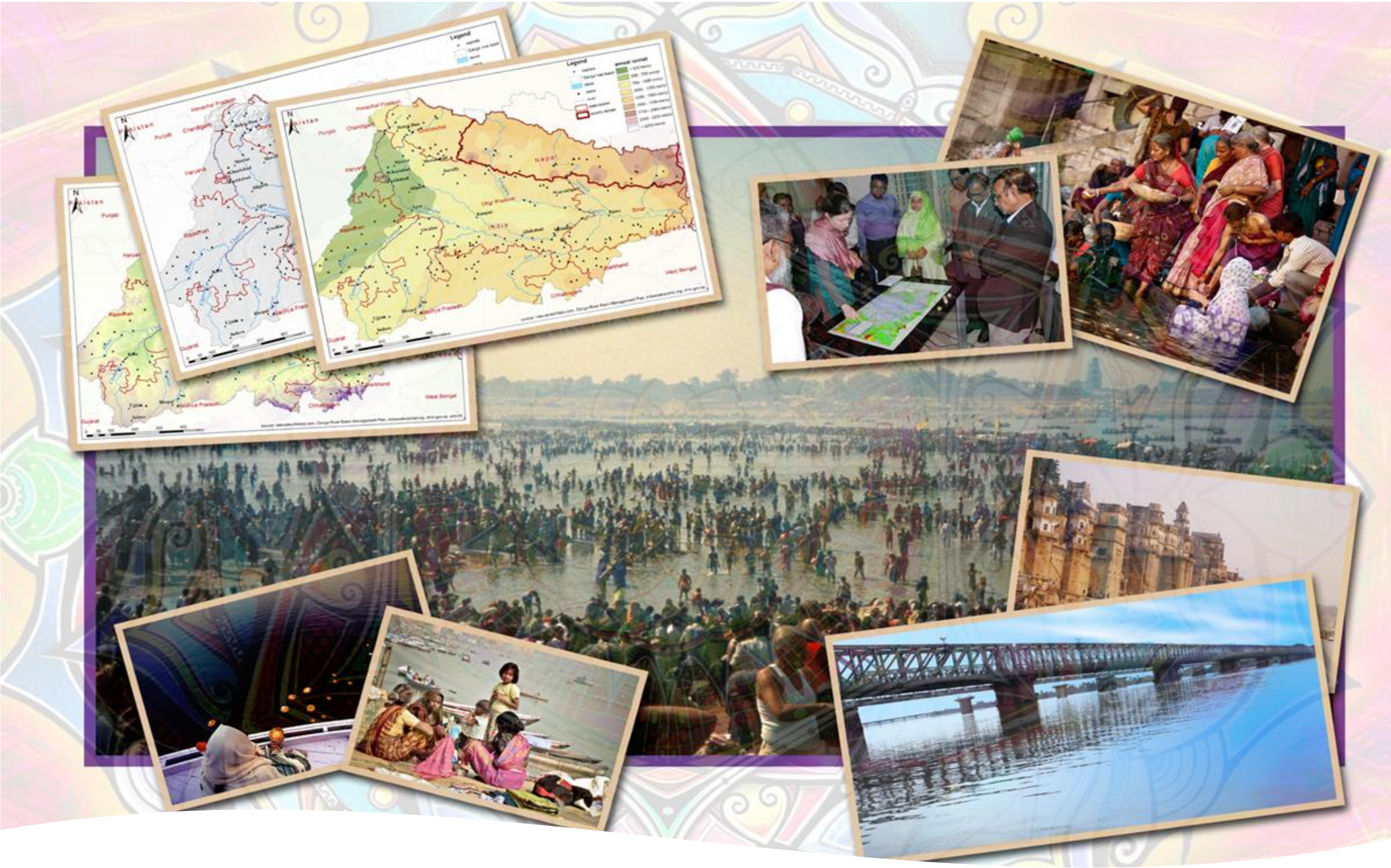
Strategic Basin Planning for Ganga River Basin in India



Ganga River Basin Model and WIS Report and Documentation

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Summary
This document describes the Ganga river basin model and the Ganga water information system, GangaWIS. The river basin model includes components for hydrology, geohydrology, water management and allocation, water quality and ecology. The GangaWIS is an information system that stores model input and output and presents the results of different model runs. The system's objective is to assess the impact of future developments by comparing model results representing different what-if scenarios. Policy makers can base their decisions on quantitative information of the impact of water allocation and investment options.

For each of the model components, the report describes the concepts, set-up, input data, link with other models, calibration and validation results and policy indicators derived from the model results.

The appendices present the documentation of the model and information system. Beginning with a description of the installation procedure, a detailed examination of the origin of the input data and the location in the system where these data are stored is outlined for each component. A number of use cases are presented as tutorials that provide step-by-step guidance to execute the most common tasks with the system, such as preparing, running and assessing the impact of a new scenario. The use cases are also available in digital form as a visual click-by-click guide. Finally, the documentation contains some exercises for self-training in the use of the system.

Reference
Vat, M. van der (Ed.), 2018. Ganga River Basin Model and Information System, Report and Documentation. Main volume and Appendices. Deltares with AECOM and FutureWater for the World Bank and the Government of India, Report 1220123-002-ZWS-0002.

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Contents

Abbreviations and Acronyms

AIR	Advanced Irrigation
ArcGIS	Geographic Information System developed by ESRI
ASCII	American Standard Code for Information Interchange
BIN	Binary
BOD	Biological Oxygen Demand
CCCR	Centre for Climate Change Research
CDM	Common Data Model
CGWB	Central Ground Water Board
CI	Chloride Ion
CIFRI	Central Inland Fisheries Research Institute
COD	Chemical Oxygen Demand
CPCB	Central Pollution Control Board
CRS	Coordinate Reference System
CSW	Catalogue Service for the Web
CWC	Central Water Commission
DAP	Data Access Protocol
DBF	Data Base File
DDFDG	Degree Day Factor for Debris-covered Glaciers
DDFG	Degree Day Factor for non-debris-covered Glaciers
DDFS	Degree Day Factor for Snow
DDV	Delta Data Viewer developed by Deltares
Delft-FEWS	Flood Early Warning System software developed by Deltares
DEM	Digital Elevation Model
DHS	Delft Hydraulic Software
DLL	Dynamic-Link Library
DSS	Decision Support System
DTM	Digital Terrain Model
DWAQ	Delft Water Quality Module developed by Deltares
E FLOW	Environmental flow
EC	Electrical Conductivity
ENVISAT	Environmental Satellite operated by ESA
EPSG	European Petroleum Survey Group
ERD	Entity Relation Diagram
ESM	Earth System Model
ESRI	Environmental Systems Research Institute is an international supplier of geographic information system (GIS) software
EUWATCH	European Union Integrated Project Water and Global Change
FAO	Food and Agricultural Organization
FEWS	Flood Early Warning System
GangaWIS	Ganga Water information system

GDAL	Geospatial Data Abstraction Library
GIS	Geographical Information System
GLIMS	Global Land Ice Measurements from Space
GLOBCOVER	Project of ESA which is now evolving to an international collaboration
GMT	Greenwich Mean Time
GST	Goods and Services Tax
GTiff	Geo Tagged Image File Format
GUI	Graphical User Interface
GW	Groundwater
HDF	Hierarchical Data Format
HTML	Hypertext Markup Language
IASME	International Association of Mechanical Engineers
IBRD	International Bank for Reconstruction and Development
ICAR	Indian Council of Agricultural Research
IHA	Indicators for Hydrological Alteration
IIASA	International Institute for Applied Systems Analysis
IIT	Indian Institute of Technology
IITM	Indian Institute of Tropical Meteorology
IMD	India Meteorological Department
iMOD	a Graphical User Interface + an accelerated Deltares-version of MODFLOW
IND	Industrial
IndiaWRIS	India Water Resource Information System
IPH	Irrigation and Public Health Department
ISPRS	International Society for Photogrammetry and Remote Sensing
ISRIC	International Soil Reference and Information Centre
ISRO	Indian Space Resources Organization
ISSCAS	Institute of Soil Science, Chinese Academy of Sciences
IWRM	Integrated Water Resources Management
JRC	Joint Research Center of the EU
LCC	Lambert Conformal Conic map projection
LOG	Logarithm
LOGNSE	NSE with logarithmic values
MERIS	MEdium Resolution Imaging Spectrometer
MLD	Million Liter per Day
MODFLOW	USGS's modular hydrologic model
MOU	Memorandum of Understanding
MoWR,RD&GR	Ministry of Water Resources, River Development and Ganga Rejuvenation
MS	Microsoft
MW	Mega Watt
NB	Nota Bene
NetCDF	Network Common Data Form
NIH	National Institute of Hydrology

NMCG	National Mission for Clean Ganga
NRSC	National Remote Sensing Center
NSE	Nash-Sutcliffe Efficiency
OGC	Open Geospatial Consortium
OOXDEN	Optimal oxygen concentration for denitrification
OOXNIT	Optimal oxygen concentration for nitrification
OPeNDAP	Open-source Project for a Network Data Access Protocol
OXY	Oxygen
PC	Personal Computer
PHP	Hypertext Preprocessor.
PNG	Portable Network Graphics
PostGIS	An open source software program that adds support for geographic objects to the PostgreSQL object-relational database
PostgreSQL	An open source object-relational database system developed by the PostgreSQL Global Development Group
PWS	Web Processing Service or Public Water Supply
PyWPS	Web Processing Service written in Python
QGIS.	Quantum Geographic Information System
RAM	Random Access Memory
RDBMS	Relational Database Management System
REV	Relative Error in Volume
RIBASIM	River Basin Simulation Model developed by Deltares
SAGA	System for Automated Geoscientific Analyses
SEQ	Sequence
SLD	Styled Layer Descriptors
SPHY	Spatial Processes in Hydrology, a distributed hydrological model developed by FutureWater
SQL	Structured Query Language.
SRID	Spatial Reference ID
SRS	Spatial Reference System
SRTM	Shuttle Radar Topography Mission
SRTM DEM	Digital Elevation Model based on SRTM
STP	Sewage Treatment Plant
SVN	Apache Subversion
SW	Surface Water
TDS	Total Dissolved Solids
TDS	THREDDS Data Server
THREDDS	Thematic Real-time Environmental Distributed Data Services
TSS	Time Series
UI	User Interface
UNESCO-IHE	IHE Delft Institute for Water Education
URI	Uniform Resource Identifier
USA	United States of America
USB	Universal Serial Bus

WAQ	Water Quality
WATCH	Integrated Project Water and Global Change
WCS	Web Coverage Service
WFDEI	WATCH Forcing ERA-Interim
Wflow	a distributed hydrological model platform developed by Deltares
WFS	Web Feature Service
WGS	World Geodetic System
WIS	Water Information System
WLM	Waste Load Model
WMS	Web Map Services
WPS	Web Processing Service
WQ	Water Quality
WRIS	Water Resources Information System
XML	Extensible Markup Language

Executive Summary

The Ganga basin is the most populated river basin in the world and is home to half the population of India including two-thirds of the nation's poor people. The basin provides over one-third of the available surface water in India and contributes to more than half the national water use of which 90 percent is diverted to irrigation.

The ecological health of the Ganga river and some if its tributaries have deteriorated significantly as a result of high pollution loads; high levels of water abstraction for irrigation as well as for municipal and industrial uses; and flow regime and river modifications caused by water resources infrastructure. The Government of India has committed itself to an ambitious goal of rejuvenating the Ganga and has assigned significant funds to address the problem.

The World Bank has assigned Deltares and its partners AECOM India and FutureWater to carry out the project "*Analytical Work and Technical Assistance to support Strategic Basin Planning for Ganga River Basin in India*" in cooperation with the Government of India. The objectives of the project are 1) to strengthen the capacity with respect to strategic basin planning, 2) to develop a set of scenarios for the development of the Ganga basin, 3) to build a strong and accessible knowledge base and 4) to establish a multi-stakeholder engagement process to support strategic basin planning.

The preparation of a river basin model and a water information system for the Ganga basin, jointly called GangaWIS, is an important project component. The aim of the Ganga river basin model is to support strategic basin planning by assessing the impact of different scenarios. The water information system serves to store and disseminate all relevant information for planning, i.e. maps, measurements and input and output of the river basin model.

A model to support strategic planning should try to include all essential components of the system and their interactions in order to be able to assess the impact of scenarios. However, the amount of detail that can be included in a model is limited. The strength of the model is in its schematic representation of reality. The Ganga river basin model has a wide scope that allows an integrated assessment of impacts related to hydrology, geohydrology, water resources management, water quality and ecology. Although the level of detail is limited to keep the model manageable and the complexity understandable, the model contains sufficient detail for meaningful assessment of strategies and scenarios. The model area covers the Ganga river basin within India. Upstream parts of the basin in Nepal and China have been included to calculate flows to the Indian part of the basin.

Figure 0.1 presents the workflow of the different model components. The report *Ganga River Basin Model and Information System* describes the set-up, calibration and validation of the different model components. The Appendices to the report provide a detailed description of input data used and results produced, as well as documentation of the different model components and the information system in the form of manuals, tutorials and answers to frequently asked questions. The Ganga river basin model will be applied to the impact analysis of scenarios, the assessment of environmental flows and the surface-groundwater interaction. These applications are described in separate reports. All model components are open source, or free, within India.

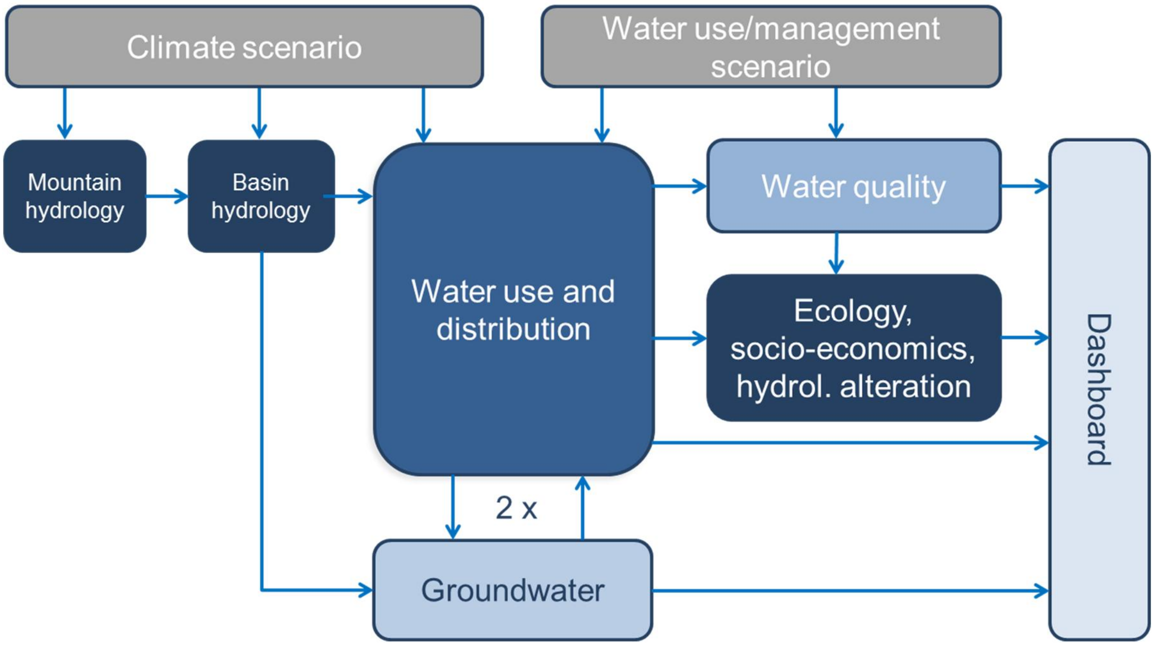

Figure 0.1: Schematic representation of the workflow of the different model components that together form the Ganga river basin model

The model can simulate the present situation with respect to water resources, infrastructure and water demand. This can best be thought of as representing the year 2015. To account for the hydrometeorological variation, longer time series for meteorological input were required. The longest time series for which sufficiently reliable data could be constructed from a combination of different sources is from 1959 to 2014. Model simulations have been limited to the period 1985–2014 in order to let the simulations be representative for the current climate and to avoid the possible impact of historic climate change.

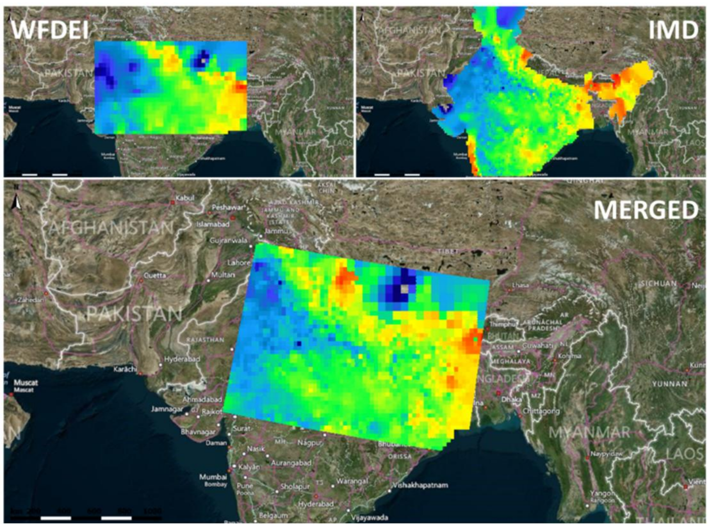

Figure 0.2: Combination of the precipitation data from IMD for India with the WFDEI data set for parts of the model area outside India as executed within the Ganga WIS to create input for the hydrological models

The simulation of the hydrology has been divided over two different models: SPHY and Wflow. These are both fully distributed models working on a grid of square cells. SPHY is used to describe the hydrological process in the mountainous areas in the Himalaya.

This model has been selected because it is specifically designed for glacier and snow hydrology and has previously been successfully applied to the Himalayas. The rainfall-runoff processes for the non-mountainous part of the Ganga basin are simulated with the Wflow model. This is a general purpose hydrological model. The river discharges calculated by the SPHY model for the Himalayas are used as upstream boundaries for the Wflow model. Figure 0.2 presents the procedure used to derive the precipitation input by combining data from the Indian Meteorological Department (IMD) for India with the public available WFDEI global data set for parts of the model area outside India.

The water resources model RIBASIM simulates the use and distribution of water. It uses the river discharges calculated by Wflow as input. The RIBASIM schematization consists of links and nodes to describe the flow of water in the rivers, the storage in reservoirs, the diversion into canals and the use and return flow by different functions. Water can be used from precipitation, rivers, canals, or from groundwater. Conjunctive use of surface and groundwater is also possible. Furthermore, return flows can be divided over rivers, canals and groundwater. This is an important aspect for modelling the water system in the plains of the Ganga basin, where extensive leakage from irrigation canals feeds the groundwater aquifers. Therefore, the RIBASIM model is also linked to the groundwater model by the simulation of extraction and infiltration rates and by the use of the flux between the river and the groundwater as simulated by the groundwater model. Figure 0.3 shows the RIBASIM schematization of the Ganga basin.

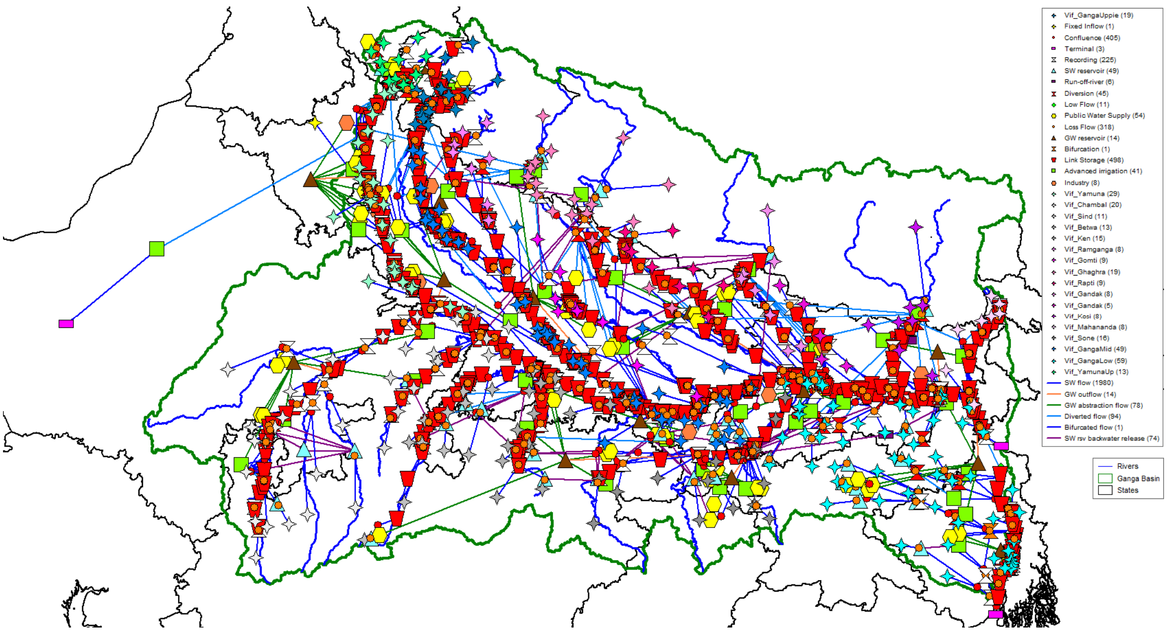

Figure 0.3: Schematization of the Ganga river basin in RIBASIM

The hydrological models have been calibrated and validated jointly with RIBASIM, since most of the river flows are influenced by water use and the operation of water infrastructure. The calibration period is 1995–2009 and the validation period is 1985–1994. Calibration and validation focused on the Ganga river and its main tributaries. Figure 0.4 shows the results of the calibration and validation for the Ganga river near Varanasi. The results show that simulated and measured flows are quite similar, with some model overestimation of the peak monsoon discharge. However, for a water resources study the very good fit of low flows is more important. Results for other parts of the Ganga river and the downstream parts of the main tributaries are comparable.

Simulation results can differ significantly from the measurements for smaller tributaries and locations further upstream in the basin due to the fact that it is not possible to include sufficient detailed information for this scale level in a strategic basin model.

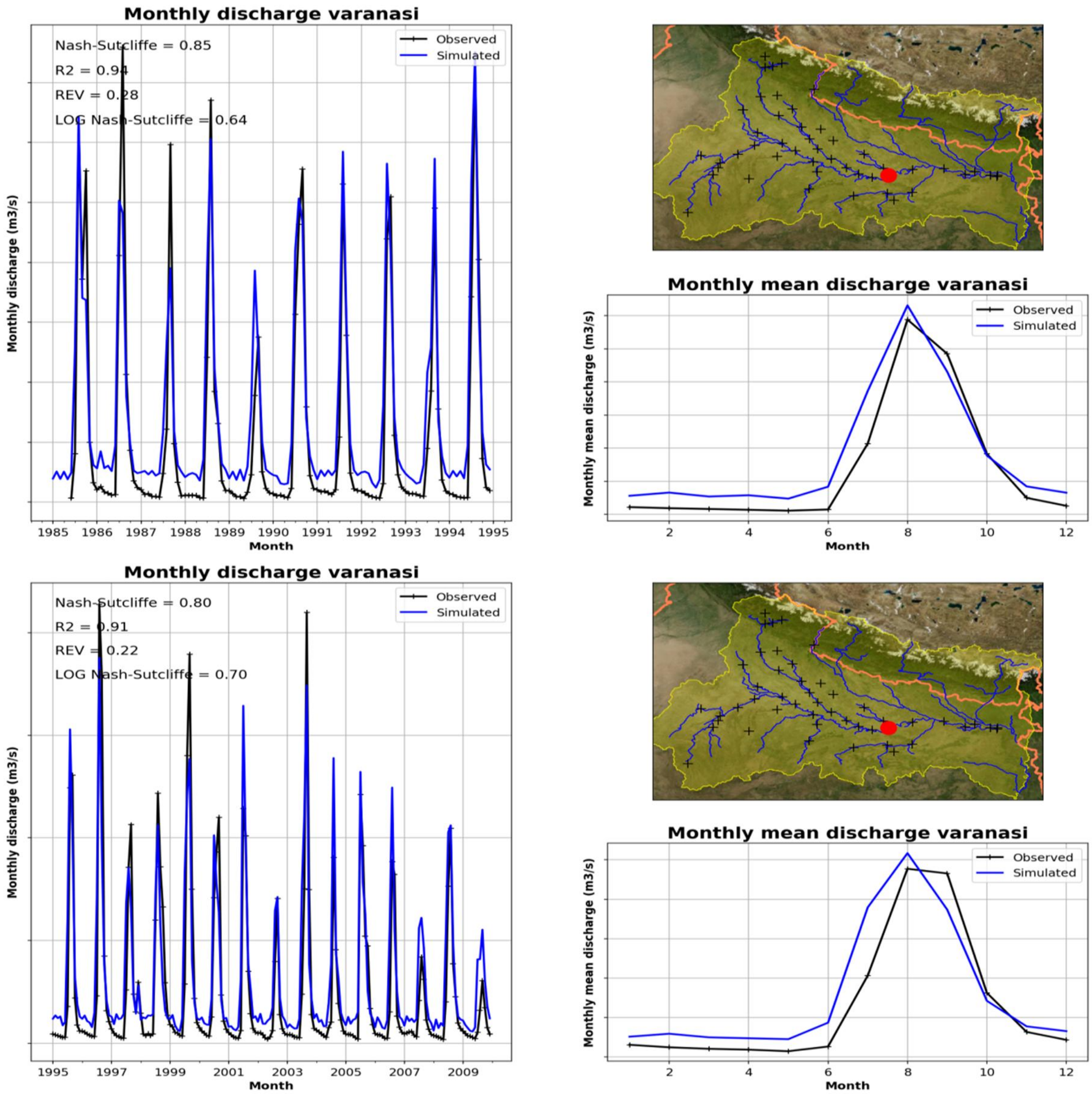

Figure 0.4: Validation (1985–1994, top) and calibration (1995–2009, bottom) results for the Ganga river at Varanasi with the monthly discharges (left), mean monthly discharges (right bottom) and location of the station (red dot on map right top)

Groundwater movement is simulated by the iMOD-MODFLOW model. The model uses the same calculation grid as the Wflow model. It is only applied to the alluvial part of the basin, since it is not possible to model groundwater in the hard rock areas due to a lack of data on connectivity between different systems and because the contribution of groundwater in the hard rock areas is relatively minor. The recharge to the groundwater is obtained from Wflow, for the non-irrigated areas, and RIBASIM, for the irrigated areas. RIBASIM also provides the data on water abstractions and river discharge. Based on river discharge, river water levels are derived and used for the calculation of the flux between the river and the groundwater.

