its tributaries differ in geomorphology, discharge and anthropogenic pressures, the system is subdivided into relatively homogeneous eco-zones. Habitat suitability of species is calculated by eco-zone with dose–effect relations for water depth, dissolved oxygen and temperature, which are extracted from the results of the other parts of the Ganga River Basin Model. Ecological scores are calculated as a percentage of agreement with the reference situation, which is the simulated pristine situation without anthropogenic pressures and with historical land use.

The ecological assessment module and its application to the analysis of different flow regimes is described in detail in [7].

2.2.6. Water Information System and Dashboard

All model inputs and all relevant outputs are stored in the database of the water information system GangaWIS (Figure 6). Delft-FEWS [65] is used to run the different model components and Delft-FEWS model connectors are used to export input data from the database to different model components and to import simulation results from the model components into the database. The database consists of a PostgreSQL/PostGIS [66] geodatabase for time series and vector data and a THREDDS server [67] to store and retrieve gridded data in NetCDF format [68].

The dissemination layer has three components. A website [69] presents static information, such as the project description and reports. The Delta Data Viewer [70] is used to present data from the database on a webpage. And the dashboard presents simulation results aggregated into eleven indicators (Table 2) supported by maps and a Ganga River long-section (profile). All indicator values are calculated based on the simulation results of the meteorological time period 1985–2014.

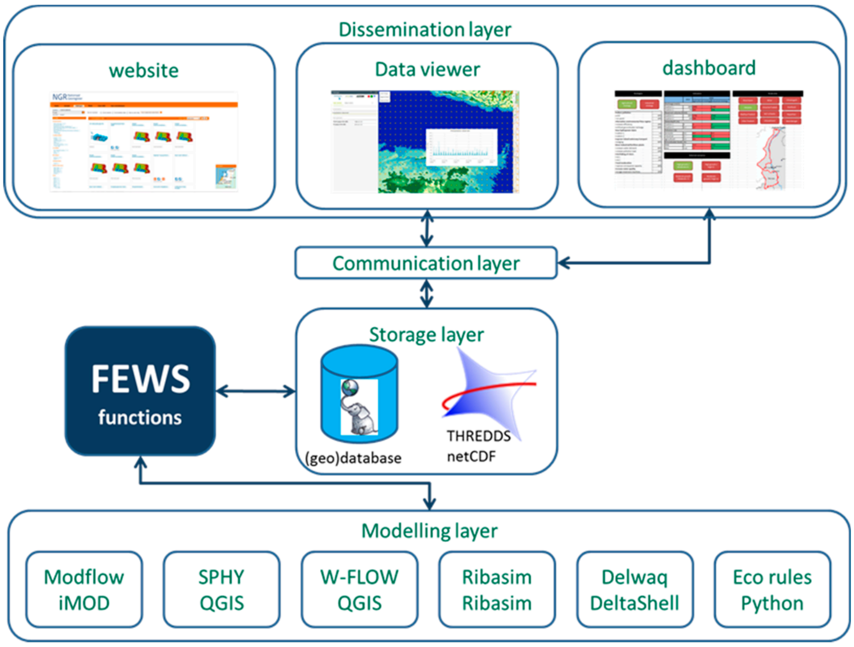

Figure 6. GangaWIS (water information system) structure.

Table 2. Description of the eleven indicators presented on the dashboard of the GangaWIS (see [5] and [7] for detailed descriptions).

Indicator	**Description**
State of groundwater development (% critical areas)	The percentage of the area where the simulated groundwater abstraction amounts to 90% or more of the simulated recharge. The basis for this information is obtained from the model irrigation nodes.
Lowest discharge at Farakka (m^3/s)	The lowest monthly simulated discharge of the Ganga River above the Farakka Barrier for the one-in-ten dry year.
Volume in reservoirs (billion m^3)	The total sum of simulated water stored in the main basin reservoirs at the end of the monsoon period, October, for the one-in-ten dry year.
Agricultural crop production (% of area harvested)	Ratio between the actual and potential harvested area at basin level for the one-in-ten lowest production year.
Deficit irrigation water (%)	The difference between simulated irrigation water supply and simulated demand as a percentage of the simulated demand for a one-in-ten dry year.
Deficit drinking water (%)	The difference between simulated drinking water supply and simulated demand as a percentage of the simulated demand for a one-in-ten dry year.
Surface water quality index	Dimensionless index based on classification as presented in [44] for the parameters total coliforms, BOD5 and dissolved oxygen.
Volume of GW (groundwater) extracted (billion m^3)	The total simulated volume of groundwater abstracted for public water supply and irrigation during the year with the one-in-ten highest abstraction.
E-flow: Ecological status (%)	Average percentage of agreement with the simulated pristine status for the habitat suitability of nine key species
E-flow: Hydrological status (%)	Average percentage of agreement with the simulated pristine status for ten hydrological discharge indicators representing magnitude, timing, duration and frequency low, average and high flows based on the Indicators of Hydrological Alteration method [71].
E-flow: Socio-Economic status (%)	Average percentage of agreement with the simulated pristine status of the indicators for the three ecosystem services religious bathing, fisheries and floodplain agriculture