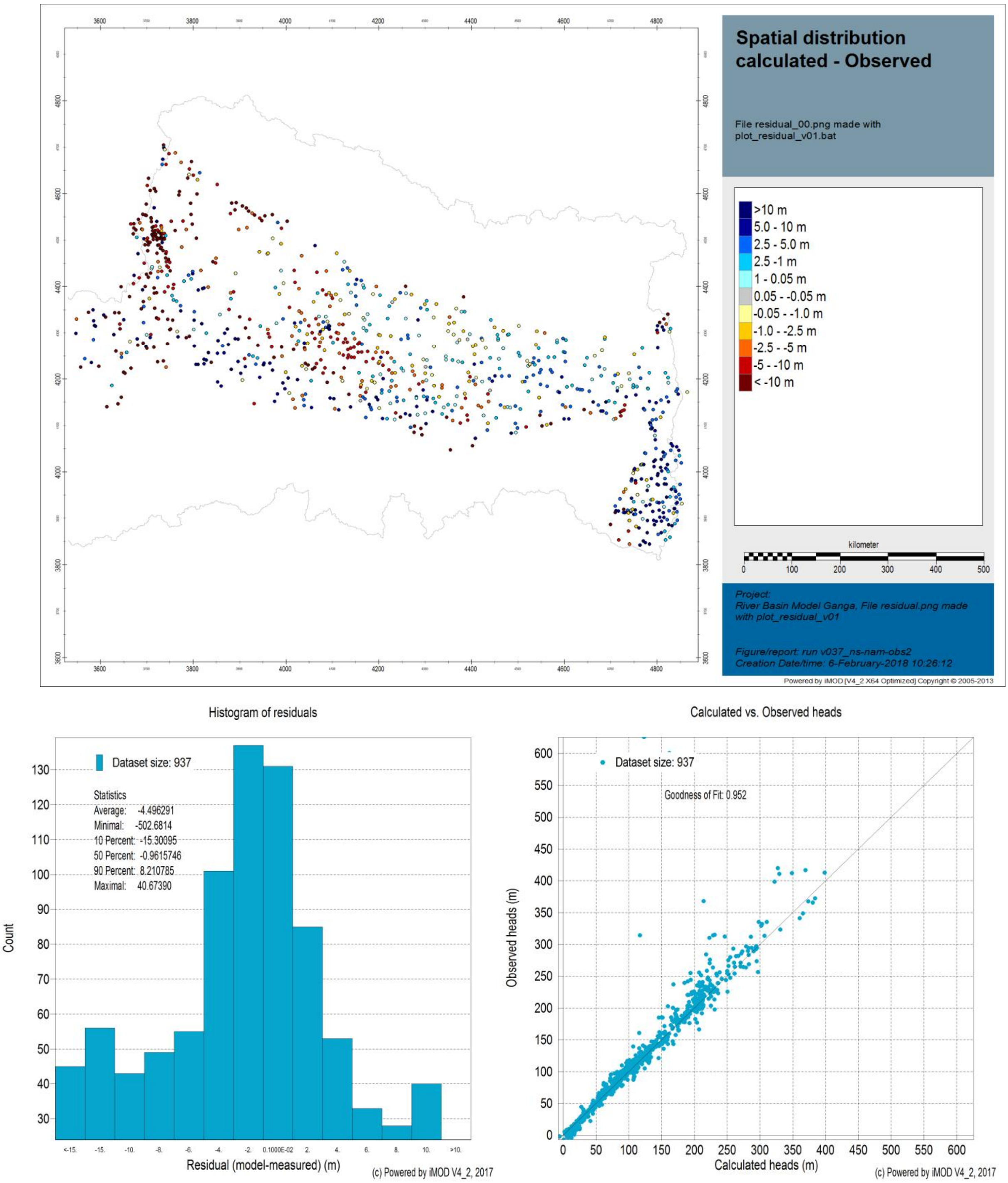

Figure 0.5: Spatial distribution, histogram and scatterplot of differences between calculated and measured heads (transient) in iMOD model calibration.

Water quality is assessed with the model DWAQ, combining RIBASIM's discharges with pollutant load estimates. Pollution loads are simulated based on domestic, industrial, and agricultural factors and subsequently reduced depending on available waste water treatment facilities. The model then simulates the river water quality based on the transport, dilution and diffusion of pollutants as well as bio-chemical processes.

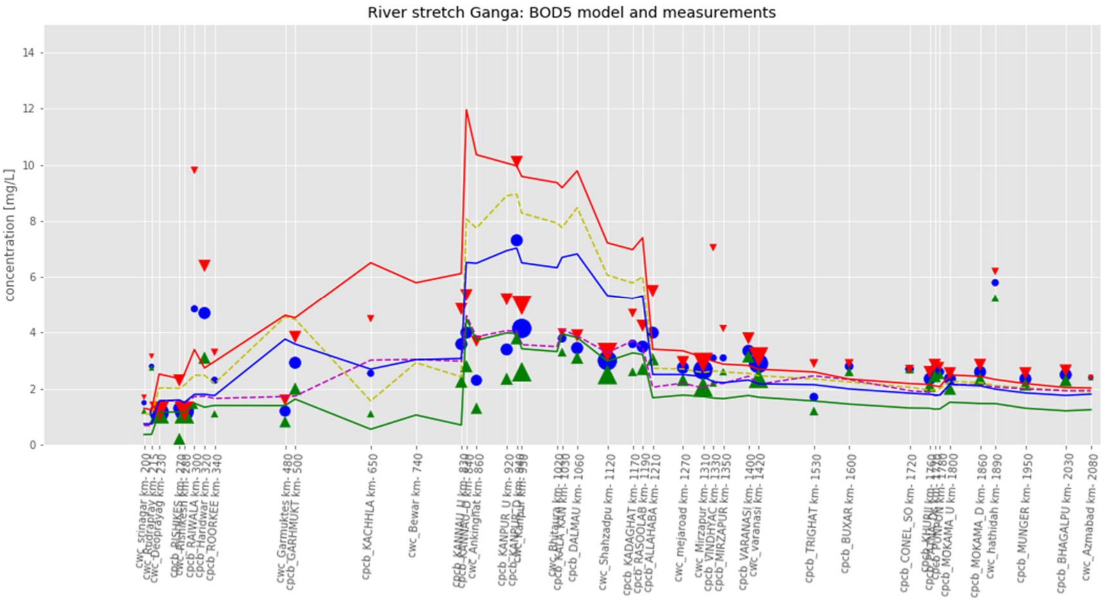

Figure 0.6: Calibration results for DWAQ model showing biochemical oxygen demand (BOD5, mg/L) along river Ganga. Measurements (▲:10-,●:50- and ▼:90- percentile) and simulations (solid lines 10-, 50-, 90- percentile, dashed lines are 50-percentile values for monsoon and winter) .

The impact on the ecology and ecosystem services of the changed discharges, water levels and water quality, resulting from simulated interventions, is evaluated using knowledge rules. These rules are site specific and have been developed jointly with stakeholders during the project. For this purpose all rivers have been divided into ecozones based on their ecologically relevant characteristics. Results are expressed in classes that express deviation from the pristine situation. These range from Class A (0-20 percent deviation) to Class E (81-100 percent deviation). Figure 0.7 shows and example of these results for the ecological impacts for selected zones.

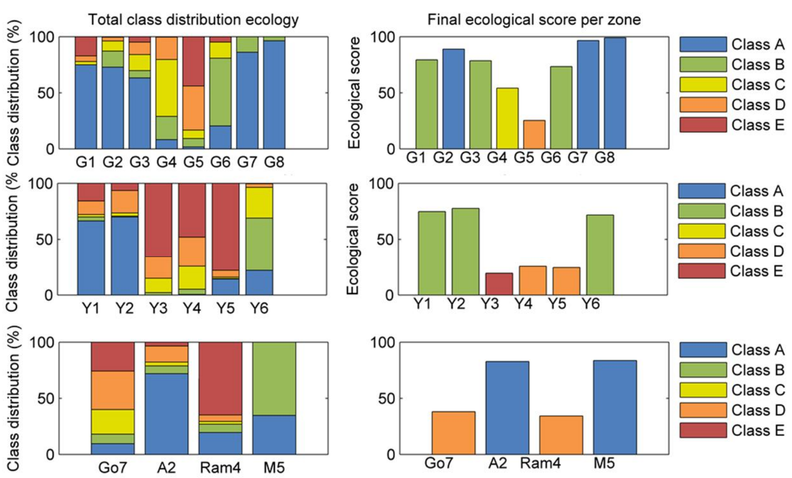

Figure 0.7 : Class distribution of all ecological indicators per selected ecozone (left panels) and the final weighted ecological score (right panels). G = Ganges, Y = Yamuna, Go = Gomti, A = Alaknanda, Ram = Ramganga and M = Mahananda. Numbering from upstream to downstream.

All model input/output is stored in the water information system. A dashboard has been created that depicts the stakeholder chosen indicators to judge the impact of the different scenarios. The dashboard provides a comparison between two scenarios: for example, with and without the implementation of a certain intervention at the level of the whole Ganga basin within India or for a selected state in the basin. Figure 0.8 presents a screen capture of the dashboard.

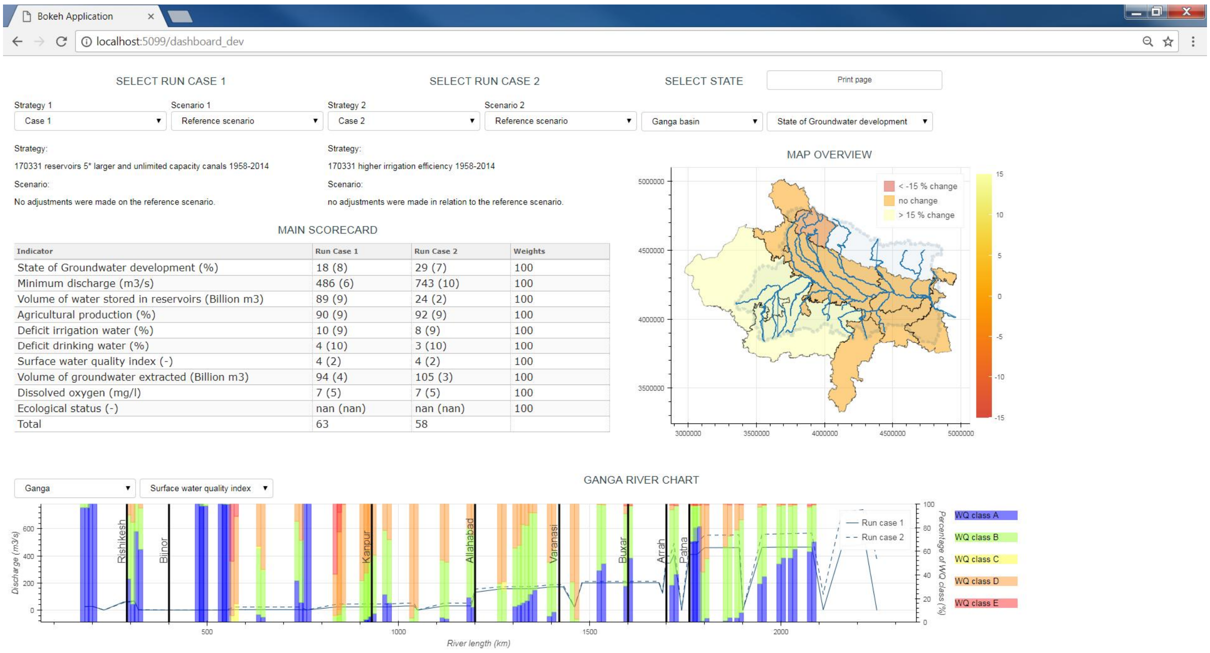

Figure 0.8: Screen capture of the Ganga river basin dashboard showing results for two scenarios

It is important to realize that model results may be more or less sensitive to different values of input data and parameters, and that model results contain a certain level of uncertainty. Figure 0.9 presents some results of the sensitivity analysis. It compares the result for the present case with one in which all model input is chosen to reflect the pristine situation, meaning without water infrastructure and anthropogenic water use, and with the assumed pristine land-use and land-cover. This provides an indication of the sensitivity of the model to land-use changes. The difference in simulated discharges is marginal for a catchment in the Himalayas, upstream of current water demands and infrastructure. It shows that the vegetation modifications have a limited impact on the flow. On the other hand, the results for the Ganga near Kanpur and the Yamuna near Delhi show a large impact with a reduction of nearly 60 percent in the average discharge compared to the pristine situation. This is caused by the substantial diversion of water to the irrigation systems in the present situation. The impact observed at Delhi and Kanpur is attenuated further downstream by the inflow from other tributaries. Consequently, the result for Varanasi shows about a 50 percent reduction in discharge.

The results of the calibration, validation and sensitivity analysis provide confidence that the Ganga river basin model is capable of assessing the impacts of future developments and measures at basin scale by comparison of simulation results. This makes the model a valuable tool to support strategic basin planning.

Results outside the Ganga river and its main tributaries and results for locations further upstream in the basin are less reliable since the strategic nature of the model has limited the amount of detailed information included at this scale level.

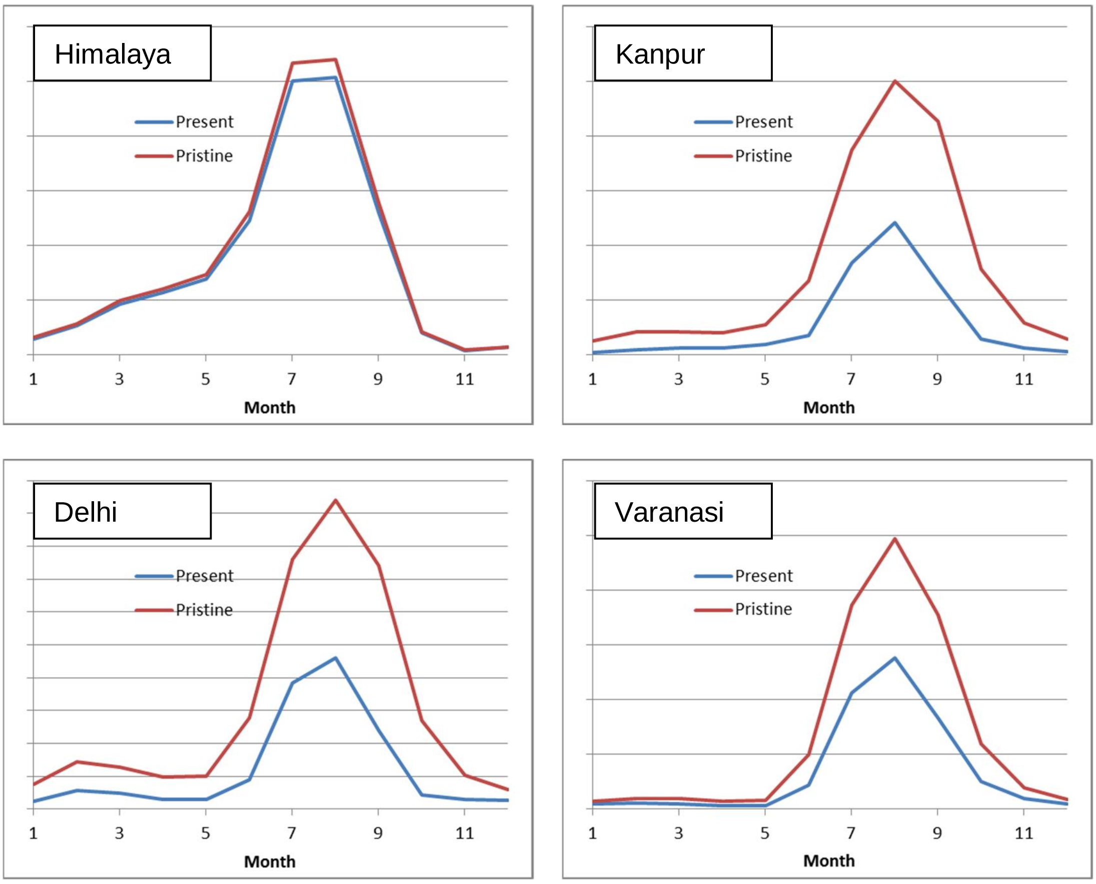

Figure 0.9: Comparison of average monthly simulated discharges for the period 2000–2014 for the Present and the Pristine scenario for (clockwise from top-left) a catchment in the Himalaya, the Ganga near Kanpur, near Varanasi, and the Yamuna below Delhi.

The Ganga River Basin Model uses input data from Indian sources as far as these are available and reliable. This applies to the data used for precipitation, land use, water supply, waste water treatment and statistical information to derive water demands and waste loads. Information from global data sets have been used where no national information was available or where this information was deemed not to be reliable. This applies to all meteorological information outside India, temperature and the earth observation data for actual evaporation. Although the quality of global data sets based on combinations of earth observation, ground observation and global models continually improves, national data and especially ground observations remain important for validation of global data sets as well as for providing additional detail.

The reliability and accuracy of the Ganga river basin model for supporting strategic basin planning can be further improved. It is recommended that there be a continuous effort to improve the model using new data and knowledge. However, improvement of the model should not delay its application for scenario analysis. Application will provide important information on where model improvement is most urgently required.

Improvement of the river basin model should aim to improve its relevancy as a tool to support strategic basin planning. Adding more detail to the model input does not automatically improve the relevancy or accuracy. On the contrary, excessive detail will result in a model too complex for strategic planning application and realistic result interpretation. Furthermore, the improvement of the calibration and validation of the model does not by definition improve the relevancy for supporting strategic basin planning.

The improvements should be sought in more reliable and accurate representation of the impacts of scenarios and strategies and more insight into the value of the impact assessment. Of course, improved calibration could contribute to this aim.

Based on the calibration and validation results, it is recommended that the following topics be considered for improvement:

- Add missing data on important input items, such as the storage capacity of some reservoirs;
- Improve the cropping calendar used to derive the water demand for irrigation;
- Add data on hydropower demand and generation;
- Add data on operation rules for dams and barrages;
- Calibrate the groundwater extraction from the inventory of installed pumping capacity and depth;
- Add an economic valuation of the societal benefit of different uses of water that would become input for a cost-benefit analysis of management strategies.

It is recommended that application and further development of the river basin model and the GangaWIS be executed by staff of the relevant Indian organizations, such as CWC, CGWB, CPCB, NIH and IIT in order to ensure that the system is maintained and utilized following project completion.

1 Introduction

The Ganga basin is the most populated river basin in the world and is home to half the population of India including two-thirds of the nation's poor people. The basin provides over one-third of the available surface water in India and contributes to more than half the national water use of which 90 percent is diverted to irrigation.

The ecological health of the Ganga river and some if its tributaries has deteriorated significantly as a result of high pollution loads from point and non-point sources; high levels of water abstraction for consumptive use, mostly for irrigation, but also for municipal and industrial uses; and flow regime and river modifications caused by water resources infrastructure, dams and barrages for diverting and regulating the river and generating hydropower.

The Government of India has committed itself to an ambitious goal of rejuvenating the Ganga and has assigned significant funds to address the problem. However, in addition to the technical complexity and scale, the rejuvenation of the Ganga is an inherently "wicked problem" given the wide diversity of stakeholder values and perspectives and the political and institutional dimensions that come from distributed responsibilities across multiple jurisdictions and institutions. The World Bank has assigned Deltares and its partners AECOM India and FutureWater to carry out the present project "*Analytical Work and Technical Assistance to support Strategic Basin Planning for Ganga River Basin in India*".

The key objectives of the project are:

- Significantly strengthen the capability of relevant central and state government agencies to undertake comprehensive evidence-based strategic basin planning for the Ganga river basin;
- Develop, document and disseminate, through detailed analytical work and stakeholder engagement, a set of plausible scenarios that balance significantly improving the health of the river and maintaining an acceptable level of economic productivity;
- Build stronger and more accessible information and knowledge base to guide on-going dialogue and management of the Ganga river basin; and
- Establish on-going multi-stakeholder engagement processes in the basin to support strategic basin planning.

These objectives will be achieved by:

- Developing a detailed and robust water resources planning model for the entire Ganga basin in India and training central and state government engineers and planners in its use;
- Characterizing and analyzing surface-groundwater interactions across the basin, using this information to refine the river modelling;
- Undertaking a multi-scale environmental flow assessment across the basin and using these assessments to inform the scenario modelling;
- Developing, modelling and disseminating a series of plausible scenarios that explore alternative options for improving water management including improving river health;
- Establishing and facilitating a multi-stakeholder consultation process, inside and outside of government, to guide and share the work above; and
- Ensuring wide access to the models and analyses, with quality documentation.

The main final deliverables of the project consist of:

- Report on river basin modelling and documentation of information systems;
- The software and data files of the river basin model and the water information system for strategic planning of the Ganga basin, including the model input and output for the plausible scenarios;
- Report on surface – groundwater analysis;
- Report on environmental flow assessment;
- Report on scenario modelling; and
- Final project management report including stakeholder engagement processes and executive summaries of technical reports.

This report is the first deliverable listed above and describes the river basin model and the water information system for strategic planning of the Ganga basin. Its starting points are the previous reports on the conceptualization of the river basin model (Van der Vat et al, 2016) and the design of the Ganga water information system (Deltares et al, 2017).

The river basin model describes the functioning of the water system of the Ganga basin within India with respect to rainfall-runoff, flow storage and diversion, water use and water quality and ecology. The interaction between surface and groundwater is included in the model concept but is described in a separate report. The aim of the model is to support strategic basin planning by analyzing the impact on basin scale of possible future developments, such as climate change and socio-economic scenarios and possible management strategies. The extent of the basin has required trade-offs to be made during the modelling between the amount of detail to be included and the strategic purpose of the modelling.

Stakeholders have contributed extensively through a collaborative modelling process that has provided information on the issues, future developments, possible measures and indicators to aggregate simulation results. Furthermore, different versions of model schematizations and results have been discussed during a series of stakeholder workshops to obtain feedback. This process is described in detail in a separate stakeholder engagement report (Ottow et al., 2017).

This report contributes to project milestone 5 and combines the following deliverables into one report:

- Deliverable 12 River Basin Modelling Report; and
- Deliverable 14 Final documentation of information systems.

Chapter 2 outlines the components of the river basin model and describes component interaction.

Chapters 3–7 describe a separate component of the river basin model:

- Chapter 3: Hydrology;
- Chapter 4: Geohydrology;
- Chapter 5: Water resources management;
- Chapter 6: Water quality;
- Chapter 7: Ecology.