Separate pages zoom to state-level and add state-specific indicators, maps and graphs. Indicators of interest were determined through the participatory modelling process. The dashboard was designed for end-users to assess the impact of scenarios and strategies by comparing results between two model runs with different inputs.

3. Results

3.1. Results of Participatory Modelling Process

3.1.1. Broad Participation

One of the results of the adopted approach was broad participation from different national-level government departments/agencies and those from the eleven Ganga states, both in the series of basin-wide workshops as well as in the different state-level workshops (Tables 3–5). Participants were particularly positive about the opportunities the approach offered counterparts in different government agencies to collaborate and share cross-sectoral information relevant to Ganga basin planning. Many reported gaining new insights into the river basin, users' needs and interests and the role modeling can play in the planning process.

Table 3. Participation of national-level and state-level organizations in basin-wide workshops.

	1st Workshop New Delhi 29 January 2016	2nd Workshop Lucknow 18 July 2016	3rd Workshop Kolkata 2 March 2017	4th Workshop New Delhi 20 February 2017	Total	Average
# participants from central agencies	51	21	24	38	134	34
# participants from state government	40	33	21	12	106	27
# of participants from other organizations	12	11	1	16	40	10

Table 4. Participation of stakeholder organizations in state-level participatory modelling workshops, July–October 2016.

State [1]	HP	UK	Har	Del	Raj	MP	UP	Jhar	Chh	Bih	WB	Total	Average
# participants per workshop/state	34	26	27	23	25	27	27	32	19	22	22	284	26
# of different departments/organizations present	11	12	8	7	8	10	12	10	8	10	9	105	10

[1] HP = Himachal Pradesh, UK = Uttarakhand, Har = Haryana, Del = Delhi, Raj = Rajasthan, MP = Madya Pradesh, UP = Uttar Pradesh, Jhar = Jharkhand, Chh = Chhattisgarh, Bih = Bihar, WB = West Bengal.

Table 5. Participation of stakeholder organizations in state-level model validation workshops, April–June 2017.

State	HP	UK	Har	Del	Raj	MP	UP	Jhar	Chh	Bih	WB	Total	Average
# participants per workshop/state	28	30	17	29	28	20	25	38	18	36	26	295	27
# of different departments/organizations present	14	17	10	10	14	10	15	8	12	11	12	133	12

3.1.2. Input to the Dashboard

The interactive workshops in 2016 provided input on the most important problems in the basin and provided data for model development. The workshops paid special attention to identifying indicators relevant for stakeholders. The dashboard is based on the indicators identified through this process. Where indicators were proposed that could not be evaluated using the modeling framework, the participatory process helped to manage expectations.

3.1.3. Use of the Ganga River Basin Model in Workshops

In the third round of workshops in April 2017 participants articulated priority interventions. Group discussions confirmed four potentially effective strategies:

- increasing irrigation efficiency
- limiting groundwater abstraction
- increasing waste water treatment, and
- increasing reservoir volume

Demonstration model runs were carried out for the strategies with updated inputs representing the different strategies.

3.1.4. Opportunities for Follow-Up

Following project conclusion, the dashboard and underlying models provide a foundation for coordinated strategic planning in the Ganga Basin. Key to success will be continued stakeholder engagement. In the future, stakeholder engagement could be expanded to include representatives from a wider range stakeholder organizations and community bodies.

3.2. Calibration and Validation of the Ganga River Basin Model

The model components for hydrology, geohydrology and water resources management have been jointly calibrated and validated, as river flows are influenced by water use and water infrastructure operations. Flows were calibrated using 1995–2009 data and validated against 1985–1994 data. Flow calibration and validation focused on the Ganga mainstream and its main tributaries. Calibration and validation data for iMOD were specified by location not time period. The entire calibration process had six steps:

1. Calibration of SPHY flows at locations in the Himalayan catchments upstream of any significant water demand or water infrastructure;
2. Calibration of Wflow flows at locations in the catchments outside the Himalayas upstream of any significant water demand or water infrastructure;
3. Calibration of iMOD groundwater levels with a fixed river water level;
4. Calibration of pumping capacities for irrigation and public water supply in RIBASIM, using estimates of 2011 annual pumping from CGWB (2014), and where data unavailable using canal capacities, assuming no supply shortages in wetter than average years;
5. Combined calibration of SPHY, Wflow and RIBASIM using measured river discharges assuming no supply shortages in wetter than average years and zero flux between rivers and the groundwater; and
6. Combined calibration of SPHY, Wflow, RIBASIM and iMOD using measured river discharges after incorporation of river-groundwater exchanges from step simulation of iMOD.

A complete description of calibration and validation results as well as sensitivity analysis results are in [5]. Figures 7 and 8 show calibration and validation for monthly flows at two locations on the Ganga River. Observed flow data are from CWC. Flow values are omitted in compliance with the Government of India Water Data Policy for classified data. Figure 7 shows results for Rishikesh, where the Ganga descends from the Himalayas onto the plains. Simulations generally agree well with the measurements but underestimate peak monsoon flows. These peak flows are less important from a water supply perspective, as during the monsoon demands (including to fill storage) are far lower than supply. Figure 8 shows results for Varanasi, the most downstream location on the Ganga for which data were available. Again, simulations match measurements well, but with an overestimation of dry season flows.