For each of these components the following information is provided: concepts, input data, link with other components, calibration and validation results and indicators. The GangaWIS is presented in Chapter 8 and the Dashboard in Chapter 9. Chapter 10 describes how the river basin model can be applied for scenario analysis and presents the results of a sensitivity analysis of the model. The results of the scenario analysis are described in a separate report.

The main report ends with conclusions and recommendations for further development of the river basin model for strategic planning. All model results and all calibration data not presented in this report, such as results for all subbasins, can be assessed through the GangaWIS as explained in Appendix H.2.1.2.

The Appendices describe in detail the input data for each component, where the data are stored in the system and references to data origin. Furthermore, detailed tutorials are included with step-by-step descriptions of tasks to be performed with the system, such as installation of the system, adaptation of the input, running of different simulations and comparison of results to assess the impact of a scenario and/or strategy. These appendices can be used as material for courses and self-study.

2 Components of the Ganga River Basin Model and their Interlinkage

2.1 Background and Context

The aim of the Ganga river basin model is to support strategic planning for the Ganga basin. It enables strategic planning by supporting the impact assessment of different possible future situations. To describe these future situations, scenarios and strategies are distinguished. Scenarios consist of developments outside the scope of the decisions to be supported, but that influence the impact of the decision. Examples are scenarios for climate change, population growth, urbanization and economic growth. Strategies consist of combinations of measures and interventions that are the object of the decision making process and that will be incorporated in the strategic plan. Examples include construction of new infrastructure, e.g. dams, barrages, canal and sewage treatment plants; operation modification of existing infrastructure; efficiency improvements in water supply and demand management. The impact assessment will be based on comparison of model results. For this purpose, the results will be aggregated into quantitative and semi-quantitative indicators, such as minimum flow, water shortage, water quality index and ecological state. The absolute values of the model results are only used for calibration and validation.

A model to support strategic planning should try to 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 a model is limited. The strength of the model is its schematic representation of reality. Therefore, the Ganga river basin model has a very wide scope allowing for an integrated assessment of impacts related to hydrology, geohydrology, water resources management, water quality and ecology. The level of detail is limited to keep the model manageable and the complexity understandable.

The Ganga river basin is huge with a surface area within India of 860,000 km^2 (FAO Aquastat, assessed December 19, 2017) and a population of 485 million people (derived from 2011 census data, Office of the Registrar General & Census Commissioner, India, 2011). Population is concentrated in the plains of the Ganga basin. Most of this area supports irrigated agriculture. The plain has a very limited slope from some 250 m above sea level in the east to approximately 25 m near Farakka at the border with Bangladesh. North of the plain the Ganga and its tributaries flow from the Himalaya with elevations over 6000 m above sea level. The Himalaya Mountains are covered by snow and glaciers, which has a significant influence on the flow pattern of the rivers. The mountains and hills to the south are much lower with an average elevation around 1000 m. There is a decreasing gradient in water availability in the plain from west to east. The flow of the Ganga and Yamuna rivers from the Himalaya supplies a large portion of the water supply. Conjunctive irrigation in the western part of the plain using both surface and groundwater has locally led to decreasing groundwater tables. Further to the east in the basin, precipitation increases as does the flow in the Ganga river fed by its tributaries.

Figure 2.1 presents a schematic overview of the main interactions between surface and groundwater and the use of water for irrigation in the plain of the Ganga. Irrigation water supply depends on surface water delivered from rivers through canals and on pumped groundwater. A large part of the irrigation water is not used for plant transpiration and will return to the water system in the form of aquifer recharge and drainage to canals and rivers. Furthermore, there is a direct exchange between surface and groundwater.

Depending on the relation between the level of surface and groundwater, the flow will be either from the groundwater to the surface water, 'the river is gaining water' or from the surface to the groundwater, 'the river is losing water'. Water quality and ecology of the river and its floodplains depend strongly on the flows resulting from the interaction between geohydrology and water resources management.

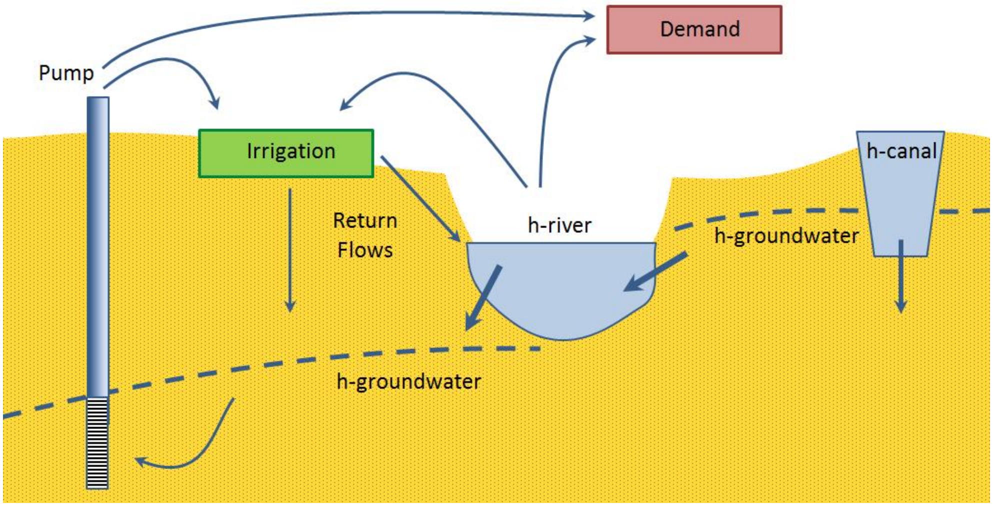

Figure 2.1: Schematic relations between hydrological models and groundwater model

2.2 Modelling Components and GangaWIS Database

Different models are combined in the river basin model to allow for the required integrated impact assessment. These models have been selected because they cover the dominant processes in the basin and allow for the assessment of the impact of future developments and interventions. The following two Figures present the models in slightly different ways. Figure 2.2 presents the workflow of the model components, i.e. the sequence in which the models are run. Figure 2.3 presents an overview of the components and their interactions.

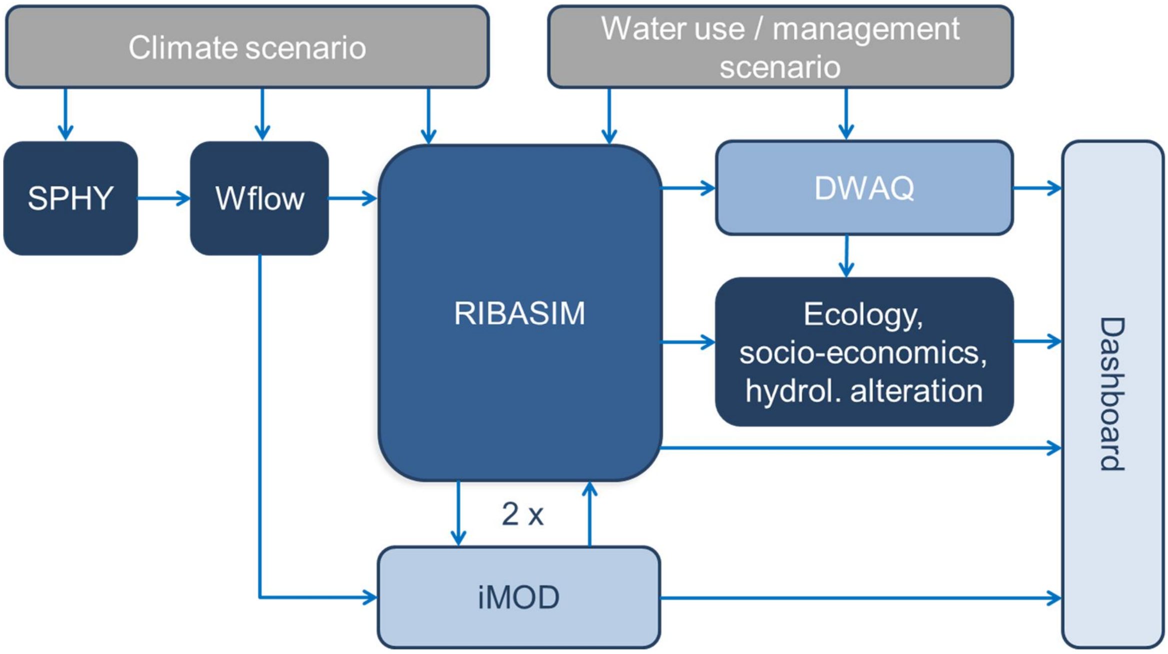

Figure 2.2 Schematic presentation of the workflow of the components of the Ganga river basin model

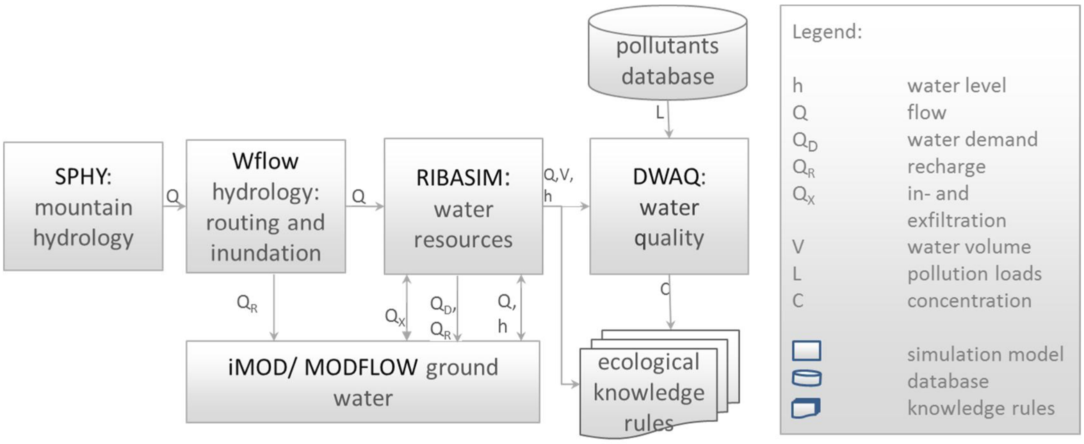

Figure 2.3: Components of the river basin model and their interaction

The description of the hydrology has been divided over two different models: SPHY and Wflow. They are both fully distributed models working on a grid of square cells. SPHY is used to describe the hydrological process in the mountainous areas in the Himalaya. This model has been selected because it is specifically designed for glacier and snow hydrology and it has previously been successfully applied to the Himalaya. Section 3.1 provides a detailed description of the concepts, set-up, input data and calibration and validation of the SPHY model.

The rainfall-runoff processes for the non-mountainous part of the Ganga basin are simulated with the Wflow model. This is a general purpose hydrological model. The river discharges calculated by the SPHY model for the Himalayas are used as upstream boundaries for the Wflow model. The application of the Wflow model is described in Section 3.2.

Groundwater movement is simulated by the iMOD-MODFLOW model. The model uses the same calculation grid as the Wflow model. It is only applied to the alluvial part of the basin, since it is not possible to model groundwater in the hard rock areas due to a lack of data on connectivity between different systems. Groundwater recharge is obtained from Wflow for the non-irrigated areas and from RIBASIM for the irrigated areas. Figure 2.4 presents a schematic of the interactions between the models. RIBASIM also provides the data on water abstractions and river discharge. Based on river discharge, river water levels are derived and used for the calculation of the flux between the river and the groundwater. The application of iMOD-MODFLOW is described in Chapter 4.

The water resources model RIBASIM describes the management and use of water. Its hydrological input is derived from the river discharges calculated by Wflow. RIBASIM uses a schematization of links and nodes to describe the flow of water in the rivers, the storage in reservoirs, the diversion into canals and the use and return flow by different functions. Water can be used from rivers and canals or from groundwater. Conjunctive use of surface and groundwater is also possible. Furthermore, return flows can be divided over rivers, canals and groundwater. This an important aspect for the description of the water system in the plains of the Ganga basin, where extensive leakage from irrigation canals feeds the groundwater aquifers, that are themselves used for irrigation water supply. Therefore, the RIBASIM model is also linked to the groundwater model to provide extraction and infiltration rates and to obtain the flux between the river and the groundwater.

Water demand for hydropower has not been included in the RIBASIM model application for the Ganga due to a lack of input data. The concept, set-up and input data, calibration and validation results and output to the dashboard of the RIBASIM model are described in Chapter 5.

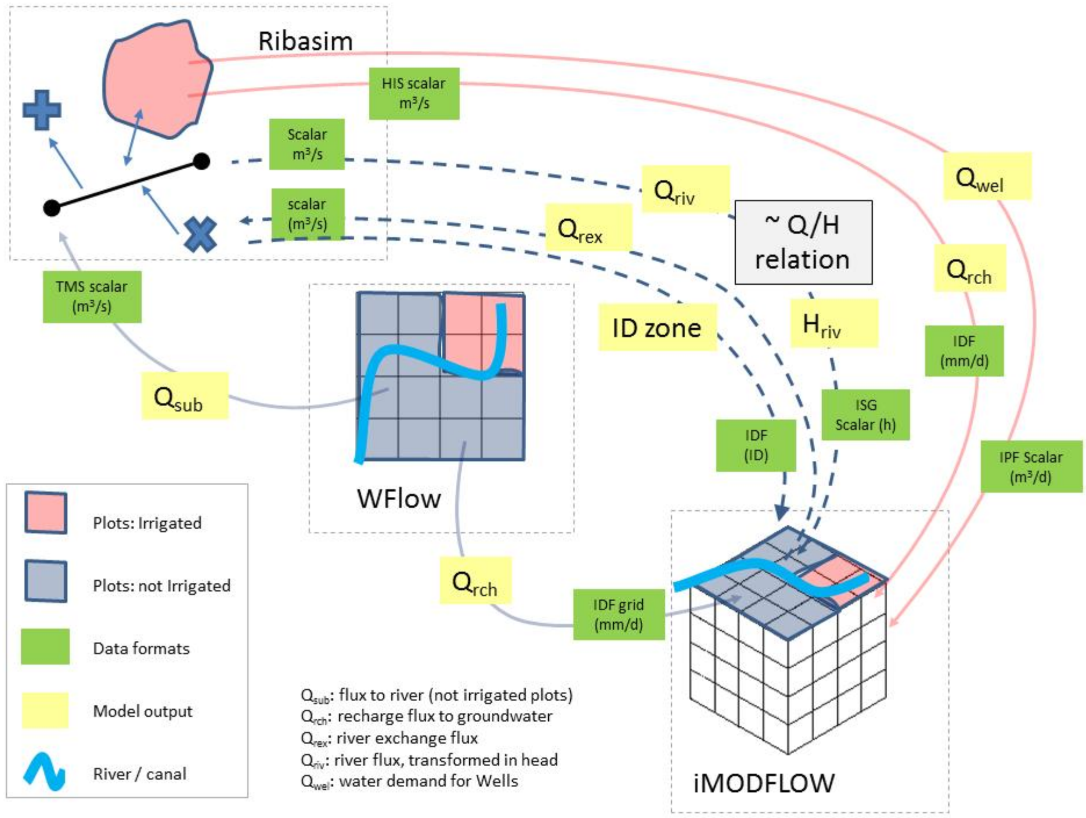

Figure 2.4: Schematic representation of technical interaction between RIBASIM, Wflow and iMOD (interaction between SPHY and Wflow has been omitted for reasons of clarity)

Water quality is assessed with the model DWAQ by combining RIBASIMs' discharges with pollutant load estimates. The DWAQ model is described in Chapter 6.

The impact of model results with respect to discharges, water levels and water quality on the ecology and ecosystem services are evaluated using knowledge rules. These rules are site specific and have been developed jointly with the stakeholders. A further description of this component can be found in the report detailing the approach for the environmental flow assessment. A description of the module used for evaluation of the knowledge rules and its links with the other models is provided in Chapter 7.

All model input and all relevant output is stored in the database of the water information system called GangaWIS. The exchange of information between the components of the river basin model is done by the GangaWIS. The management of different versions of model input and output, to represent different scenarios and strategies, is included in the GangaWIS. Furthermore, the model results stored in the GangaWIS provide the input for the dashboard presentation of results. GangaWIS is described in Chapter 8 and the dashboard in Chapter 9.

Most of the components of the river basin model are open source. This applies to SPHY, Wflow, iMOD, MODFLOW and DWAQ. This means that both the source code and the executable form of the software is publicly available on the internet to all interested parties and can be downloaded free of charge. The RIBASIM software is licensed software under transition to become open source. Deltares as the owner of RIBASIM has agreed to make the software available in an executable form free of charge for application within India during and after execution of this project. The GangaWIS and the evaluator for the knowledge rules are built entirely with open source components. Any new code prepared for this system during this project is included in the delivery of the software.

2.3 Project Area and Model Area

The project area is defined in the terms of reference to "*encompass the entire Ganga river basin in India including all tributaries upstream of Farakka Barrage on the Ganga river*". Furthermore, it is stated that "*the modelling will need to ensure robust assessment of the flows that enter the Ganga via the Nepalese tributaries*". Therefore, the combined application of the hydrological models SPHY and Wflow covers 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, that part of the catchment west of the Hoogly branch below Farakka has also been included in the model area.

The application of the models iMOD, RIBASIM and DWAQ is mostly limited to the Indian part of the model area defined above, with the exception of the major reservoirs on the Nepalese tributaries that have been included in RIBASIM to describe consistently their operation.

2.4 Setup of the Models

The setup of the models SPHY, Wflow and iMOD-MODFLOW is on a cell size of 1x1km. The models RIBASIM and DWAQ work on a schematization of links and nodes.

The models have been applied for different periods. For calibration and validation this depended on the length of the time series available for model input and for comparison of model results with measurements. Calibration and validation periods are reported in the separate chapters on the individual models. The potential application period of the model for the impact assessment of scenarios and strategies depends only on the availability of sufficiently reliable meteorological input and is 1959–2014. Model simulations have mostly been limited to the period 1985–2014 in order to ensure that the simulations represent the current climate and to limit the possible impact of historic climate change.

The time step of the calculations in SPHY and Wflow is one day and for RIBASIM and DWAQ one month. The reasoning: the main hydrological processes take place within periods of days and require calibration on this temporal resolution; the main processes regarding water resources and water quality, on the other hand, can be dealt with on the larger time scale of a month.

The aim of the river basin model is to support strategic planning on a basin level. Therefore, it has been very important to keep the temporal and spatial schematization relatively simple without including a high level of local detail, which does not support strategic level planning and might even present results with a false sense of accuracy. During the collaborative modelling process, trade-offs were made between the amount of detail to be included in the models and the strategic purpose for which the models will be applied.

3 Hydrological Models

The first step in the GangaWIS workflow is the rainfall runoff modelling, as indicated in Figure 3.1. The output of this step are the discharge values that are used in the RIBASIM model and the recharge values that are used in the iMOD model.

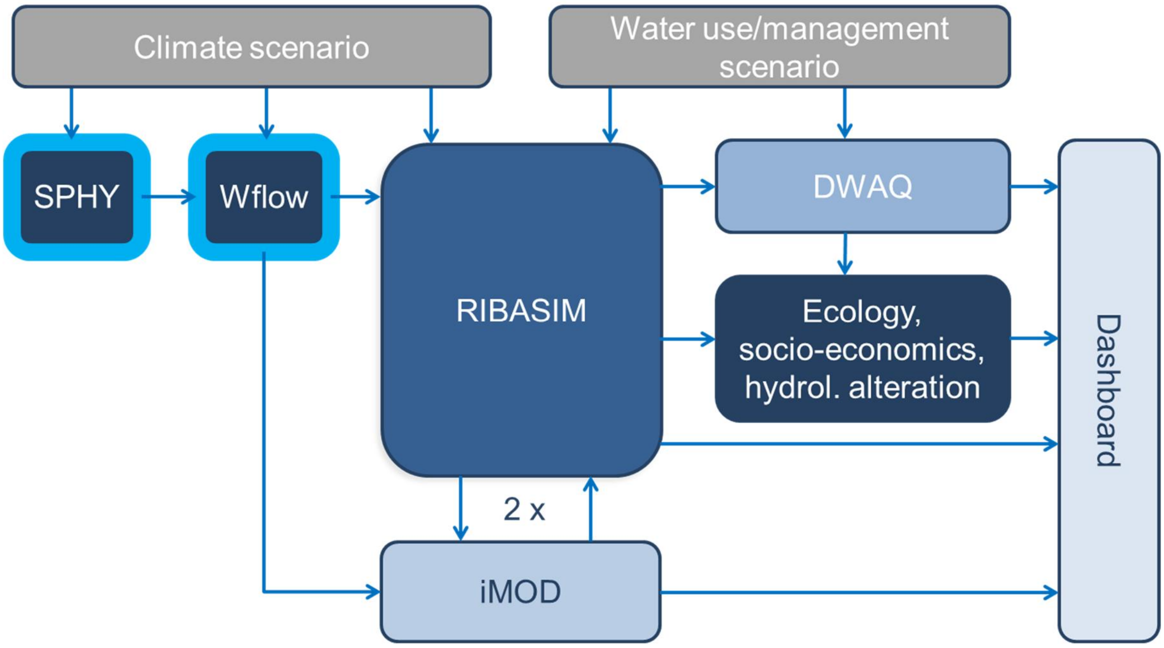

Figure 3.1: Schematic representation of the workflow in the GangaWIS.

To simulate the runoff generating processes from rainfall, hydrological models are used. For the snow and glacier dominated parts of the basin, the specialized SPHY model (Section 3.1) is applied. For the main part of the basin, the Wflow-SBM model is used (Section 3.2).

Both models are distributed or gridded models. The models use gridded input and can produce gridded output. Using gridded inputs, static maps for land-use and dynamic input maps for model forcing, allows for using high resolution input data up to the model resolution. The distribution of inputs adds more realism to the model, compared to lumped model approaches in which the input data is often lumped at the subcatchment level. Lumping of rainfall data generally introduces errors in the discharge simulation. The gridded inputs also allow for easy spatially distributed adjustment of model inputs, e.g. changing land-use for a certain district or state only.

Because the framework produces gridded outputs, in principle every grid-cell of the model can generate output time series, as demonstrated in Figure 3.2. This makes the application of the framework well suited for basin planning studies, since definition of output locations of the model has not been determined in advance. New output locations, e.g. for calculating the inflow into new surface water reservoirs, can be added later without the need to change the schematization and revising the calculations.

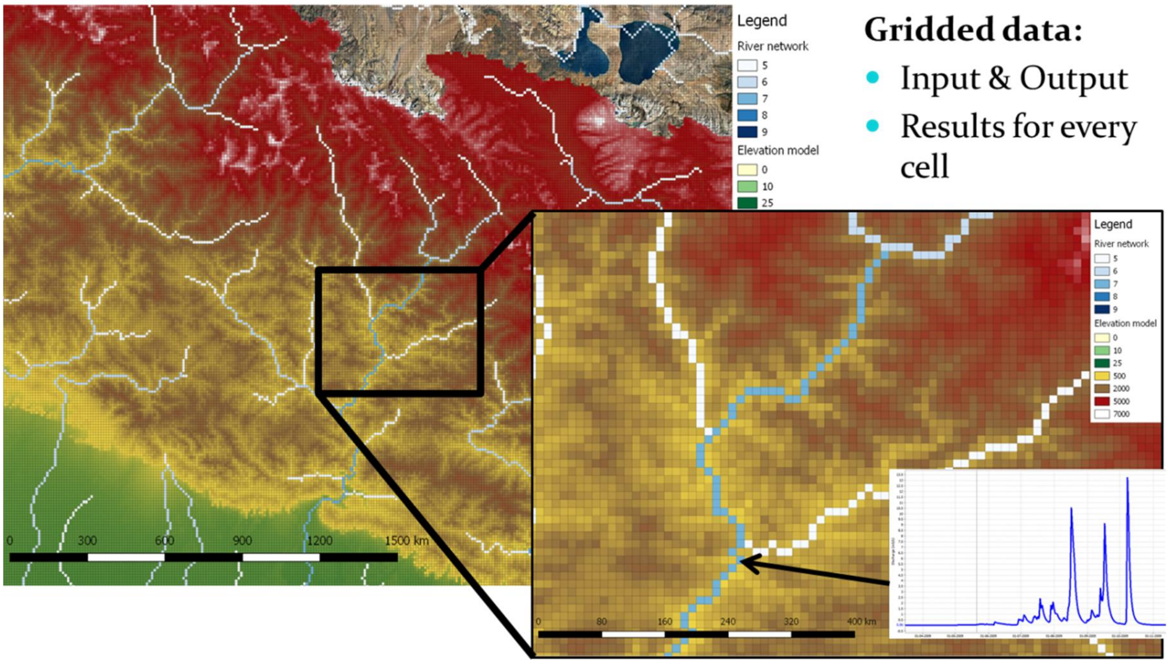

Figure 3.2: The hydrological models produces gridded outputs, meaning that at every location in the model, output time series can be easily produced.