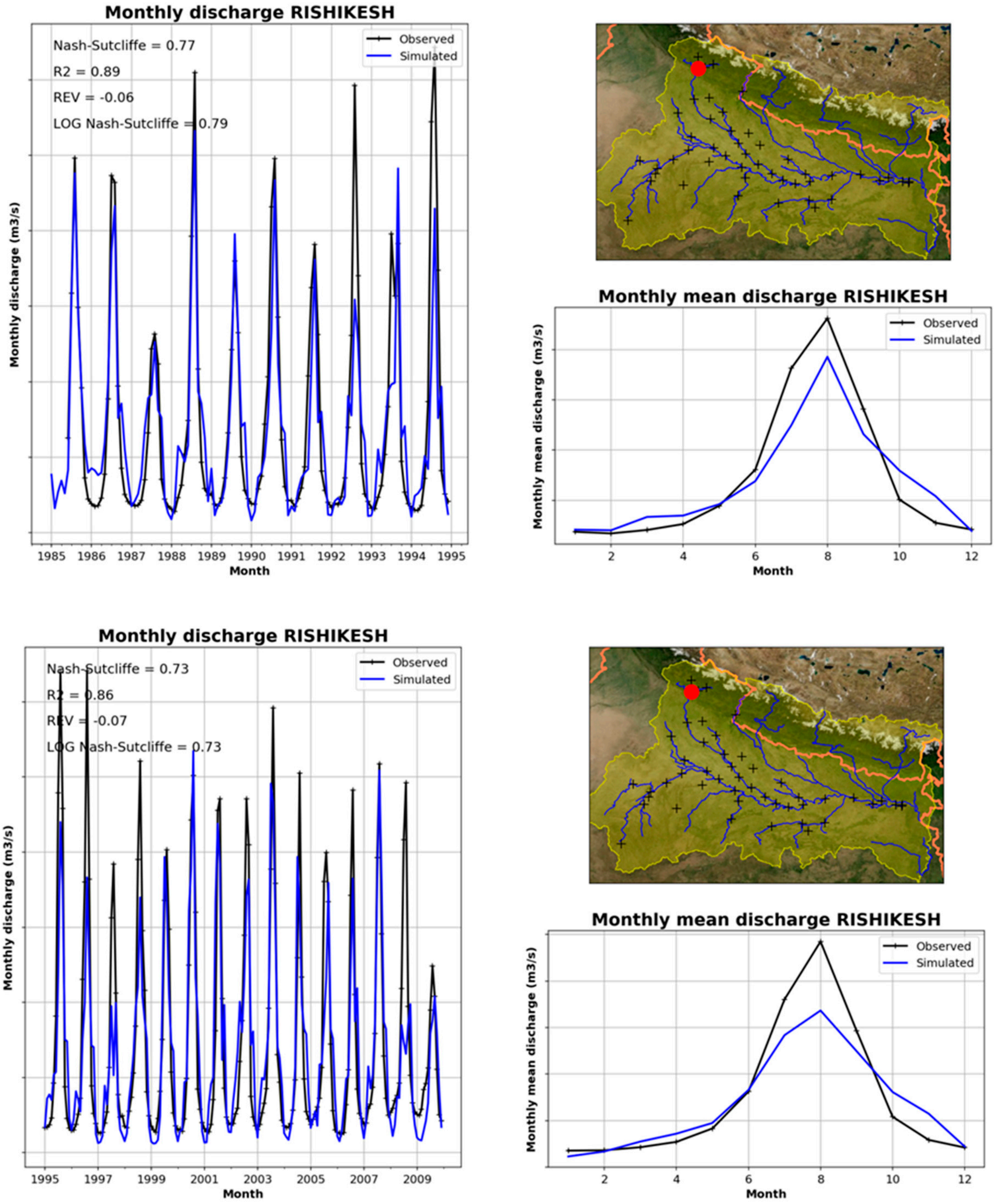

Figure 7. Validation (1985–1994, **top**) and calibration (1995–2009, **bottom**) results for the Ganga River at Rishikesh; monthly discharges (**left**), mean monthly discharges (**right bottom**) and location of the station (red dot on map **right top**).

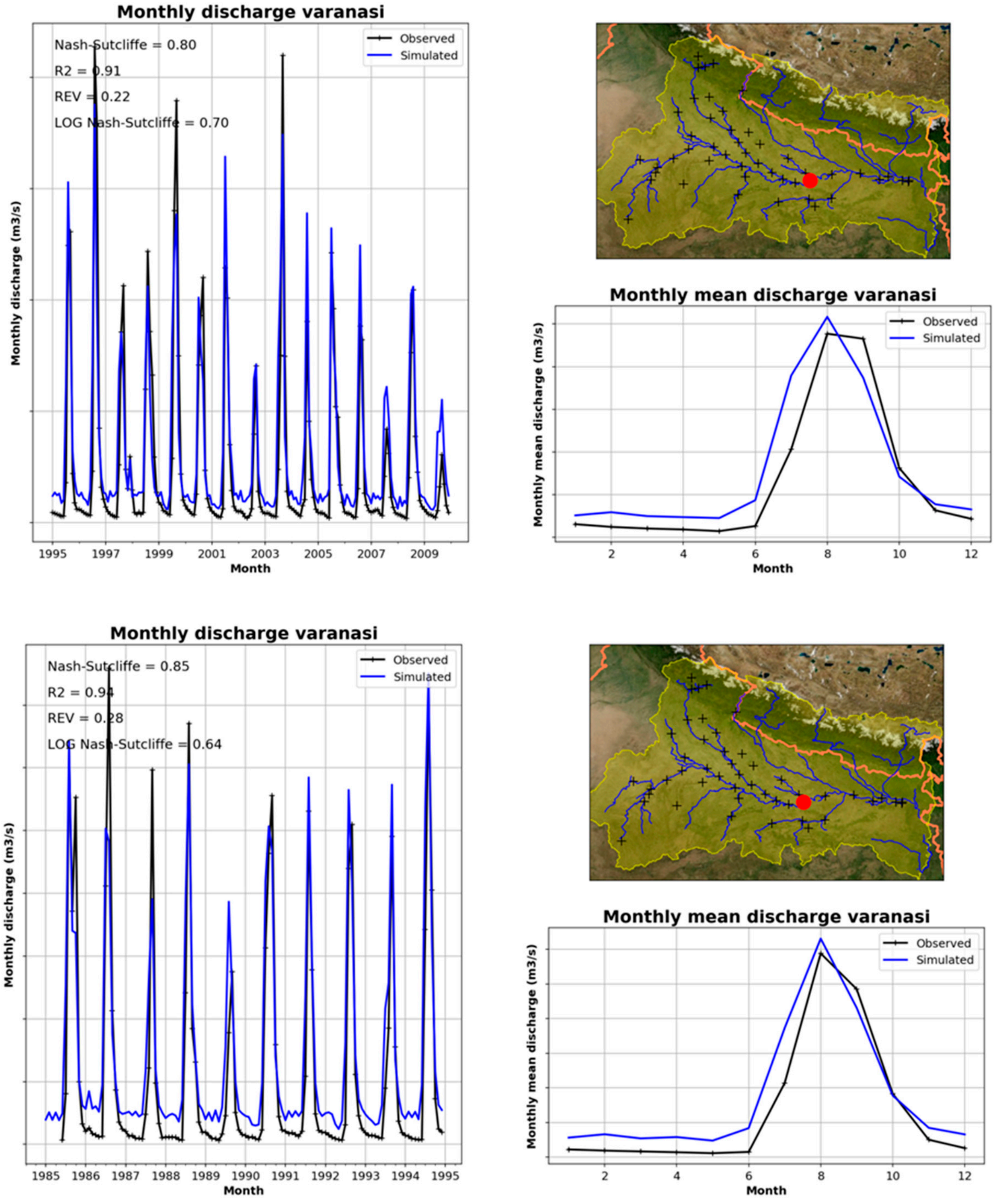

Figure 8. Validation (1985–1994, **top**) and calibration (1995–2009, **bottom**) results for the Ganga River at Varanasi; monthly discharges (**left**), mean monthly discharges (**right bottom**) and location of the station (red dot on map **right top**).

It is difficult to compare the results of model calibration and validation with those of previous studies, since model results of previous studies are only available in the form of reports and since different data were made available to prior studies. Limited availability of measured discharge data within India for the studies reported in [12,13] made these studies focus on stations in Nepal. Ref. [13] reports results for the station Hardinge Bridge in Bangladesh for the period 1998 to 2006. These results show Nash–Sutcliffe efficiency (NSE) coefficients of 0.85 to 0.89, which is comparable to the values presented here for Varanasi (Figure 8), the most downstream station for which data were available in this study. Ref. [14] presents NSE and volume bias for simulation results for 1990 to 2004 for a number of stations within India. For Rishikesh an NSE of 0.60 and a volume bias of +30% is reported, which compares unfavorably with the results presented here where NSE of 0.73 to 0.77 and a bias of −6% to −7% were achieved (Figure 7). There are two more stations both on the Ganga River for which both this study and [14] reports results: Ankinghat and Kanpur. Both studies show comparable values for the NSE, but the volume bias reported in [14] is +30%, while our results vary between −18% to −32%.

Overall, the calibration and validation of this study benefited from better data availability than previous studies. As far as results can be compared, the hydrological results of the Ganga River Basin Model appear to be comparable to the results of previous studies and sometimes represent a slight improvement.

3.3. Assessment of the Impact of Scenarios and Strategies

Herein, the term scenario describes developments that impact water resources, but that are outside the direct influence of water managers (e.g., population growth or climate change); and the term strategy describes a combination of interventions designed to address current or future management issues. The effectiveness of strategies can be assessed for different scenarios.

Except for the present scenario, all scenarios are based on assumptions or projections and are, therefore, uncertain. The ‘pristine’ scenario describes the basin without water resource development. Other scenarios describe possible futures for around the year 2040. All include increases in domestic, industrial, and agricultural water demand. Three climate change futures are considered: no climate change, climate described by the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 4.5 scenario and climate described by the IPCC RCP8.5 scenario.

Based on stakeholder inputs, strategies were developed that could be implemented in combination or separately:

- **Business as Usual (BAU):** No changes in water resources management.
- **Approved Infrastructure (Appr.Inf)**: Implementation of infrastructure projects approved as of early 2018.
- **Inter-Basin Transfer Links (IBTL+)**: Implementation of the main proposed inter-basin transfers relating to the Ganga Basin.
- **NMCG Planned Treatment (Pl.tr)**: Implementation of the additional treatment plants planned by National Mission for Clean Ganga (NMCG).
- **Improved Treatment (Imp.tr)**: All planned wastewater treatment plants implemented and fully operational, and rural wastewater impact reduced by additional treatment.
- **Increased Irrigation Efficiency (Eff):** Surface water irrigation efficiency increased from 40% to 48% and groundwater irrigation efficiency increased from 70% to 74%.
- **Conjunctive Use (Conj.use)**: Groundwater abstraction reduced by 50% at over-extracted nodes. (Six nodes are over-abstracted in the present scenario and 12 nodes in the 2040 scenarios).
- **E-Flow (e-flow)**: Minimum flow forced to 40% of pristine flow for each month, whenever possible.