To quantify the agreement between the simulated and observed discharge a series of correlation coefficients are calculated. These coefficients are used for the quantification of model performance for the SPHY, Wflow and RIBASIM models. A well-known example is the **Nash-Sutcliffe Efficiency coefficient (NSE)**, (Nash and Sutcliffe, 1970)):

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_s^t)^2}{\sum_{t=1}^{T}(Q_o^t - \bar{Q}_o)^2}$$

where $\bar{Q}_o$ is the mean of observed discharge, and Q_s is simulated discharge. Q_o^t is observed discharge at time t. The closer the value of NSE is to 1, the better the model performance (Table 3.1).

Table 3.1: Description of fit linked to Nash-Sutcliffe model efficiency coefficient (Adapted from (Foglia et al., 2009)*)*

Fit	Nash-Sutcliffe efficiency
Observed mean is a better predictor than the model	<0
Insufficient	0– 0.2
Sufficient	0.2–0.4
Good	0.4–0.6
Very good	0.6–0.8
Excellent	>0.8

The **NSE with logarithmic values (LOGNSE)** is less sensitive to extreme values and calculated with logarithmic values of observed and simulated discharge. Through the logarithmic transformation of the runoff values, the peaks are flattened and the low flows remain more or less at the same level.

As a result, the influence of the low flow values is increased in comparison to the flood peaks resulting in an increase in sensitivity to systematic model over/under prediction (Krause et al., 2005).

The **Coefficient of determination (R^2)** indicates the proportion of the variance in the observed discharge that is predictable from the simulated discharge:

$$r^2 = \left(\frac{\sum_{i=1}^{n} (Q_{o,i} - \overline{Q_o})(Q_{s,i} - \overline{Q_s})}{\sqrt{\sum_{i=1}^{n} (Q_{o,i} - \overline{Q_o})^2 \sqrt{\sum_{i=1}^{n} (Q_{s,i} - \overline{Q_s})^2}}} \right)^2$$

with Q_o being observed discharge values and Q_s being simulated discharge values. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation.

The **Relative Error in Volume (REV)** is an indication for the correct simulation of the volumes. The REV can be either positive, the model simulates more water than is observed, or negative the model simulates less water than is observed. The REV score is calculated as follows:

$$REV = \frac{\sum_t \left[Q_s(t) - Q_o(t) \right]}{\sum_t Q_o(t)}$$

Ideally, the REV values are on average 0 percent and preferably not exceed 10 percent.

3.1 SPHY

3.1.1 Concepts

The SPHY hydrology model is a spatially distributed hydrological model (Terink et al., 2015a). The main terrestrial hydrological processes are included in the model so that changes in storages and fluxes can be assessed adequately over time and space. Figure 3.3 shows a schematic diagram of the simulated processes in the SPHY model.

SPHY is grid based and cell values represent averages over a cell. For glaciers, sub-grid variability is taken into account: a cell can be glacier free, partially glaciered, or completely covered by glaciers. The cell fraction not covered by glaciers consists of either land covered with snow or land that is free of snow. Land that is free of snow can consist of vegetation, bare soil, or open water. The dynamic vegetation module accounts for a time-varying fractional vegetation coverage, which affects processes such as interception, effective precipitation, and potential evapotranspiration.

The SPHY model provides output variables that can be selected based on user preference. Spatial output can be presented as maps of all the available hydrological processes, i.e. actual evapotranspiration, runoff generation separated by its components, and groundwater recharge. These maps can be generated daily, but can also be aggregated at monthly or annual time periods. Time series can be generated for each cell in the study area.

The most often used important results are streamflow, actual evapotranspiration and groundwater recharge.

For a more detailed description of the concepts of modelling high mountain hydrology in SPHY, please refer to the inception report, the theoretical manual (Terink et al., 2015b), and open access scientific journal publication (Terink et al., 2015a).

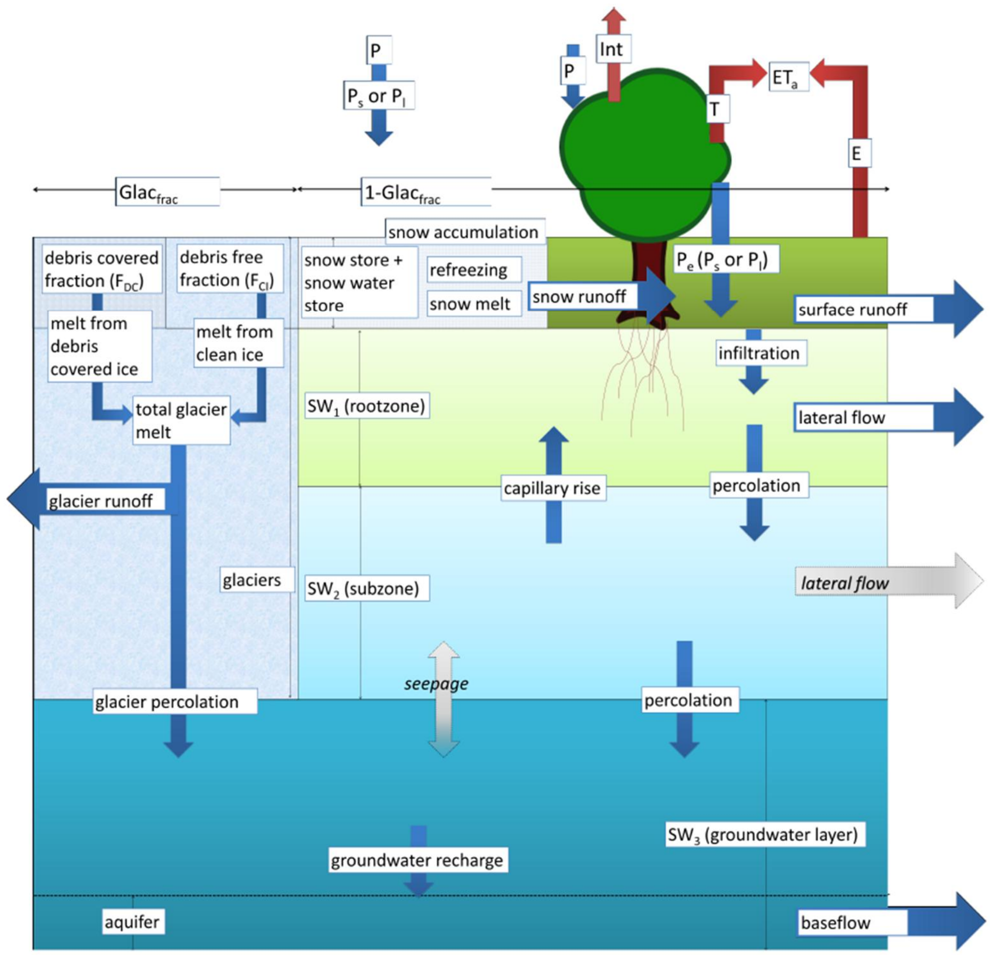

Figure 3.3: SPHY modelling concepts.

3.1.2 Set-up and Assumptions

The SPHY-model is set up for the upstream, mountainous part of the Ganga basin. This domain covers large parts of Himachal Pradesh and Uttarakhand in India, a large part of Nepal and parts of China on the Tibetan Plateau. The discharge generated in the SPHY model domain culminates at the model's nine outflow locations that form the input to the Wflow hydrological model. The model extension and the nine outflow points are shown in Figure 3.4. The spatial resolution of the model is 1x1 km. The model runs with a daily time step over a period of 57 years (1 January 1958 until 31 December 2014).

3.1.3 Input Data

SPHY requires static input maps as well as series of input maps for meteorological forcing. The model input is briefly described in this section; a more detailed description will be found in Appendix A.

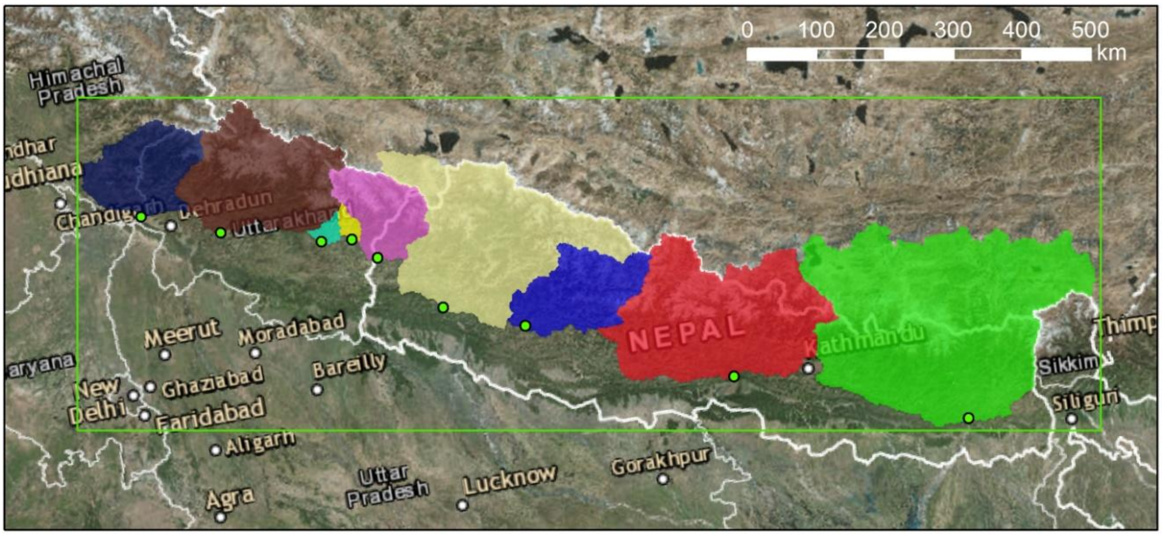

Figure 3.4: Simulated domain of the SPHY model, indicating the 9 outflow locations where SPHY is coupled to Wflow.

For the delineation of the subbasins of the model, the HydroSheds SRTM DEM (Lehner et al., 2006) is used and resampled to the model resolution, projection and extent. Based on the DEM a local drain direction map is calculated, which indicates the drain direction of each grid cell. With this procedure, the stream network of the model is defined, which is used to route water from upstream to downstream. A slope map, which is derived from the DEM as well, is used for the calculation of lateral flow of water through the soil layers.

Furthermore the model uses a land-cover map (Defourny et al., 2007) with associated evapotranspiration coefficients assigned to each land-cover type, a soil map with quantitative soil properties for the topsoil and subsoil (De Boer, 2015) and a map of glacier outlines and distinction in debris-covered and debris-free glacier surfaces (Arendt and 87 others, 2015).

For the meteorological forcing, SPHY uses series of daily grids of precipitation (mm/day), and daily mean air temperature, daily maximum air temperature and daily minimum air temperature, all in ˚C. After comparison of several forcing products, as described in the Inception report and Progress report, the SPHY model has been set up with a combination of forcing data from WATCH Forcing ERA-Interim, WFDEI (Weedon et al., 2014) for 1979–2014, and EU-WATCH (Weedon et al., 2011) for 1959–1978, since WFDEI data is not available before 1979.

The input data, their sources, preprocessing and their locations in the modelling system are described in more detail in Appendix A.

3.1.4 Link with Other Components of the Ganga River Basin Model

As indicated in Figure 3.4, the SPHY model has nine connection points to the Wflow surface hydrology model. This connection is one-way: daily discharge series from the SPHY model feed into the Wflow model, but there is no feed-back coupling. A selection of SPHY model outputs is connected to the GangaWIS for dashboard visualization. These simulated outputs are:

Daily, for 9 outlet locations:
- Total discharge (m^3/s);
- Glacier melt runoff (m^3/s);
- Snow melt runoff (m^3/s);
- Rainfall-runoff (m^3/s);
- Baseflow (m^3/s).

Daily, as spatial maps covering the model domain:
- Total discharge (m^3/s);
- Glacier melt (m^3/s);
- Snow pack (mm).

Details on file formats and locations of the output files in the system are described in Appendix A.

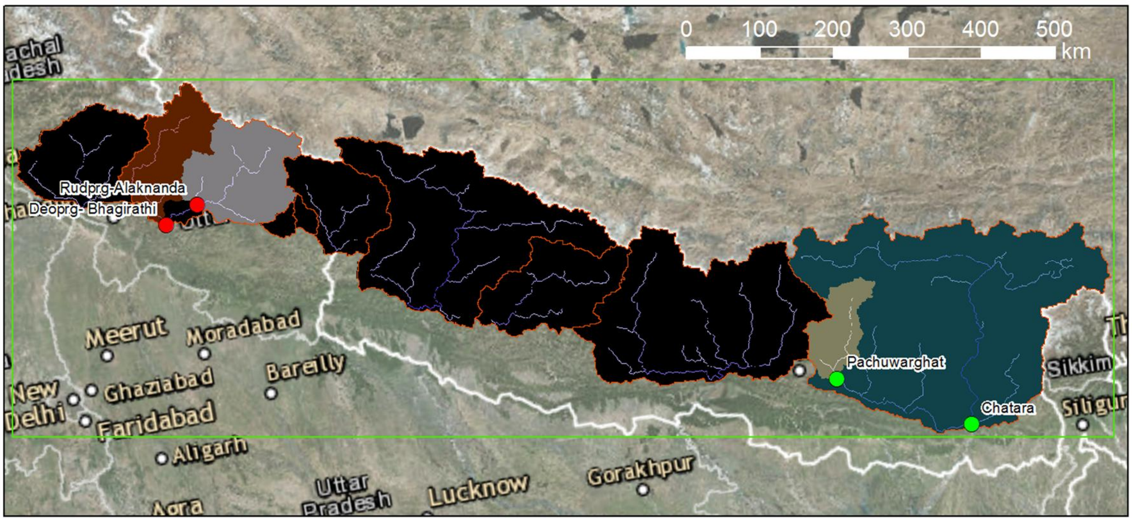

Figure 3.5: Discharge measurement locations used for model calibration and validation. Red dots indicate locations in India, green dots indicate locations in Nepal. Upstream areas of the locations are indicated by colored shading.

3.1.5 Calibration and Validation Results

The calibration and validation procedure is based on the visual comparison of simulated discharge hydrographs to observed discharge hydrographs. SPHY model parameters are optimized to reach a satisfactory agreement between the simulated and the observed discharge. The SPHY model was calibrated and validated for locations in the Koshi river basin, using data from the Department of Hydrometeorology for Nepal, and locations in the Indian part of the upper Ganga, using data from the Central Water Commission (Figure 3.5). For the Chatara and Pachuwarghat locations in the Koshi basin in Nepal, daily discharge records for the period 1998–2007 were used. For the Rudprg-Alaknanda and Deopgr-Bhagirathi locations in India, monthly discharge records for 1985–2009 were used, as no daily values were available. The stations have been selected based on data availability, diversity of catchment locations and sizes, completeness of records and confidence about the correct locations of the stations. Because flow data records for India are not public, actual discharge amounts cannot be indicated in any table or graph in this report.

3.1.5.1 *Calibration and Validation Criteria*

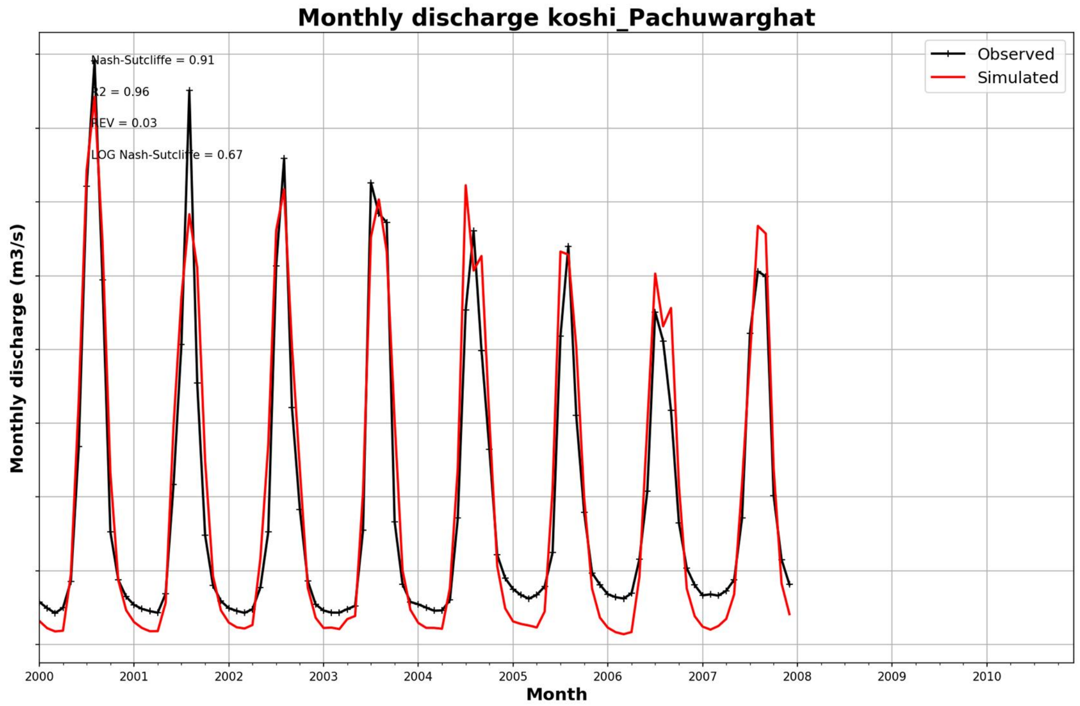

Figure 3.6: SPHY model performance at Pachuwarghat (monthly comparison).

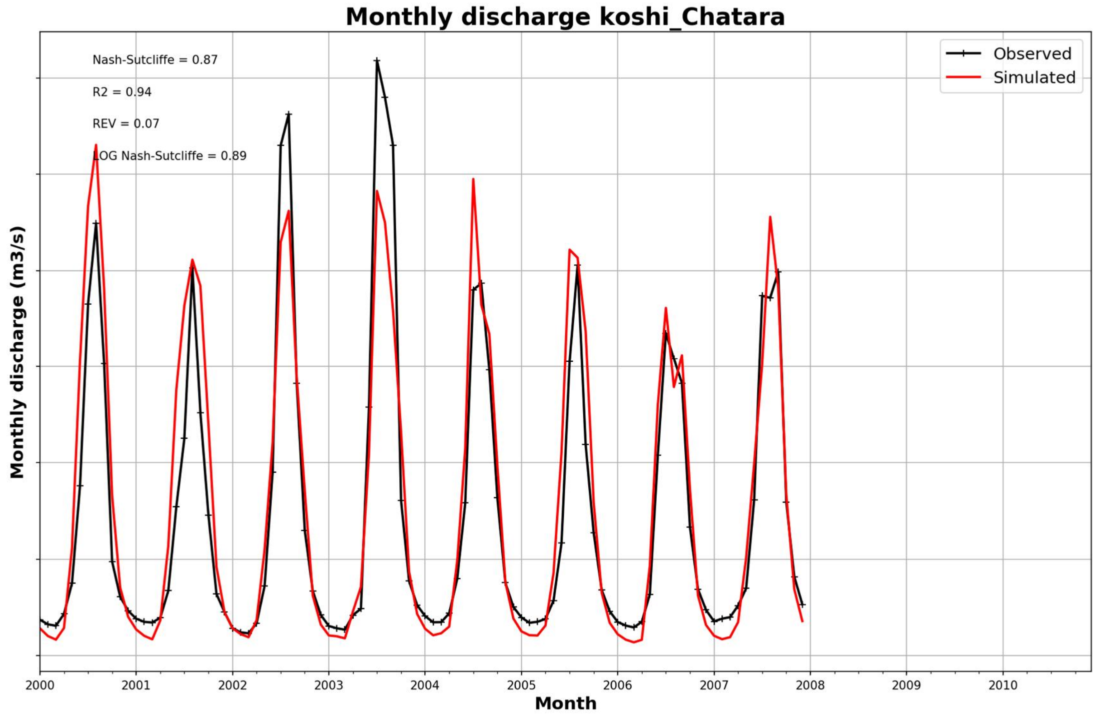

Figure 3.7: SPHY model performance at Chatara (monthly comparison).

3.1.5.2 *Results Koshi basin*

For the Koshi basin, data was available for 1998–2007 at daily time step. The Pachuwarghat station was used to *calibrate* and Chatara station to *validate* the model for this period.

Figure 3.6 and Figure 3.7 indicate the performance of the calibrated model at these locations when monthly simulated flows are compared to monthly observations, with indication of the correlation coefficients discussed earlier. In general, the model performs well. This is reflected by the high correlation coefficients and low bias. The major weaknesses are the underestimation of the low flows and the lack of coincidence of the highest discharges at Pachuwarghat. At Chatara, low flows and peaks are captured somewhat better. Interannual variability is captured quite well, but not for all years. The correlation coefficients can be considered high, especially for complex mountainous catchments, where small scale climatic variability is usually insufficiently represented in forcing data.

For the Indian part of the upper Ganga monthly data were used for 1985–2009. The Deopgr-Bhagirathi station and the Rudprg-Alaknanda station were used to validate model performance. For this part of the basin, the model was run with two different precipitation datasets. The first consisted of only WFDEI precipitation (Figures 3-8 and 3-9), the second replaced WFDEI precipitation with IMD precipitation when available in space and time. For the model forced with WFDEI precipitation the bias is overall smaller for Deopgr-Bhagirathi than for the model forced with WFDEI/IMD precipitation. For the location at Rudprg-Alaknanda it is the opposite. NSE coefficients are significantly higher when the model is forced with WFDEI precipitation. This leads to the conclusion that for the upper Ganga, forcing of the model with WFDEI precipitation is the preferable choice, although the difference in performance compared to the WFDEI/IMD forced model is acceptable.

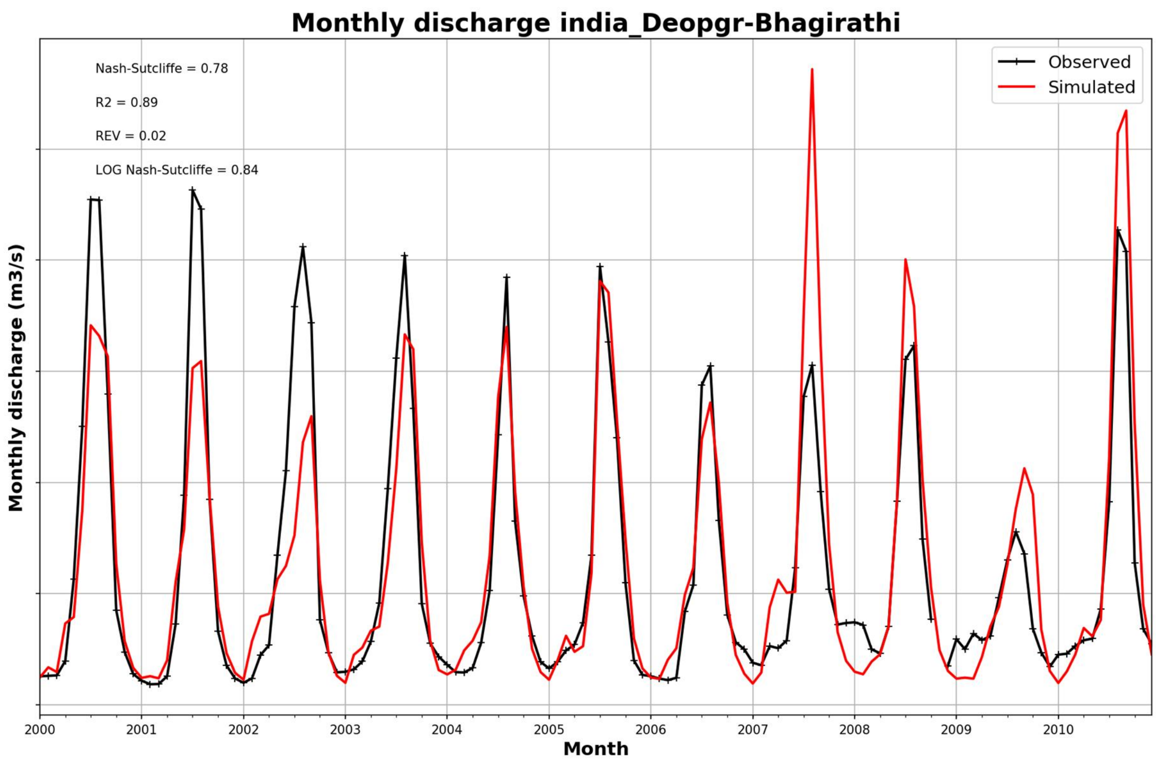

Figure 3.8: SPHY model performance at Deopriag on the Bhagirathi for model run with WFDEI precipitation forcing (monthly comparison).

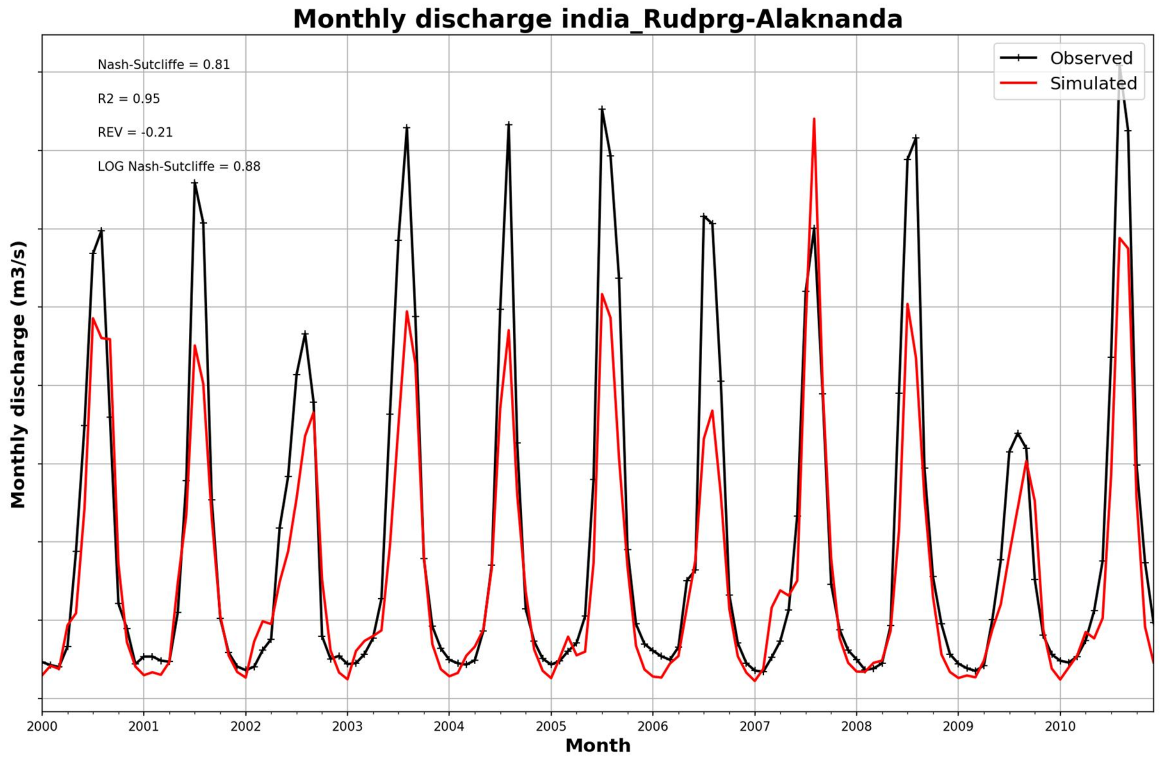

Figure 3.9: SPHY model performance at for model run at Rudraprayag on the Alaknanda with WFDEI precipitation forcing (monthly comparison).

The comparison of the observed and simulated discharges can also be made for the discharge regime, based on mean monthly discharge. The results of this comparison are shown in Figure 3.10. The model performs well in the low flow situations although the model tends to underestimates the low flows. The high flows are represented well in the calibration period, with exception of the Rudraprayag station. Over the validation period, the performance of the model for high flows is less accurate.

3.2 Wflow

3.2.1 Concepts

The hydrological modelling framework Wflow simulates the rainfall-runoff processes in the lower parts of the Ganga basin, i.e. downstream of the basins modelled in SPHY. The Wflow framework consists of different hydrological concepts, including the HBV and SBM concepts. The Wflow framework is based on a raster-based dynamic framework, PCRaster that uses gridded inputs and produces gridded outputs. Details on the setup and data requirements of Wflow are given in Appendix B.

As stated earlier, the Wflow framework can work with different hydrological concepts, i.e. different conceptualizations of the real world hydrology. For the purpose of the model, the availability of the data and for an optimal connection to the groundwater model, the SBM modelling concept is well suited for the Ganga model.

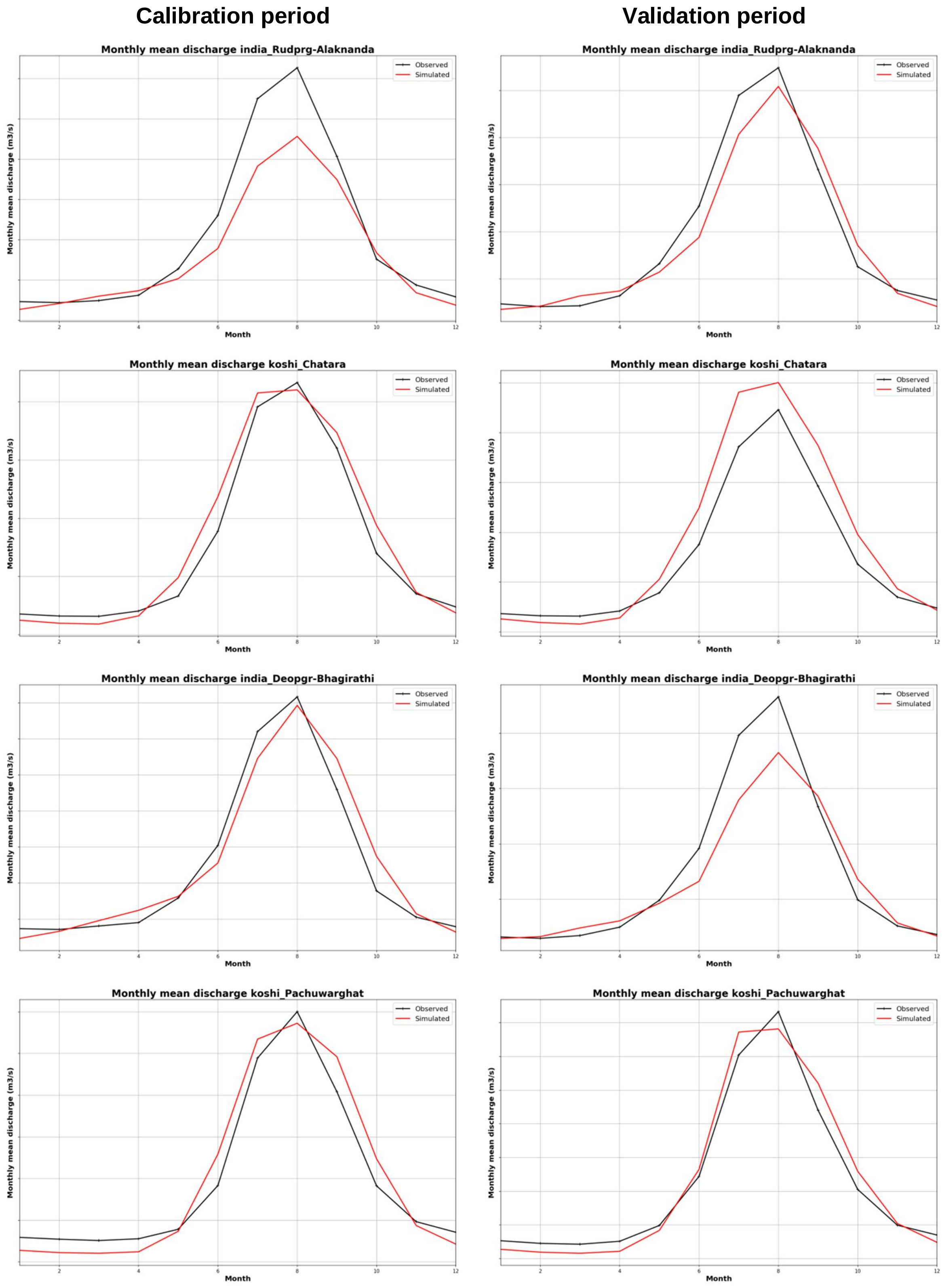

Figure 3.10: Comparison of mean monthly discharges for 4 locations for calibration (left) and validation period (right).

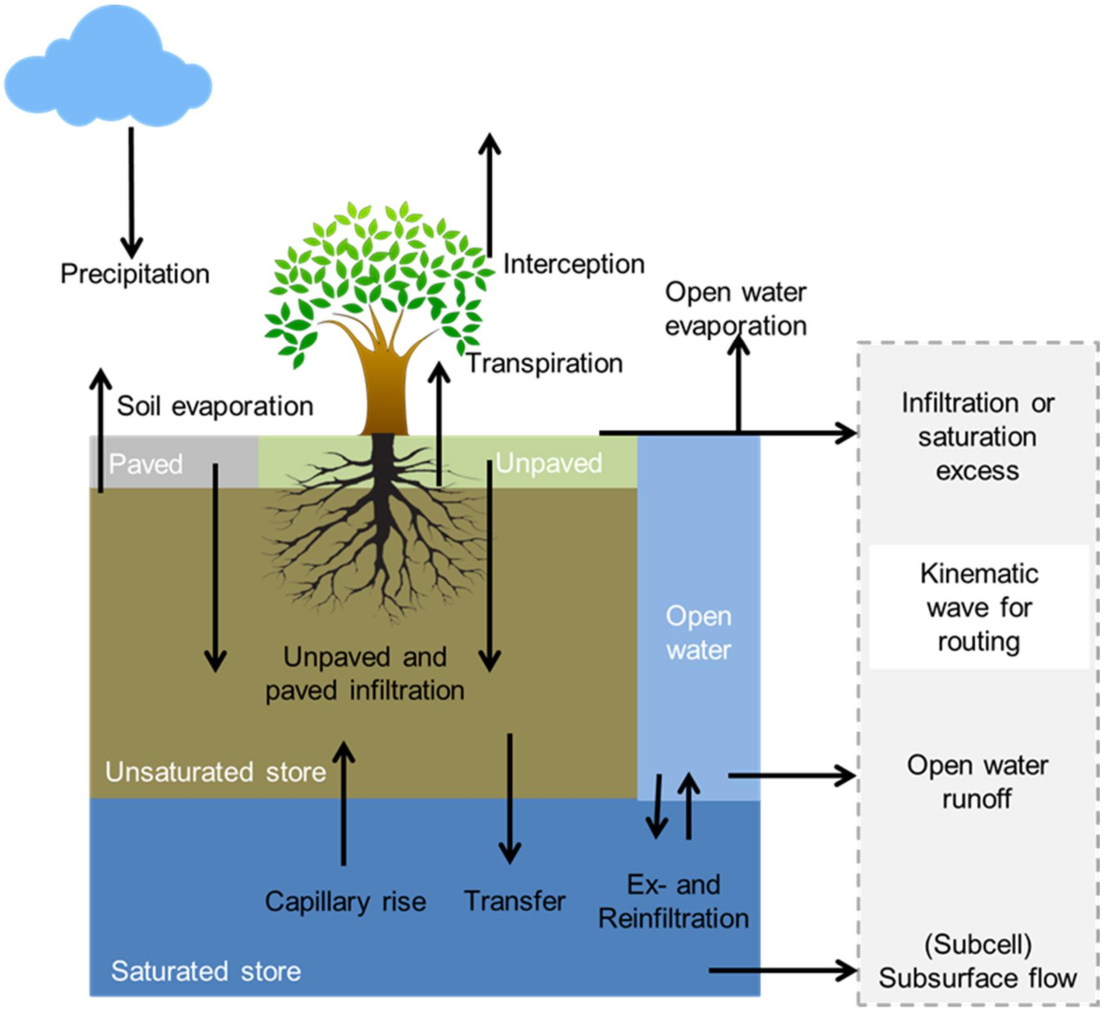

Figure 3.11: Schematic overview of the hydrological processes that are taken into account in the Wflow-SBM model.

The forcing of the model consists of time series of rainfall and potential evaporation. The first process, from top to bottom, is the interception process.

The interception process determines how much water is captured in the canopy and subsequently evaporates. Rainfall that evaporates from interception does not contribute to runoff. Only the stem flow and through fall from interception contribute to the runoff.

The interception model is based on the analytical Gash model (Gash, 1979). A schematic of this model is presented in Figure 3.12. The parameters in the Gash interception model depend mainly on the type of land-use. Therefore, the parameters related to this process can be linked to the land-use classes. For example, more rainfall is intercepted in forest areas than in areas with mainly grass lands. Rainfall can also be intercepted from paved areas. For these areas, mainly urban areas, rainfall that cannot infiltrate can either generate direct runoff or is evaporated.

The output of the interception module is input for the soil module. The input consists of the direct rainfall or direct through fall, the through fall from the canopy and the stem flow. The soil module determines how much water infiltrates into the soil and how much of the rainfall is generating direct runoff or saturation excess overland flow. The infiltration capacity is the main parameter that determines the process of infiltration and depends mainly on the land-use.

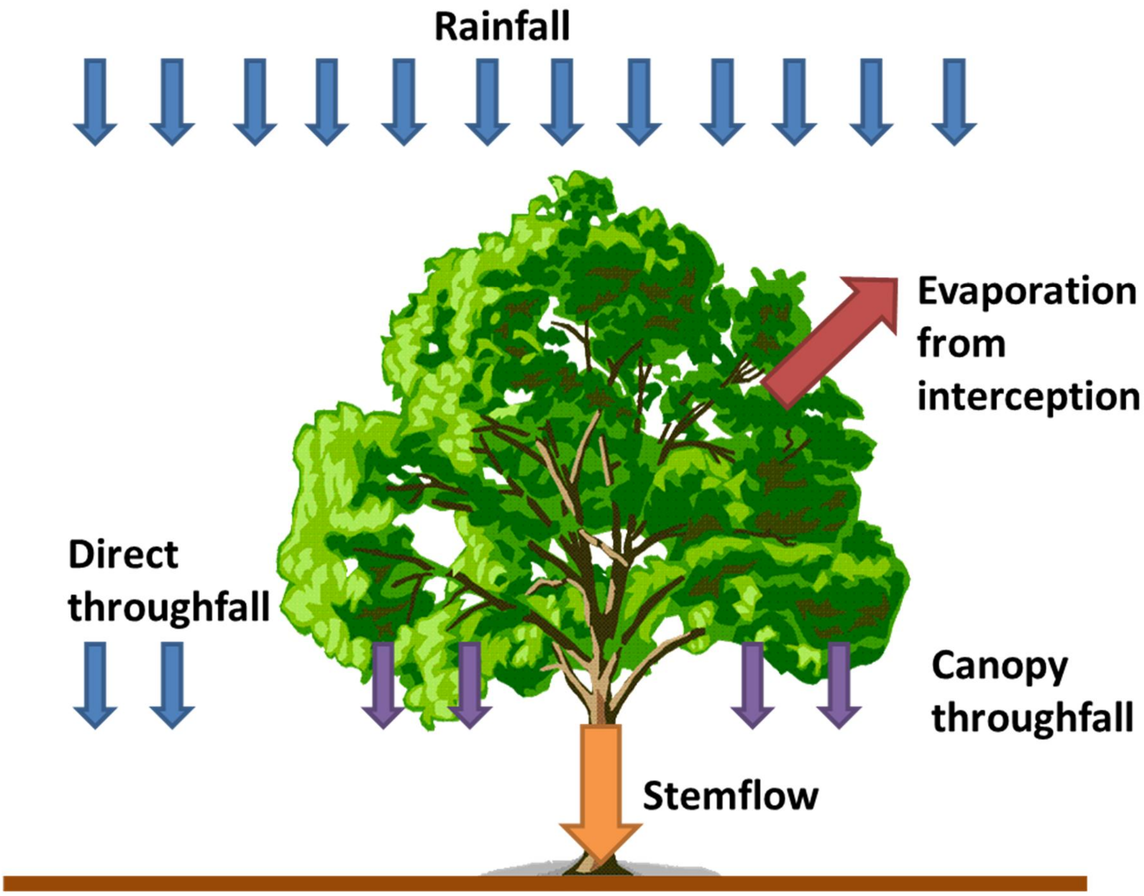

Figure 3.12 : Schematic overview of the Gash interception model.

The soil module consists mainly of two stores, the unsaturated store and the saturated store. The movement of the interface between the unsaturated part of the soil and the saturated part of the soil is calculated at each time step. The main parameters controlling the behavior of the soil module are the hydraulic conductivity, both vertically and horizontally, and the depth of the soil. Both are strongly dependent on soil type.

These processes are calculated for each grid cell in the model. The movement of the water from one cell to the other is determined from the elevation model and the derived drainage network. The drainage network is calculated from the elevation of each cell. It is assumed that water will flow towards the neighboring cell via the steepest path. The steepness of the path or the slope is determined by the height difference between the cells, and the horizontal distance between the cell centers. Figure 3.13 depicts the derivation of the drainage network.

The runoff that is generated in each cell, both direct runoff from the surface and subsurface flow, is routed through the model via the drainage network. For the routing, a kinematic wave module is used. The kinematic wave module is a simplification of the Staint-Venant equations, or shallow water equations. The main parameters of the kinematic wave module are the roughness parameter (Manning coefficient) and the slope. The Manning coefficient can be set differently for river cells and non-river cells which normally have a higher roughness value.

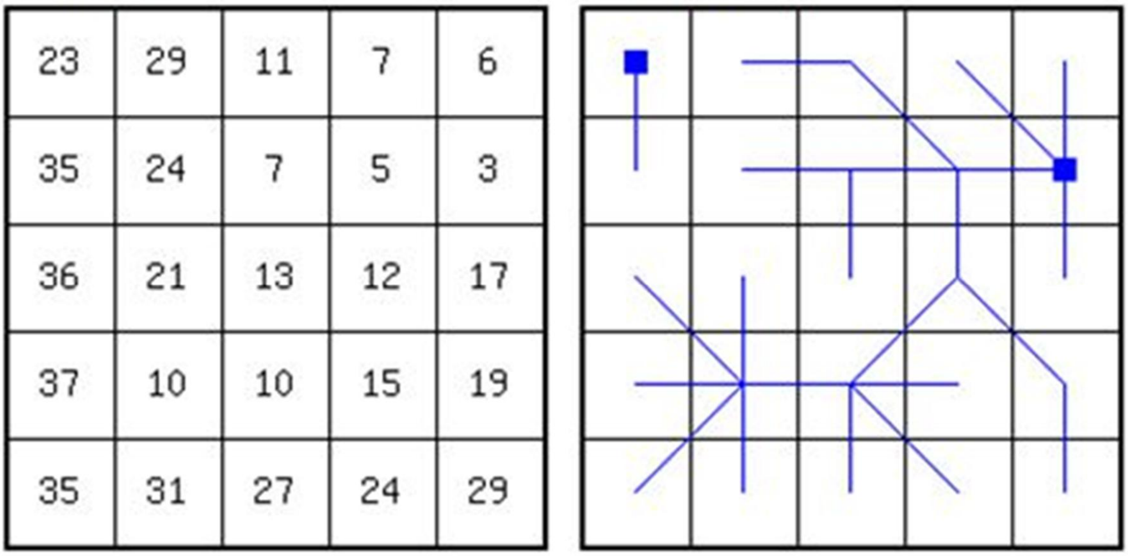

Figure 3.13 : Example of a drainage network (right panel) derived from the digital elevation model (left panel).

The output of the Wflow model consists of discharge maps for each grid cell and for each time step and maps showing groundwater recharge. Other outputs can also be generated easily, if deemed necessary. A complete list of possible model outputs can be found in the online documentation[1].

3.2.2 Set-up

Although only the lower basins are used in the modelling, the Wflow model has been setup for the complete Ganga basin.
The model covers the Ganga basin in India, Nepal and China to the boundary with Bangladesh and also includes the Hoogly branch that flows through the Indian state of West-Bengal to the Bay of Bengal. Focus is on the Indian part of the basin. The model is setup with a resolution of 1x1 km, resulting in approximately 1.8 million grid cells.

The parameters of the model are defined either in maps or in tables. Two examples of map defined parameters are shown in Figure 3.14, hydraulic conductivity, and Figure 3.15, infiltration capacity of the soil.

All parameters and their calibrated values can be found in Appendix B.

[1] http://Wflow.readthedocs.io/en/latest/Wflow_sbm.html#model-variables-stores-and-fluxes

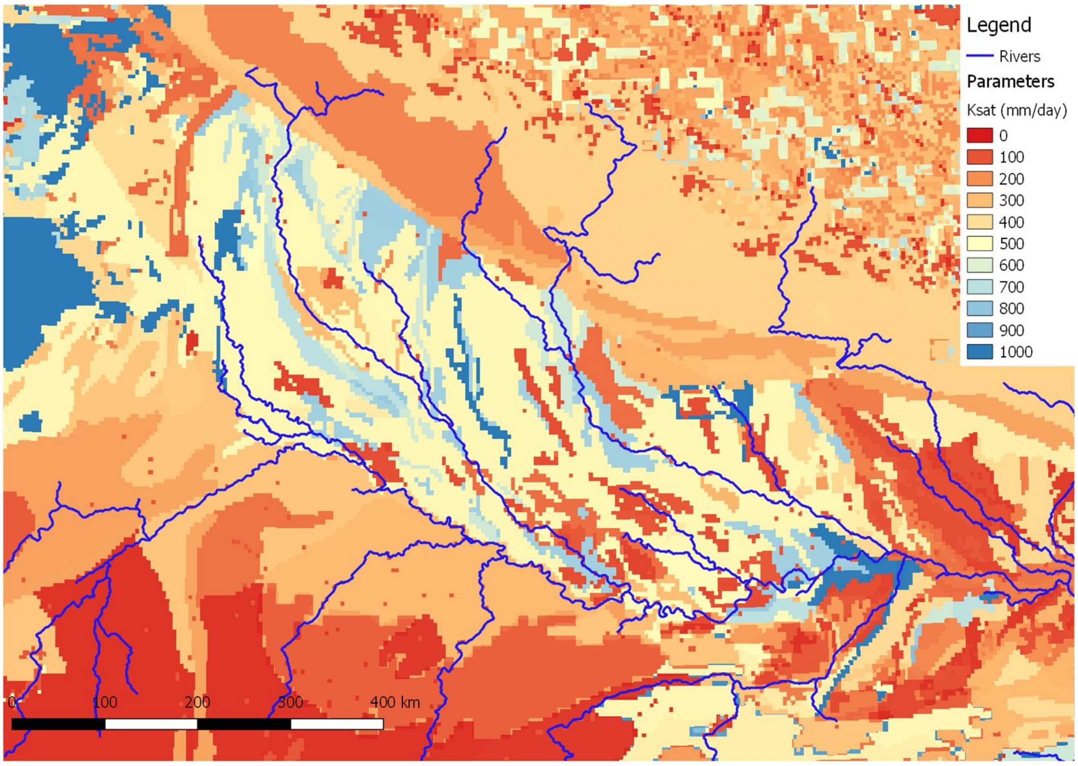

Figure 3.14: Map with the hydraulic conductivity values (K_{SAT} in mm/day) derived from the FAO soil map of the world.

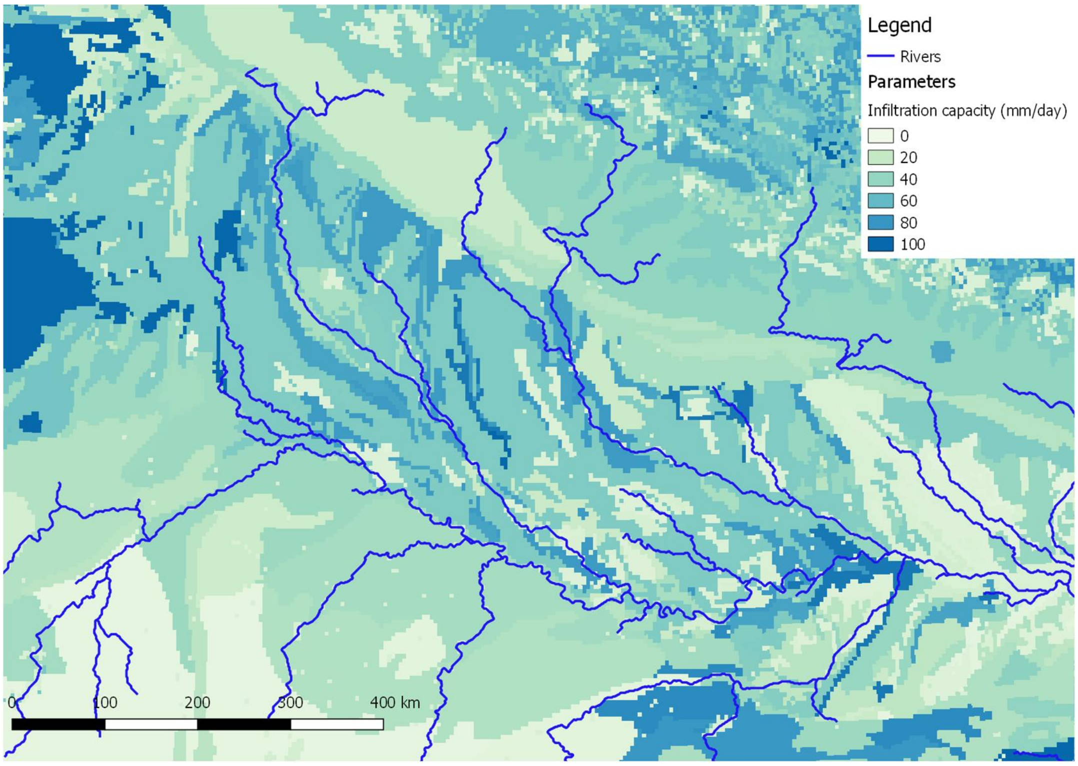

Figure 3.15: Map with the infiltration capacity of the soil (mm/day) derived from the FAO soil map of the world.