Most strategies can be scaled to increase their impact. Figure 9 shows basin-wide indicator values for the modelled scenarios. Impacts are most visible in the hydrological indicators: areas with critical groundwater use increase significantly, and the lowest dry-year river discharge diminishes significantly. The e-flow indicators differ significantly from the pristine condition, however, there are only small differences in e-flow indicators between future scenarios. Scenario assessments (without management interventions) indicate a significant decrease in future water availability, water quality and ecological status. Changes are mainly caused by socio-economic factors, not climate change.

Table 6. Basin wide indicator scores for eight strategies under the IPCC 2040_RCP4.5 scenario.

Indicator	Code	BAU	Appr. Inf	Conj.use	IBTL+	Eff	Pl.tr	Imp.tr	e-flow
State of Groundwater development (% critical areas)	GW over-abstraction	88	88	79	83	88	88	88	95
Lowest discharge at Farakka (m^3/s)	Low Q	1502	1458	1622	1258	1483	1502	1502	1528
Volume in reservoirs (billion m^3)	Res. Store	52	55	53	41	53	52	52	20
Agricultural crop production (% of area harvested)	Agr. Harv.	87	89	74	92	89	87	87	84
Deficit irrigation water (%)	IRR deficit	31	31	47	30	29	31	31	39
Deficit drinking water (%)	DR deficit	34	34	35	35	34	34	34	39
Surface water quality index (-)	WQ index	4	4	4	4	5	4	4	5
Volume of GW extracted (Billion m^3)	GW used	217	215	176	206	207	217	217	235
E-flow: Ecological status (%)	E-ecol	65	65	66	63	66	65	66	73
E-flow: Hydrological status (%)	E-hydr	47	46	49	44	47	47	47	56
E-flow: Socio-Economic status (%)	E-socio	66	66	67	68	66	67	69	75

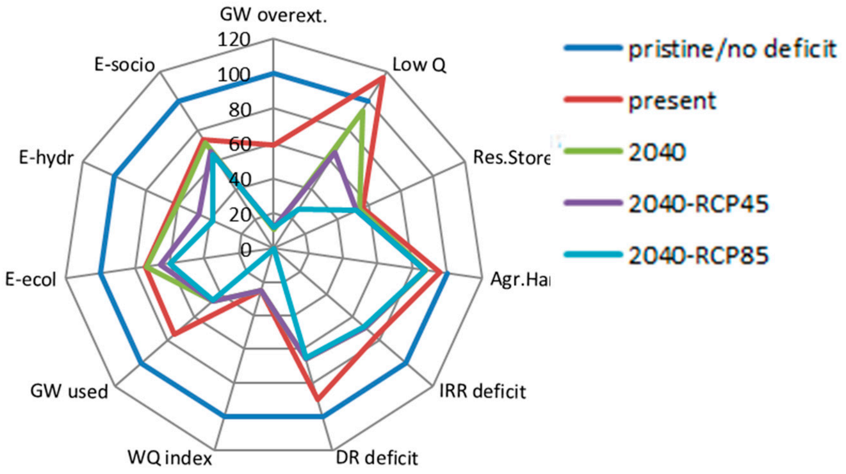

Figure 9. Basin-wide indicators for five scenarios. Values are scaled from 0 to 100, with the pristine scenario as 100). Indicator codes are explained in Table 6 and described in Table 2.

Given the significant potential degradation by 2040, it is informative to evaluate the effectiveness of strategies proposed by stakeholders. Table 6 and Figure 10 show indicator scores for individual strategies under the IPCC 2040_RCP4.5 scenario. If multiple strategies were combined, a greater response would be expected. Details of the assessment are available in [7].