3.2.3 Input Data

The Wflow model needs static input maps as well as a series of input maps for meteorological forcing. The model input is briefly described in this section, and a more detailed description can be found in Appendix B.

Static Input

Elevation Data

The same Digital Elevation Model (DEM), based on the HydroSheds SRTM DEM (Lehner et al., 2006), as incorporated in the SPHY model, is applied and resampled to the model resolution, projection and extent. Based on the DEM, a local drain direction map is derived, which indicates the drainage direction of each grid cell. With this procedure, the stream network of the model is defined, which facilitates water routing from upstream to downstream. The full extent of the DEM is shown in Figure 3.16.

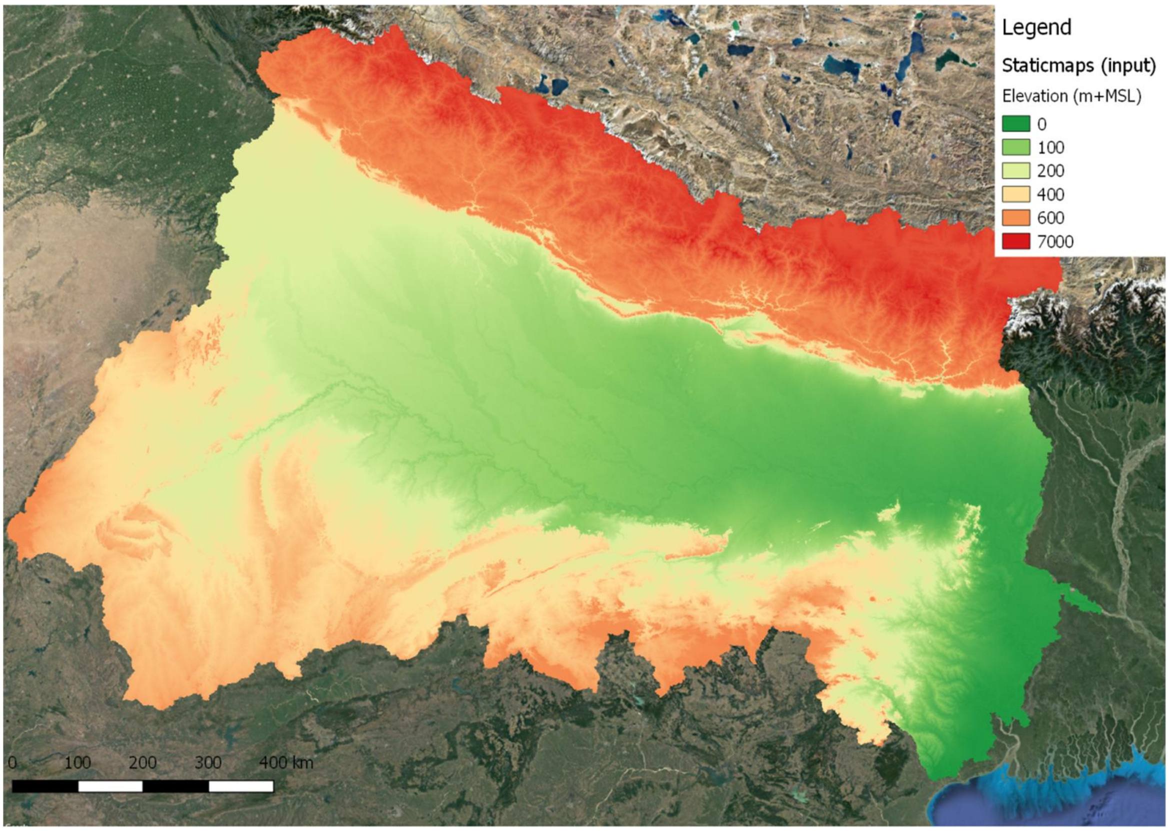

Figure 3.16: SRTM Digital Elevation Model (DEM) for the project area.

River Layer

To make sure that the derived drainage direction follows the actual rivers accurately, a shapefile of the river, based on Open Street Map, is used to force the drainage direction derivation algorithm. This is especially needed for the shallow parts of the basin, in which the digital elevation model is less accurate. The shape file, shown in Figure 3.17, is used to burn the river network into the DEM before determining the drainage direction map (LDD), thus overriding the drainage pattern derived from the DEM itself.

Land-use/Land-cover Data

The land-use or land-cover map is an important input map to the model. Many parameters in the model do depend on the land-use. For example, the rooting depth varies greatly for different types of vegetation, e.g. grass versus trees. Also, the Manning coefficient, which determines roughness, differs considerably between dense vegetation and urban areas.

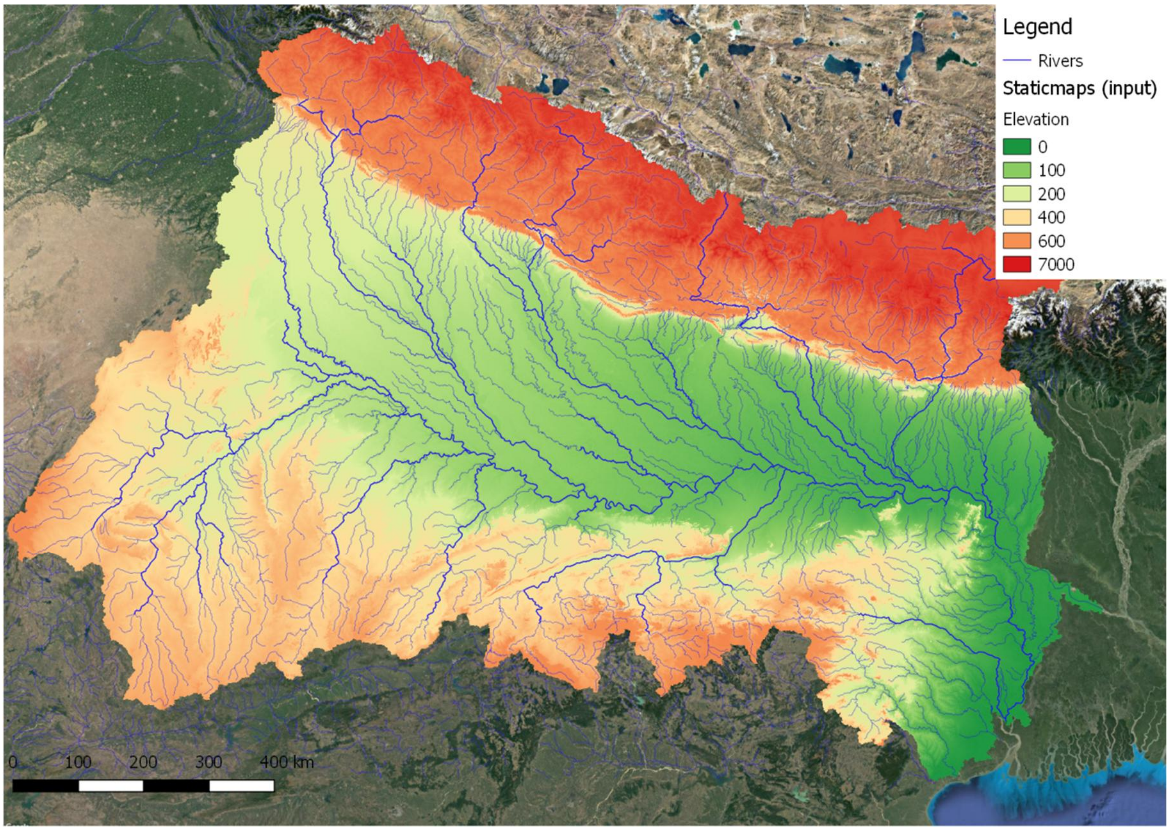

Figure 3.17: River layer from Open Street Map, used as input layer for the derivation of the model.

The land-use map from the Indian Institutes of Technology (IIT), based on data from the National Remote Sensing Centre (NRSC), is the basis for the Wflow land-use map. This map covers the Indian part of the basin, but excludes the Nepalese parts of the basin. Since the model needs a land-use map that covers the complete basin, the missing parts reflect data from the GlobCover map (Defourny et al., 2007). The GlobCover map, covering the complete globe, is resampled from 300x300 m to 1x1 km to fit the model requirements. Figure 3.18 shows the model's combined land-use map. Land-use classes are itemized in Table 3-2.

Table 3.2: Land-use classes in the combined Wflow model land-use map.

ID	Description	ID	Description
0	Water	9	Savannas
1	Evergreen Needle leaf Forest	10	Grasslands
2	Evergreen Broadleaf Forest	11	Permanent Wetland
3	Deciduous Needle leaf Forest	12	Croplands
4	Deciduous Broadleaf Forest	13	Urban and Built-Up
5	Mixed Forests	14	Cropland/Natural Vegetation Mosaic
6	Closed Shrublands	15	Snow and Ice
7	Open Shrublands	16	Barren or Sparsely Vegetated
8	Woody Savannas		

Soil Data

The soil map, containing information on the different soil types found in the Ganga basin, is an important map input to the model. As with the land-use map, many parameters depend strongly on the soil type. Examples are the saturated conductivity (K_{SAT}) and the infiltration capacity of the soil. The soil map in the Wflow model is adapted from the FAO soil map of the world, as seen in Figure 3.19. There are 12 classes defined for the Wflow model, as presented in Table 3.3.

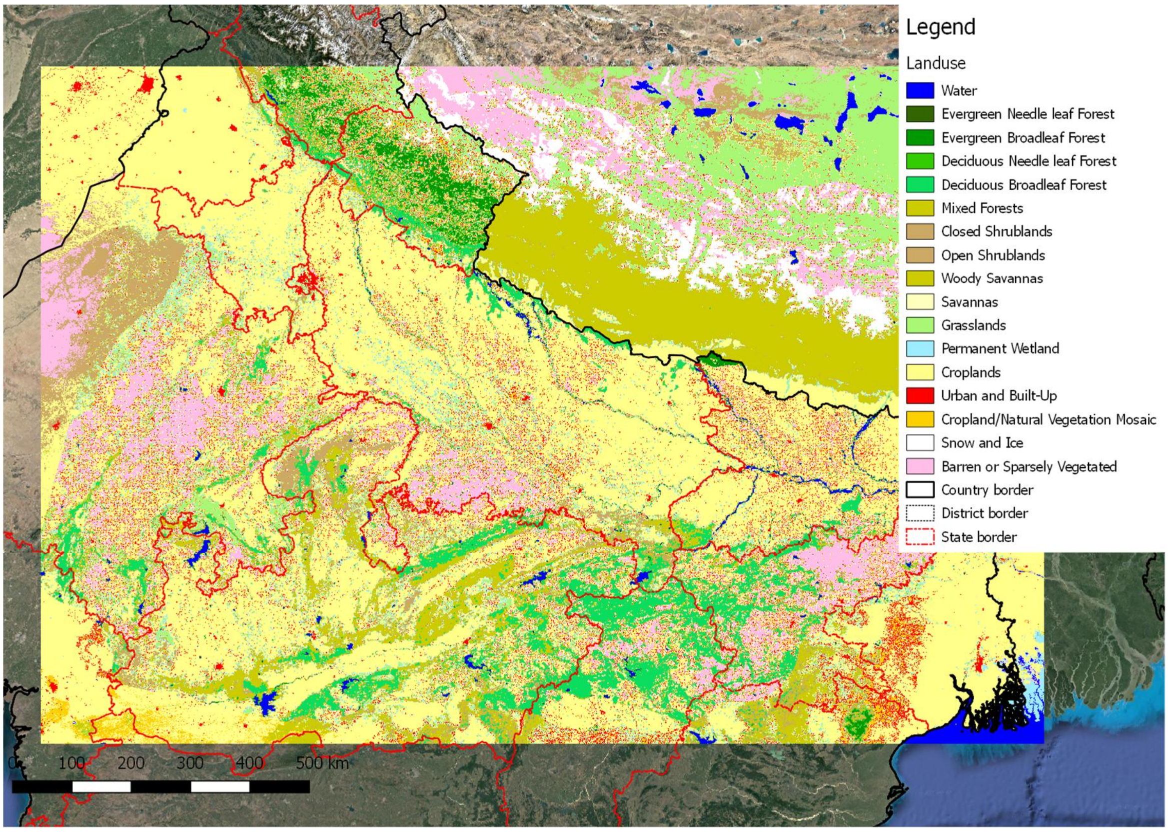

Figure 3.18: IIT land-use map, based on NRCS data.

Table 3.3: Classes in the Wflow soil map (based on FAO soil map).

ID	Description	ID	Description
1	clay(heavy)	7	sandy clay
2	silty clay	8	loam
3	clay (light)	9	sandy clay loam
4	clay loam	10	sandy loam
5	silt	11	loamy sand
6	silt loam	12	sand

Leaf Area Index

The Leaf Area Index (LAI) indicates the canopy density. The LAI changes over time with seasons, as shown in Figure 3.20. The density of the canopy has a direct relation with hydrological processes such as interception and through fall. To take into account the seasonal effect of the canopy density, the LAI is presented to the model as average values per month. Thus, 12 maps similar to the map in Figure 3.20 are input to the model. These maps represent the average variation of the canopy density over the year.

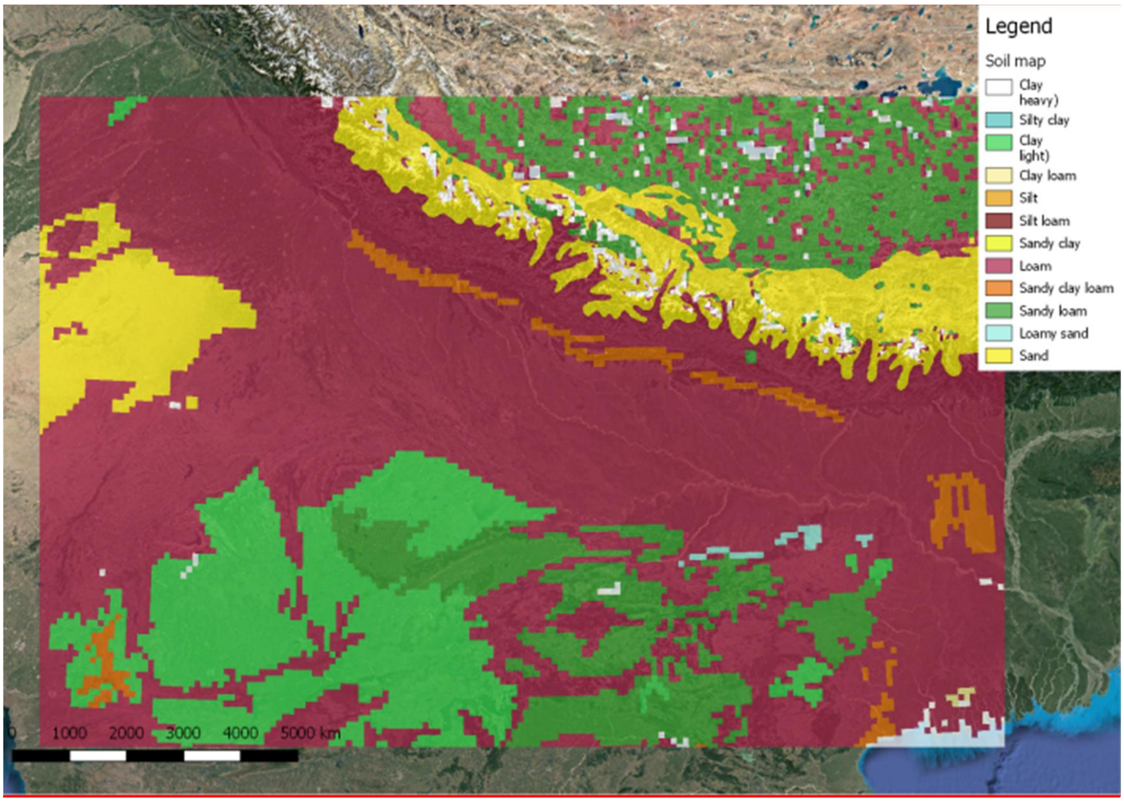

Figure 3.19: FAO soil map of the world, resampled to a limited number of separate classes.

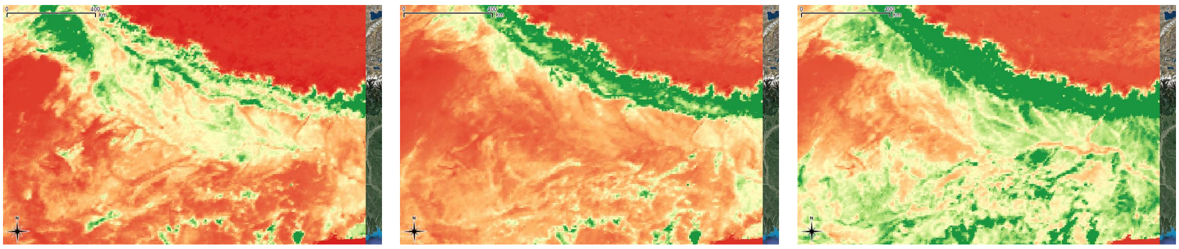

Figure 3.20: Leaf Area Index (LAI) for three months of the year. From left to right: February, June and September. A green color indicates a higher LAI value.

Meteorological forcing

The meteorological forcing in the Wflow model is entered as map series of daily grids of precipitation (mm/day), daily mean air temperature (°C) and daily potential evaporation (mm/day). After comparison of several forcing products (see Appendix B) the Wflow model uses forcing data from the following sources:

- Precipitation:
  - Inside India:
    - 1959–2012: IMD
    - 2013–2014: WFDEI
  - Outside India:
    - 1959–1978: EUWATCH
    - 1979–2014: WFDEI

- Evaporation and temperature (complete basin):
  - 1959–1978: EUWATCH
  - 1979–2014: WFDEI

The Wflow model incorporates the same input as the SPHY model. The merging of the datasets is accomplished within the GangaWIS. As an example, the result of the merging of WFDEI and IMD rainfall data is shown in Figure 3.21.

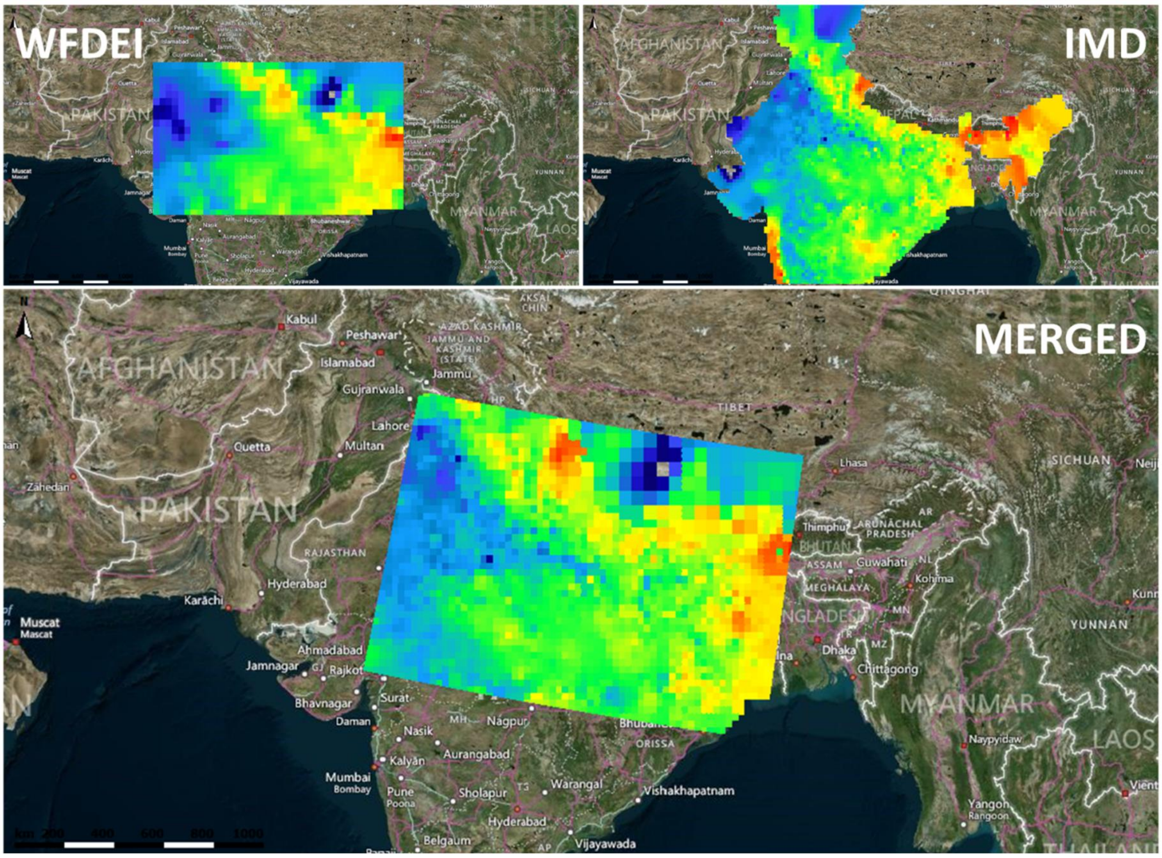

Figure 3.21 : Result of merging (bottom) of WFDEI (top left) and IMD (top right) rainfall data.

3.2.4 Link with Other Components of the Ganga River Basin Model

SPHY

The Wflow model simulates the rainfall-runoff process for the complete Ganga basin, including the Himalayan part of the basin. The SPHY model focusses on the Himalayan part of the basin and is specifically calibrated for the glacier and snow dominated parts of the basins. The Wflow model is calibrated more on the groundwater interaction in the non-Himalayan part of the basin, since this is a dominant process. In the Wflow model, the results calculated by the Wflow model are replaced by the discharges calculated by the SPHY model for selected rivers in the Himalayan part of the basin (see Section 3.1.4).

RIBASIM

The combination of the SPHY and Wflow models is used to calculate the inflow into the RIBASIM model. Together these models calculate the inflow into the upstream nodes of the RIBASIM schematization, representing the natural or undisturbed water availability. Wflow also calculates the inflow into intermediate points of the RIBASIM network that require flow input data, e.g. reservoir nodes, diversion nodes. The GangaWIS derives the flow time series for these locations from the gridded discharge time series that are stored in the database.

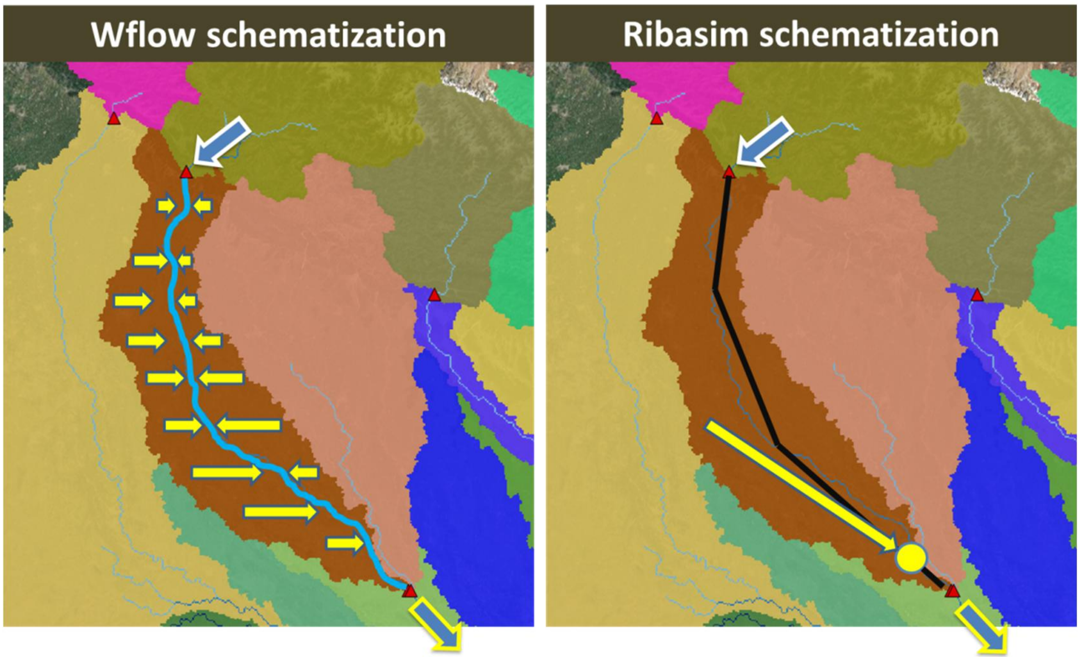

Figure 3.22: Calculated flows from the Wflow model for the connection with RIBASIM. The total flow at the outlet (yellow-blue arrow) is the calculated flow from the upstream catchment (blue-white arrow) plus the calculated flows in between the two outlet points (sum of yellow arrows). RIBASIM needs as input the value at the blue-white arrow and the sum of the yellow arrows (per subbasin).

RIBASIM routes the water through the river system. Therefore, RIBASIM only needs the flow from the hydrological model that comes into the system in between the nodes. This additional flow is calculated as the difference between the Wflow discharge at the downstream node and the sum of the Wflow calculated discharges from all upstream nodes, for each section of the river. This additional flow, averaged over a month, is used as input to the RIBASIM model. The coupling is schematized in Figure 3.22.

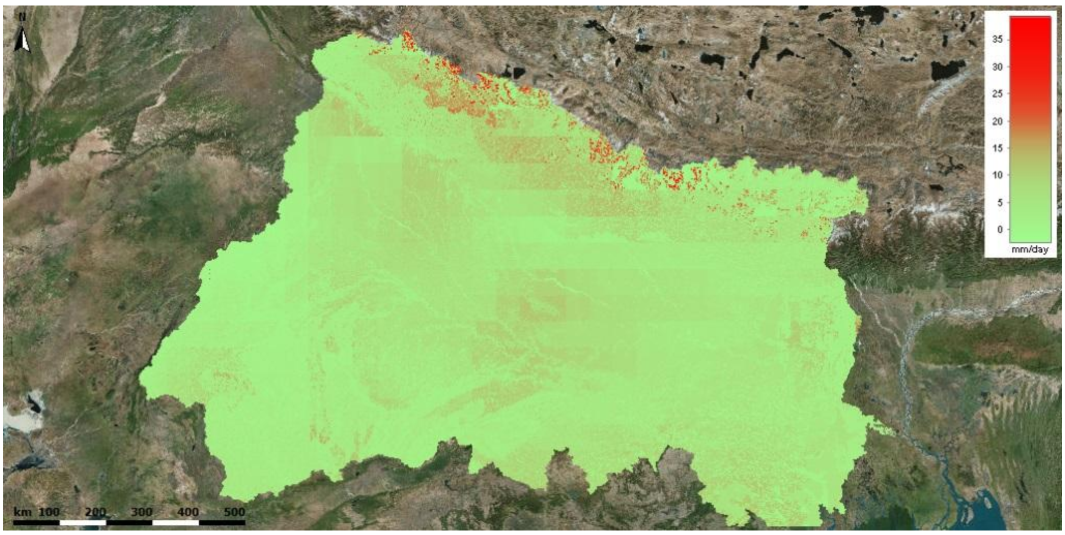

Figure 3.23 : Example recharge grid calculated by the Wflow model for the complete Ganga basin (mm/day).

iMOD
The Wflow model also calculates recharge to the saturated groundwater. For the areas that are not irrigated, this is the recharge that is used as boundary condition in the iMOD groundwater model. An example output of the model is shown in Figure 3.23.

3.2.5 Calibration and Validation Results

Because most available discharge observations were only available for locations within the RIBASIM model domain, the calibration and validation of the Wflow model has been a combined effort with the calibration of the RIBASIM model. Most of the discharge observations that were available at the time of the model calibration, i.e. before 31-1-2017, are influenced by diversions, storage and water usage. Since the Wflow model only simulates natural rainfall runoff processes, the effect of these alterations cannot be simulated using the Wflow model alone. The results of the combined calibration are shown in Chapter 5.

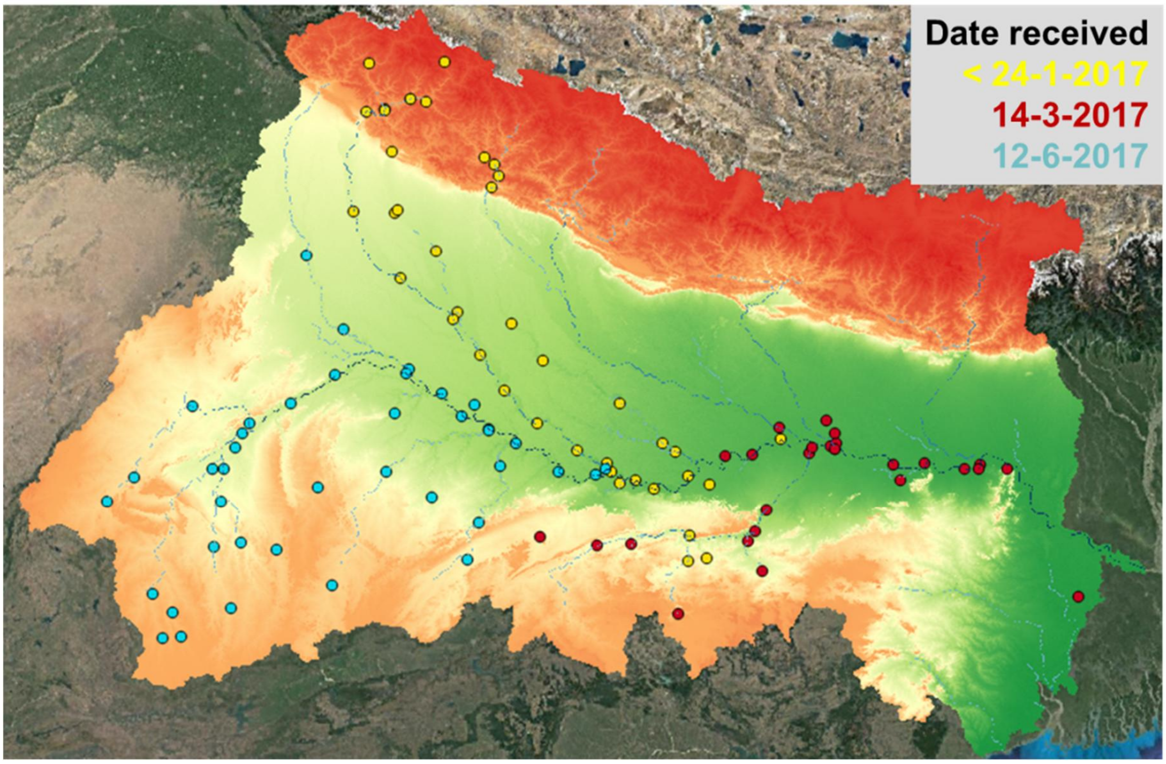

Figure 3.24: Available discharge observations and date of receiving the data from CWC.

Although the Wflow model was not used for the upstream, i.e. the Himalayan, part of the basin, it was useful to compare the model results with the results of the calibrated SPHY model to gauge the performance of the Wflow model. The results in Figure 3.24 show that there is a strong similarity between the model results of Wflow and SPHY, suggesting that the Wflow model is sufficiently well calibrated for the upper parts of the basin.

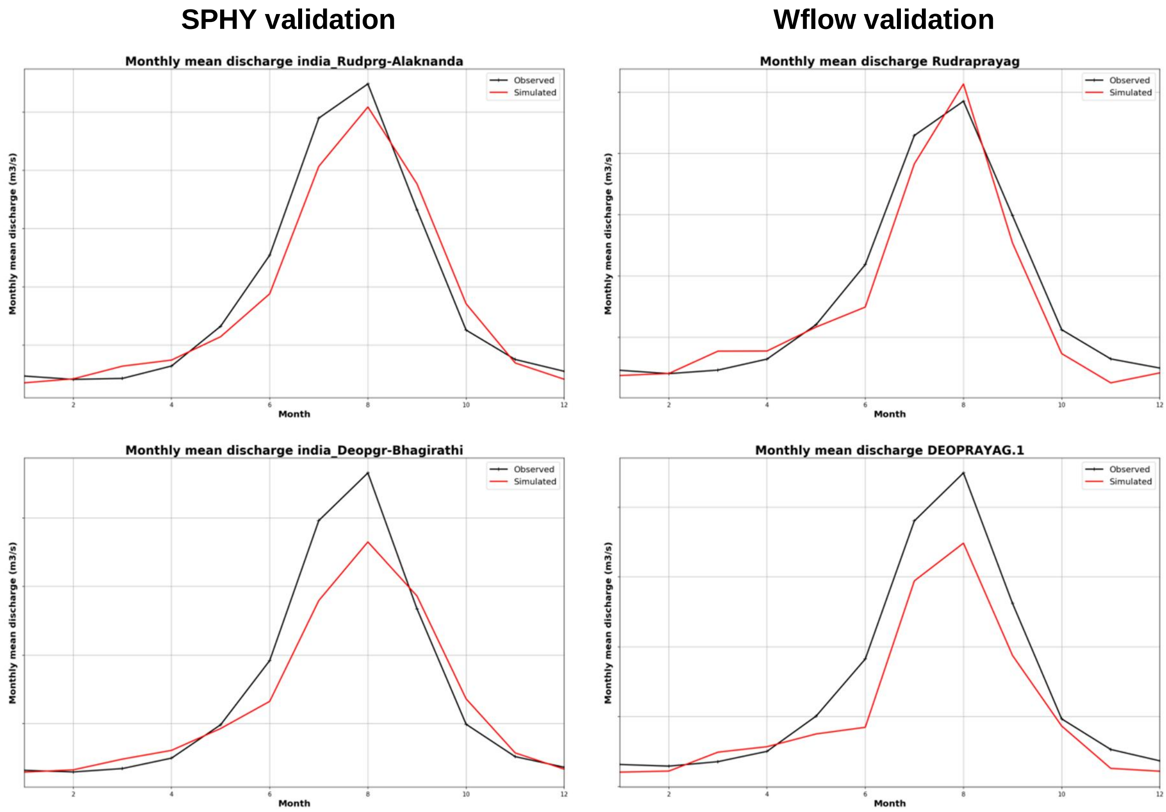

Figure 3-24: Results of the Wflow and SPHY models simulations compared with observed discharges.

4 Geohydrological Model MODFLOW / iMOD

4.1 Concepts

The groundwater flow and the surface water/groundwater interaction are modelled with MODFLOW. This software, developed by the U.S. Geological Survey, is an international standard for simulating and predicting groundwater conditions (Harbaugh 2005). It is a modular finite-difference flow model that solves the groundwater flow equation for both static and dynamic situations. The processes to be modelled can vary over long or short time frames. Time steps can be expressed as days, construction dewatering, months, seasonal influence, or years, climate change. The time step for the Ganga basin is one month, detailed enough to model the seasonal dynamics and in line with the RIBASIM model. MODFLOW is developed to simulate the flow of groundwater through granular aquifers. The prediction of groundwater conditions in karst or hard rock areas needs another approach.

Because MODFLOW is a 3 D modular finite-difference flow model (see Figure 4.1), all input and output data is traditionally specified on a cell based scale. In the present Ganga model, the cells are regular squares. At each cell a boundary condition, inactive, constant or variable, is specified. MODFLOW computes the hydraulic head at each cell node and the flow between each two cell nodes (see Figure 4.1).

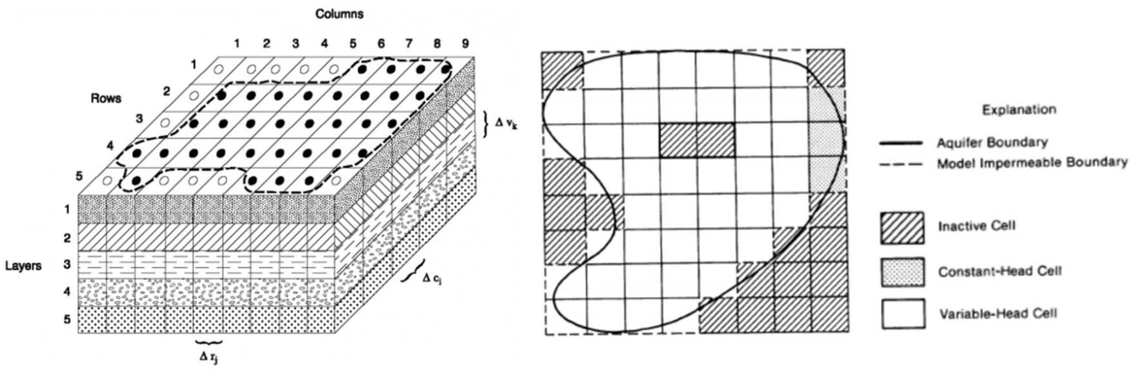

Figure 4.1: Example of a schematic set up of a MODFLOW/iMOD model left in 3D and right as a top view.

MODFLOW consists of a large number of modules that can be turned on and off depending on the requirement of the particular application. The modules used in the present application are discussed in the following paragraphs.

Geohydrological Processes

The cross-section in Figure 4.2 shows schematically the hydrological processes/stresses accounted for in a MODFLOW model. The aquifers and aquitards are represented by hydraulic parameters, thickness, permeability, resistance) for each cell.

Figure 4.3 represents the possible hydrological processes/stresses between surface water and groundwater that can be included in boundary conditions in a MODFLOW model. These boundary conditions can account for the specified stresses, e.g. heads, water fluxes, or linear combinations of both, in the river (RIV) module. The river (RIV) module has the capability to simulate the exchange of water between a stream or river and an aquifer in both directions.

The drain module (DRN) differs from the RIV module in that it only supports drainage to the system and does not allow infiltration to the groundwater system.

In the Ganga model the DRN module is used to represent the regional drainage, e.g. streams, valleys, or drainage pipes, that is lumped over a cell area of 1 square kilometer. Because local data are limited, the parameter values in the Ganga model are based on expert knowledge.

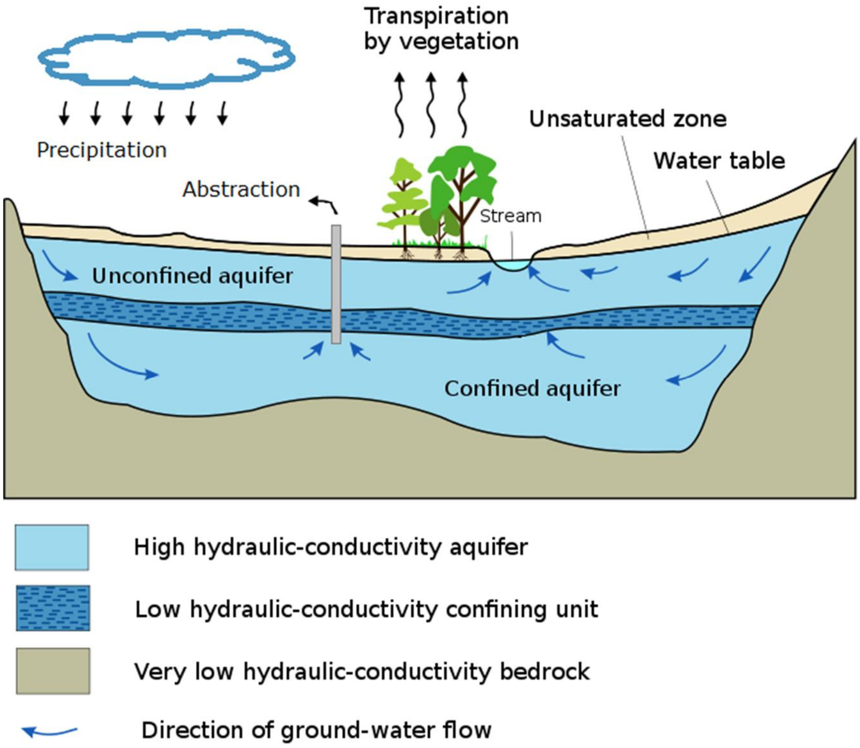

Figure 4.2: Schematic overview of the geohydrological processes accounted for in the MODFLOW iMOD model

Groundwater abstraction for domestic, industrial and agriculture use is modelled by using the WELL module. Model cells can contain one or more multiple abstractions in one or more of the distinguished layers. Net recharge from the unsaturated zone to the saturated groundwater is modelled by using the recharge module (RCH).

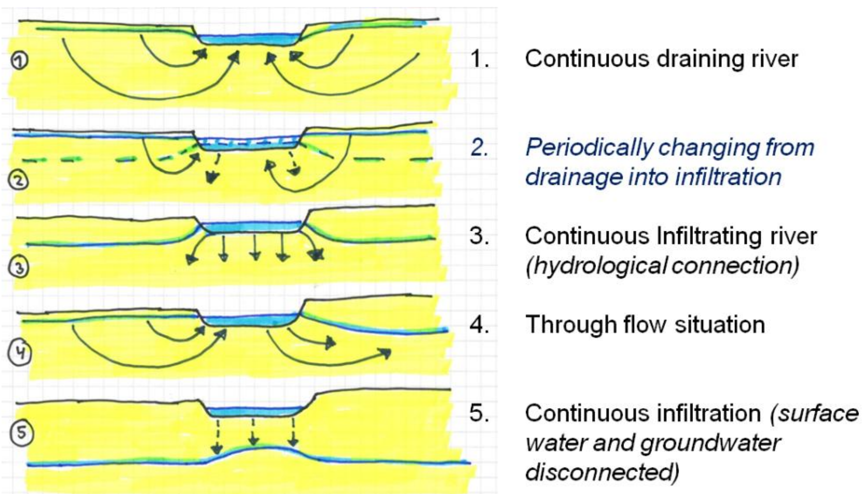

Figure 4.3: Different types of interaction between river water and groundwater possible in the MODFLOW model.

Irrigation in the Ganga basin is modelled using a combination of groundwater abstraction (WELL module) and infiltration/recharge to groundwater (Recharge module) for which parameter values are supplied by the RIBASIM model (see Chapter 5). Groundwater abstractions by industry and public water supply are modelled with the WELL module.

In the Ganga basin model, the surface water/groundwater interaction is modelled along the Ganga river itself and its main tributaries. The type of surface water/groundwater interaction can change in place and in time along the river in the different boundary conditions as illustrated in Figure 4.3.

iMOD
iMOD is used to visualize data and support fast computation. iMOD is an easy to use Graphical User Interface combined with an accelerated Deltares-version of the MODFLOW computation-kernel with fast, flexible and consistent subdomain modelling techniques (Vermeulen 2017). iMOD facilitates very large, high resolution MODFLOW groundwater modelling and also geo-editing of the subsurface. In addition to the USGS version of MODFLOW, iMOD facilitates more detailed simulation of the surface water system compared to the RIV package with the ISG package. The ISG package applies vectors and time series of each surface water segment and stores information on stages and bottom heights to describe the river. The Ganga river and its main tributaries are represented in the groundwater model using ISG.

Groundwater quality is an important issue in some parts of the Ganga Basin, especially where water use is limited by high concentrations of arsenic and fluorine. Groundwater quality is not included in the model, since the dynamics over the planning horizon up to 2040 are very limited and since climate change, socio-economic developments and measures will have very limited impact on the state of the groundwater quality.

4.2 Link with Other Components of the Ganga River Basin Model

As indicated in Figure 4.4, the groundwater model iMOD is connected to the surface hydrology model Wflow and the water resources model RIBASIM. The input maps for iMOD are dynamic modelling results calculated by Wflow and RIBASIM. The Wflow model calculates recharge to the saturated groundwater for each model cell on a daily basis for the non-irrigated part of the model area.

In addition, RIBASIM calculates recharge to the groundwater on a monthly basis for separate components:

- Recharge of groundwater from lumped irrigation areas;
- Recharge of groundwater from lumped public water supply.

For the entire model area, the Wflow and RIBASIM contributions are merged on cell basis into one raster representing monthly recharge flux (mm/day) for the iMOD groundwater model.

RIBASIM also calculates the amount of abstraction of groundwater used for irrigation, public water supply and industry on a monthly base for different zones. For all zones in the model, including irrigation and public water supply, the dynamic flux for groundwater abstraction (m^3/sec) is provided to iMOD and used as boundary condition for the WELL module in the iMOD groundwater model.

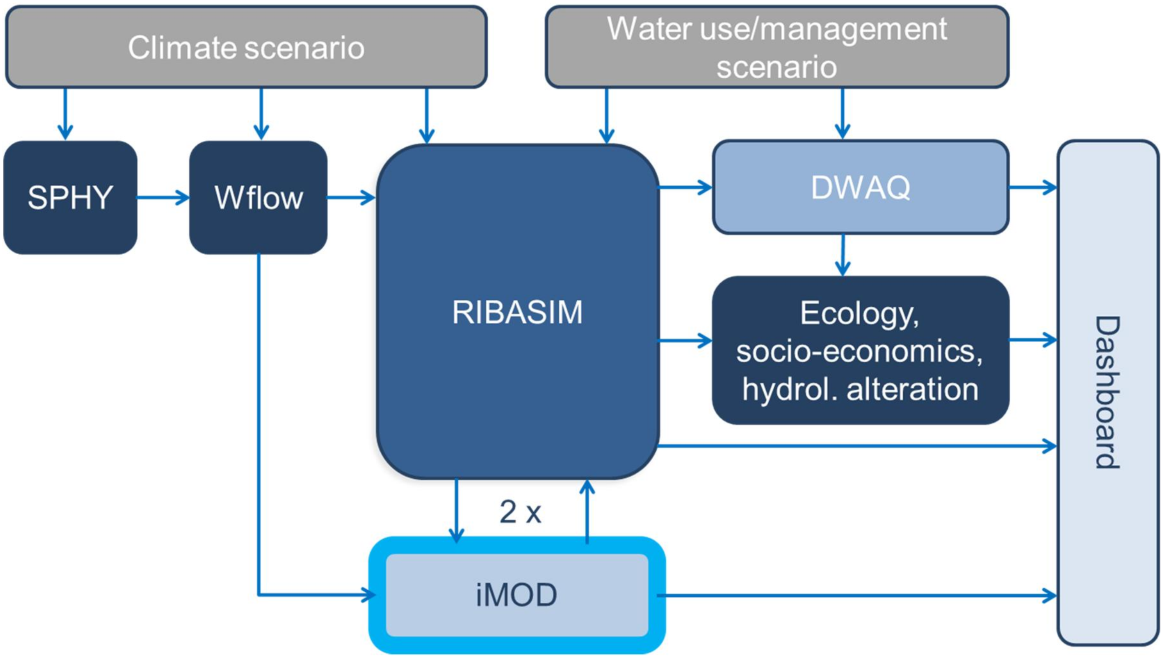

Figure 4.4: The position of iMOD in the workflow for the Ganga river basin model

The RIBASIM model determines the amount of surface water flux available in the main rivers (m^3/sec) on average per month. These time series are provided to iMOD, where these river fluxes are translated to the water level in the river. The gradient between the river level and the groundwater level will cause a flow from or a flow to the river. iMOD collects these flows and redirects them to the RIBASIM model as a correction on the preliminary fluxes.