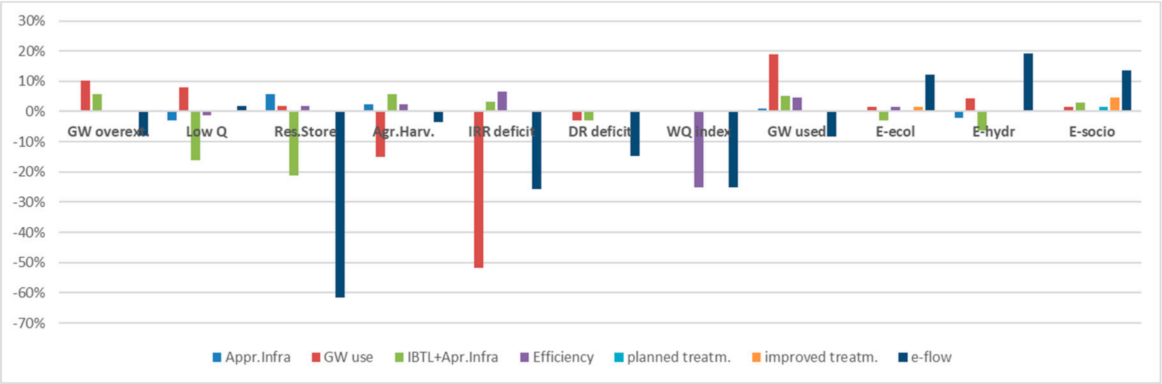

Figure 10. Percent change in basin-wide indicator values for intervention strategies. Values relative to the business as usual scenario. Increases indicate improvement and reduction indicate deterioration.

4. Discussion

The scenario assessments indicate significant degradation from the pristine condition. During part of the year a large fraction of the flow is diverted to canals, sometimes reducing flow in the river to almost zero. Groundwater levels have changed significantly. Flows in the shallow aquifers in the Ganga plains now entirely reflect anthropogenic influences. Water quality has been severely degraded by liquid and solid waste discharges into the river and its tributaries. It is the first time that these findings can be based on comparison of model results for the actual situation with a pristine scenario.

Model results suggest significant additional degradation in water availability, water quality and ecological status will occur in coming decades in the absence of strong management intervention. A new finding from the scenario analysis is that degradation will be mainly caused by socio-economic factors, not climate change. The projected significant increases in water demand by 2040 will mainly affect groundwater, because most available surface river water is already used. Scenario results show that drinking water and irrigation water deficits will increase, and water quality will further deteriorate. Despite considerable data uncertainty, climate change is expected to affect water demand more than water availability.

Results of the analysis show that there is no single simple intervention to address the multiple pressures on the Ganga. A combination of interventions is required. However, the suite of currently considered interventions, which would require huge investment and face significant technical challenges and stakeholder opposition, will not adequately address the future challenges of water availability, water quality and ecology. Indeed, they will not even address the current severe pressures on the river system. This is an important new finding of this study.

The intervention with the greatest potential benefits is further improvement of municipal wastewater treatment. Whether centralized or decentralized, high- or low-technology, greater reduction in pollution improves downstream water quality, improves ecosystem services, and reduces water-related illnesses and deaths. The next most important intervention is an increase in water-use efficiency, especially in irrigated agriculture. Increased efficiency will not immediately increase water availability; however, irrigation deficits may be reduced. This means greater agricultural production for the same level of irrigation withdrawals.

Model results show that water availability in the basin will be insufficient to meet projected future demands and that there are no easy technical solutions. Many interventions that are beneficial for one sector or outcome show negative effects for others.

The results of the scenario analysis show that ambitious strategies are needed to reduce demands across all sectors and that trade-offs need to be made between sectors. The agricultural sector will need to adapt to lower water availability in terms of crop choices, planting seasons and irrigation efficiency. Farmers will need to develop flexible approaches, choosing irrigated or non-irrigated crops depending on monsoon rainfall. This will affect agricultural production and sector employment.

Without coordination and careful balancing of interests, expensive interventions may fail, wasting scarce financial resources. The absence of a functioning water-resources management governance structure in the basin aggravates the challenges the basin is facing. Although not as a result of the presented study, the authors recommend from global experience that a basin management organization with a legal mandate to work across state boundaries is needed to plan the strategy and implement it.

The consequences of the conclusions presented above are far-reaching and will involve many departments and ministries beyond just water resources. Non-technical interventions, including incentives to change cropping patterns and to reduce water use, are required. Fundamentally, the focus will need to shift from more "crop per drop" to more "jobs per drop". Service and industrial sectors consume far less water per employment generated, supporting greater growth.

The participatory approach to prepare and apply an integrated river basin model as presented in this paper has potential to support improved strategic planning for the Ganga Basin as shown by the results for the scenario and strategies presented. A similar approach can also have added value to support strategic planning for other large river basins in South Asia and the rest of the world. The components of the integrated model should then be modified to reflect the river basin, the issues and the possible interventions.

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