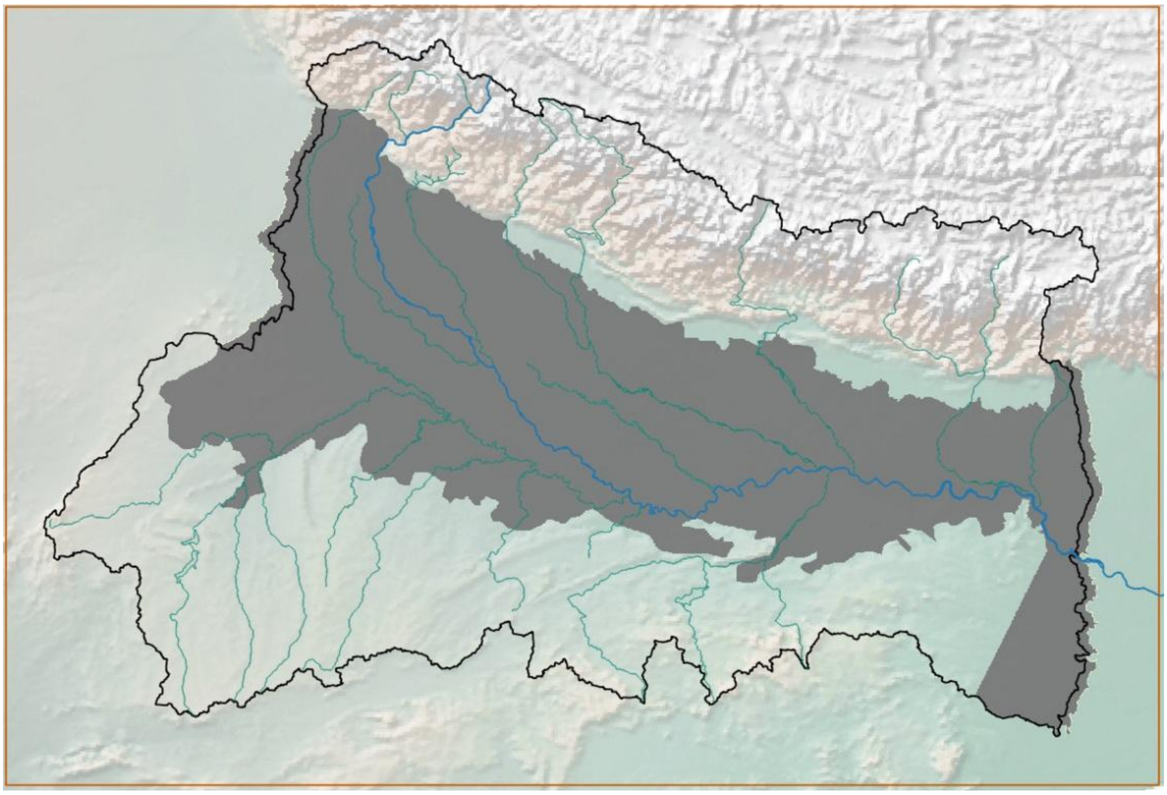

Figure 4.5: Coverage area of the groundwater model (grey) within the Ganga basin (black polygon)

4.3 Model Set-up

The area coverage of the Ganga river basin model is presented in Figure 4.5. The project window (model area, 1660 km x 1120 km) is shared with the models SPHY, Wflow and RIBASIM. The groundwater model covers the alluvial part of the Ganga basin, within a window of 1330 km by 900 km and 'active' cells in an area of 450.000 km^2, 25 percent of the project window. It was agreed to exclude the hard rock areas because the characteristics of hard-rock areas are not suitable for regional modelling and the contribution of groundwater in the hard rock areas is relatively minor. As mentioned before, the Ganga groundwater model consists of a regular mesh at 1 km by 1 km and calculates on monthly step basis. The interaction with RIBASIM is applied for cells that are active in this interaction.

4.4 Input Data

The input data consists of static maps as well as dynamic maps. A detailed description of the input data is provided in Appendix C.

Static Input

The project DEM (Digital Elevation Map) was described in Section 3.1.3. The aquifer system is described by maps of the top level and bottom level of the first 3 aquifers. These maps are created based on existing geological cross-sections, fence diagrams, and MAP files (MapInfo's vector data format) describing the thickness of layer from the Central Ground Water Board (CGWB). The value of the aquifer thickness follows from the top and bottom of the aquifer in echo cell.

The other aquifer parameters, e.g. permeability and storage coefficient, are provided by the CGWB based modelling studies by the Indian Institutes of Technology (IIT, 2014). The horizontal permeability is a spatial distributed raster; the vertical permeability is the result of the multiplication of the horizontal *permeability* and a factor for the vertical *anisotropy*. Spatial static input also includes the description of the boundary conditions of each cell, whether active, inactive, or fixed, and the start conditions given by the groundwater head.

Dynamic Input

In the integrated river basin model, RIBASIM and Wflow calculate the results that determine the dynamic, monthly, input maps for the groundwater model.

The input of stresses by regional recharge and groundwater abstraction consists of lumped data provided by RIBASIM. Figure 5.4 and Table 5.1 show the 41 irrigation areas and describe the 54 domestic water supply areas. The MODFLOW input data is lumped while for each irrigation area RIBASIM calculates one time series for both the fluxes for groundwater abstraction and leakage to the groundwater.

In the preprocessing of iMOD the option to redistribute abstractions within an area is employed. In the Ganga mode, the agricultural abstractions are redistributed within the irrigation area over cells that have groundwater fed agriculture (source: Global Irrigated Area Mapping 500 areas).

4.5 Calibration and Validation Results

This paragraph describes an analysis of behavior of the groundwater model and the calibration and validation.

The calibration and validation of the iMOD model has been an effort in combination with the Wflow and RIBASIM models. The combined river basin model was run over a 15-year period

2000–2014. The calibration of the iMOD model is based on a shorter period 2005–2016 for which time series of groundwater heads are available.

4.5.1 Selection of Groundwater Time Series for Calibration

The model is calibrated on a selection of the time series of groundwater heads that have been provided by the CGWB. Figure 4.6 shows that the 9000 monitoring wells are well distributed over the Ganga basin with data concentrations in West Bengal, Delhi and Haryana. The statistics of all data (Table 4.1) show that 13 percent of the time series covers only one year. At 50 percent of the locations, a maximum of 21 observations is available in the time series.

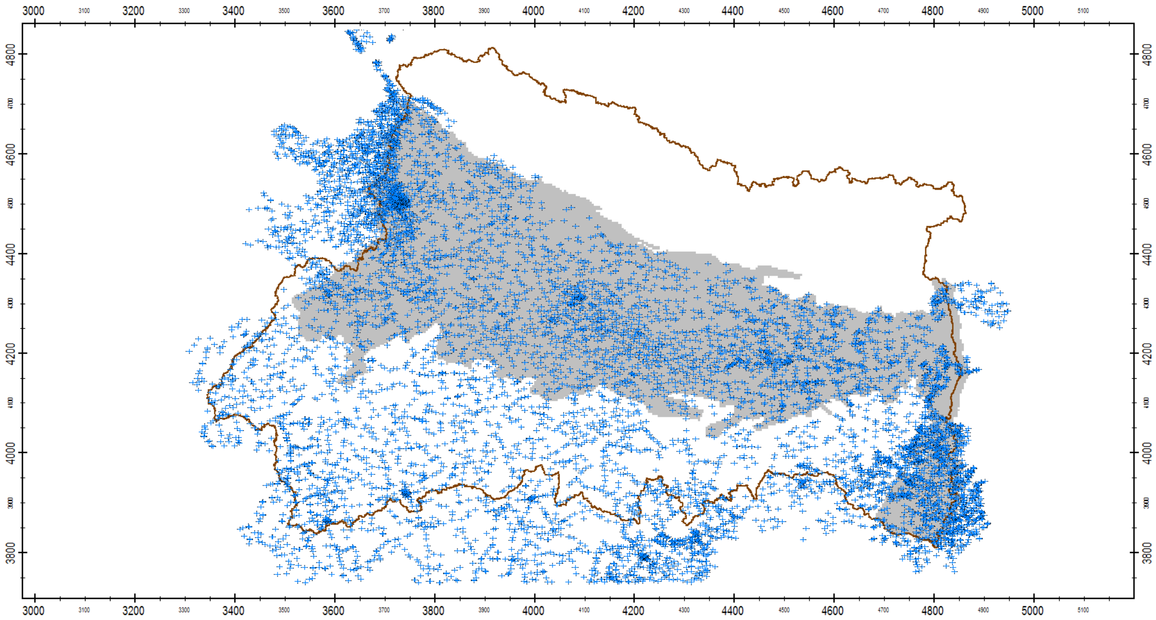

Figure 4.6: Monitoring locations within the Indian States covering the Ganga basin (source: CGWB)

Table 4.1: Statistics of the available time series for the period 2005–2016

Statistics	Locations	Perc.	Locations with.....
Total number	8998		
- Monitoring period	1211	13%	Monitoring period less than 1 year
	7787	87%	Monitoring period more than 1 year
	5147	57%	Monitoring period > 5 year
	2952	33%	Monitoring period 11 year
- Monitoring frequency	2672	30%	less than 10 registered measurements
	4500	50%	more than 21 registered measurements
	2250	25%	more than 41 registered measurements
	740	8%	More than 55 measurements, an average of 5 measurements a year
- Monitoring dynamics	4500	50%	more than 6 m difference between minimum and maximum value
	900	10%	more than 13.8 m difference between minimum and maximum value

Selected time series should be reliable and representative. Three criteria for selection of well observation data are identified: a) the time period covered by a series, b) the number of observations in a series and c) the location of the monitoring well.

Approximately 54 percent of the available time series are located outside the active groundwater model area, the alluvial part of the Ganga basin (grey zone in Figure 4.6). These are removed from the selection resulting in a data set of 4137 time series of groundwater heads. Time series must cover at least a period of 9 years of measurements and during that period an average of 2 monitoring moments each year is required, a minimum of 18 registrations. The resulting dataset contains 1839 observations locations within the model area. For analysis purposes the data set is split randomly into two equal sets of observation locations; one for calibration (939 locations) and one for validation (900 locations).

4.5.2 The Calibration Approach

The calibration process of the Ganga model is used to understand the behavior of the groundwater system and leads to a more reliable model.
Spatial analysis of deviations between calculated and observed groundwater heads forms the basis of the analysis and identifies zones that are sufficiently represented by the model and zones that need improvement.

Because the groundwater model is part of the coupled river basin model and is simplified at a regional scale based on lumped input provided by RIBASIM, calibration and improvement of the model is done manually and step by step. An automatic parameter optimization step with PEST can be a part of calibration process as a final step in order to get an impression of the model sensitivity to variations in parameter values.

In a manual calibration process as performed here, there is the temptation to give more weight to the measurements in favor of the model parameters by the assumption that measurements always represent the reality. This choice can lead to a situation in which the model parameters are unrealistically adapted over and over again forcing the model results to fit the observations. However, individual time series might not be representative for the model cell in which they are located. Deviations can have different known causes: a) a point measurement may deviate significantly from the average value in a whole cell, similar to rainfall point measurements for areal rainfall, b) the local surface level may not be measured properly resulting in shift in the head above sea level, c) the monitoring is located near a stream, an abstraction well that is averaged out by the cell size of 1 km^2, or is located near a recharge area, e.g. irrigation field, leaking sewer system or water distribution system, that is not locally present in the model. In this calibration the model parameters are set within a realistic range.

4.5.3 Adaptations in the Groundwater Model in the First Steps of the Calibration

In the first steps of the manual calibration, the following improvements to the primary model have been implemented:

- The capacity of the regional drainage system has been increased to prevent groundwater to exceed the surface level;
- The recharge to groundwater has been increased by adaptation of the leakage from irrigation canals in several locations where an unrealistic drop of the groundwater head was calculated;
- A large groundwater recharge zone in the foot hills of the Himalayas, the Bhabhar zone or Kandi belt, has been added as reported in previous studies by the CGWB.

After these adaptations, the initial groundwater model was finished and is further calibrated as will be described in the following paragraph.

4.5.4 Analysis and Evaluation of the Groundwater Model

Analysis of the spatial distribution of heads

Figure 4.7 shows the spatial distribution of the difference between observed and calculated heads for the initial model. In the main area of the groundwater model the head deviations are both positive and negative. In a zone in the utmost southeast, observed values are lower than calculated and in a zone in the center of the basin the observed values are higher than modelled.

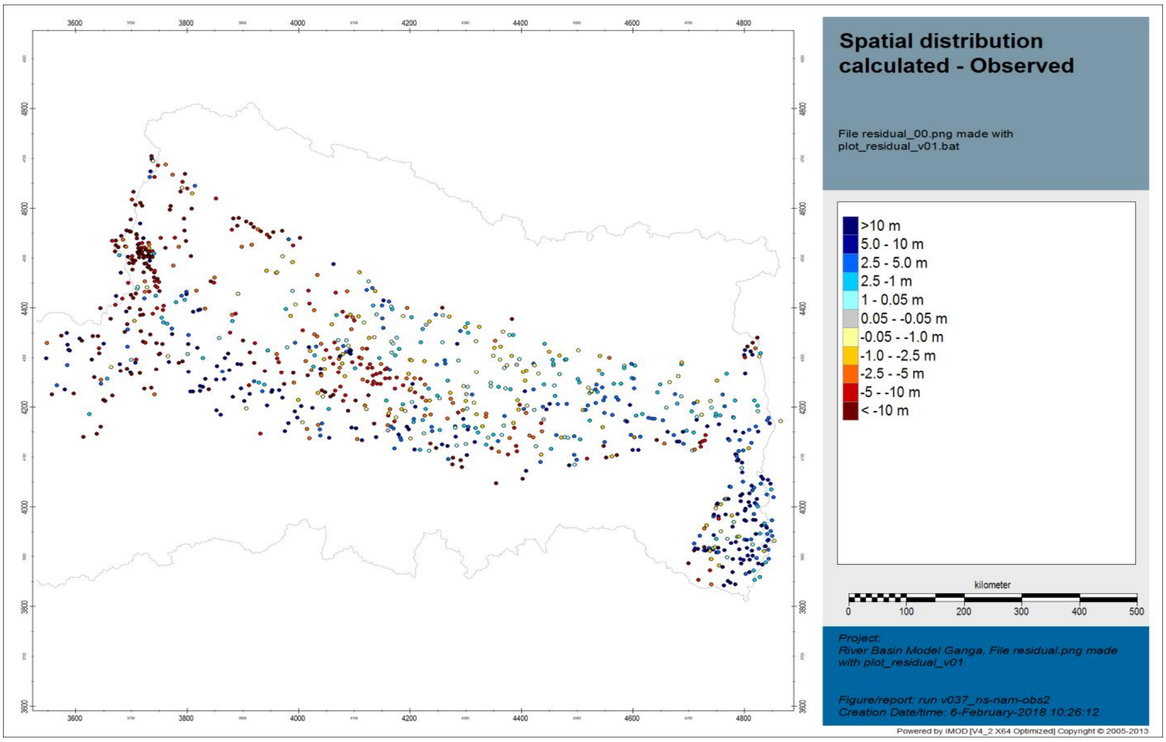

Figure 4.7: Spatial distribution of difference between calculated and measured heads (transient).

Analysis of the results in Figure 4.7 has led to the following conclusions:

- The average difference between the observed and calculated values is 4.49 m. The shape of the histogram indicates that the average value may be strongly influenced by the extreme negative values in the left part of the histogram, which also show up in the upper left part of the scatterplot. The histogram shows a skewness to the left with a median value of -0.96 m;
- These extreme negative values in the left part of the histogram, where values larger than 500 meters are found, appear to be located on the hillsides of the Himalayas or the hard rock area in the south with a high gradient in the surface levels. The observed heads are most likely related to local high surface levels, while the model uses much lower average surface levels in the cells. Therefore, these extreme values are most likely caused by scaling issues of the surface level and are therefore removed from the data set. After this correction, removing 2.5 percent of the extreme values from the histogram, the average difference reduces to -1.88 meters;
- At about 10 percent of the locations, the modelled head is 8.5 meters or more below the observed head. Figure 4.7 shows a clustering of these values around Delhi. Too low computed heads are most likely caused by a too small infiltration rate at the top of the model. In reality, probably less water is abstracted from the groundwater system or, conversely, more water might be infiltrated during monsoon rains or leakage from the sewer or drinking water system;

- At 10 percent of the locations, the modelled head is 8.3 meters or more above the observed head. These locations are randomly spread over the area, so from the spatial distribution no specific cause can be indicated. In general, these situations can occur when a monitoring location is strongly influenced as described in Section 4.5.2.

Figure 4.8 shows the histogram of the differences between calculated and observed heads as well as the scatterplot of both heads.

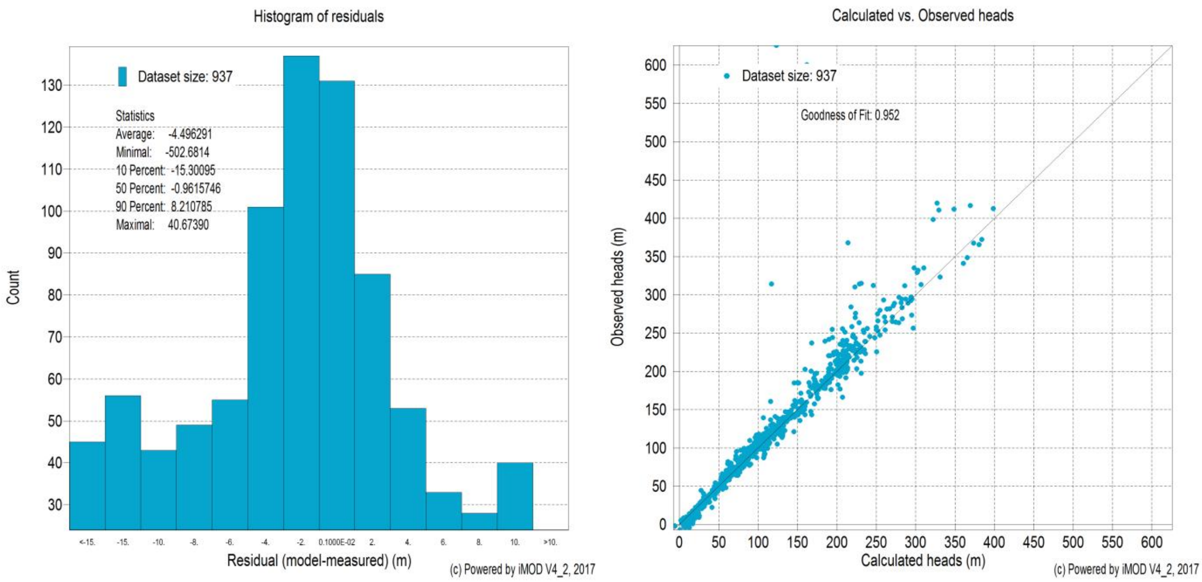

Figure 4.8: Histogram and scatterplot of differences between calculated and measured heads (transient).

These analyses have led to adaptations to the model. The recharge in the Delhi area has been increased by changes in the water distribution in RIBASIM. In the irrigation areas around Delhi, the abstraction was reduced.

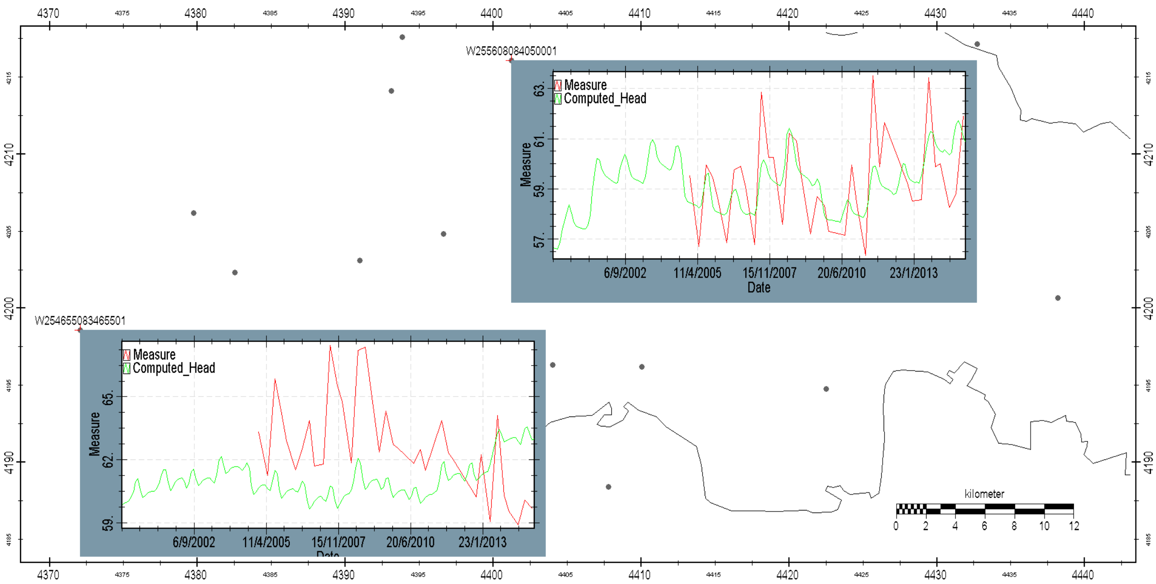

Figure 4.9: Two examples of the differences in dynamics between the observed (red) and modelled (green) time series

Analysis of the Temporary Variation of Heads
The behavior of the groundwater system is also analyzed in terms of temporary variation of the heads, also called the groundwater dynamics. The parameter “dynamics of a time series”, or dynamics, is defined here as the difference between the minimum and maximum value in the series. The value of the dynamics of the observed time series (4.9 m) is about 60 percent larger than that of the calculated time series (3.0 m). Therefore, the dynamics in the observations are 60 percent higher than in the model. This can be explained by the spatial, mitigation area, and temporary, monthly, averaging of the input data, recharge and abstraction rates, from RIBASIM. On the contrary, the distribution over time as shown in Figure 4.9 tends to show more variation in the measured head than the computed head.

Evaluation Comparison
The results of the combined iMOD and RIBASIM model are used to analyze if the model represents the areas under pressure by overexploitation. This is an important issue for future water management in the Ganga basin.

In the report on Dynamic Ground Water Resources (CGWB 2014), areas with overexploitation of the groundwater resources are indicated (Figure 4.10). These so-called critical and overexploited zones occur mainly in the west part of the basin, in the states of Delhi, Rajasthan and Haryana and in the southwest of Uttar Pradesh. This indication map is based on a block scale analysis of measurements from 2011.

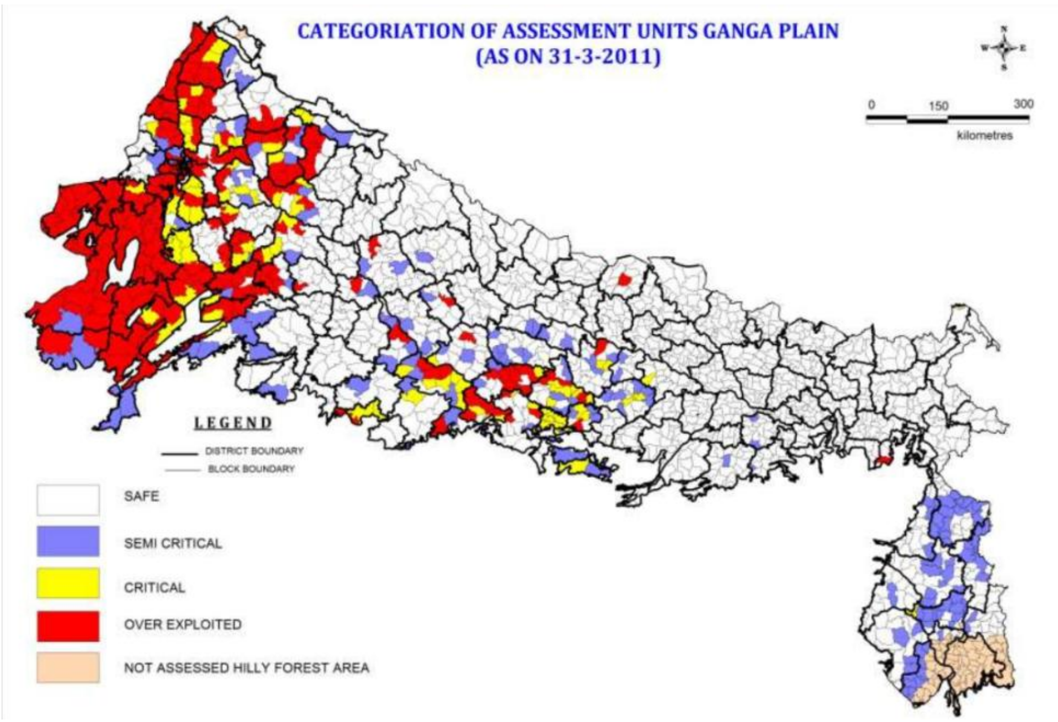

Figure 4.10 : Categorization of assessment units in the Ganga basin (source: CGWB 2014)

The iMOD model is compared to the CGWB indication map by looking at the long-term recharge and abstraction from the groundwater system as calculated by RIBASIM. The difference between the recharge and abstraction is a simplified indicator for overexploitation in which natural drainage from the system is disregarded. Figure 4.11 shows that in zones with negative values, the grey, yellow and orange zones in the west, more groundwater is abstracted than recharged, which indicates overexploitation. Zones with a low positive value,

<50 mm/year, are sensitive to overexploitation. This agrees fairly well with the CGWB indication.

This observation has led to one additional pre-calibration adaptation of the model of the recharge rate in the Delhi region.

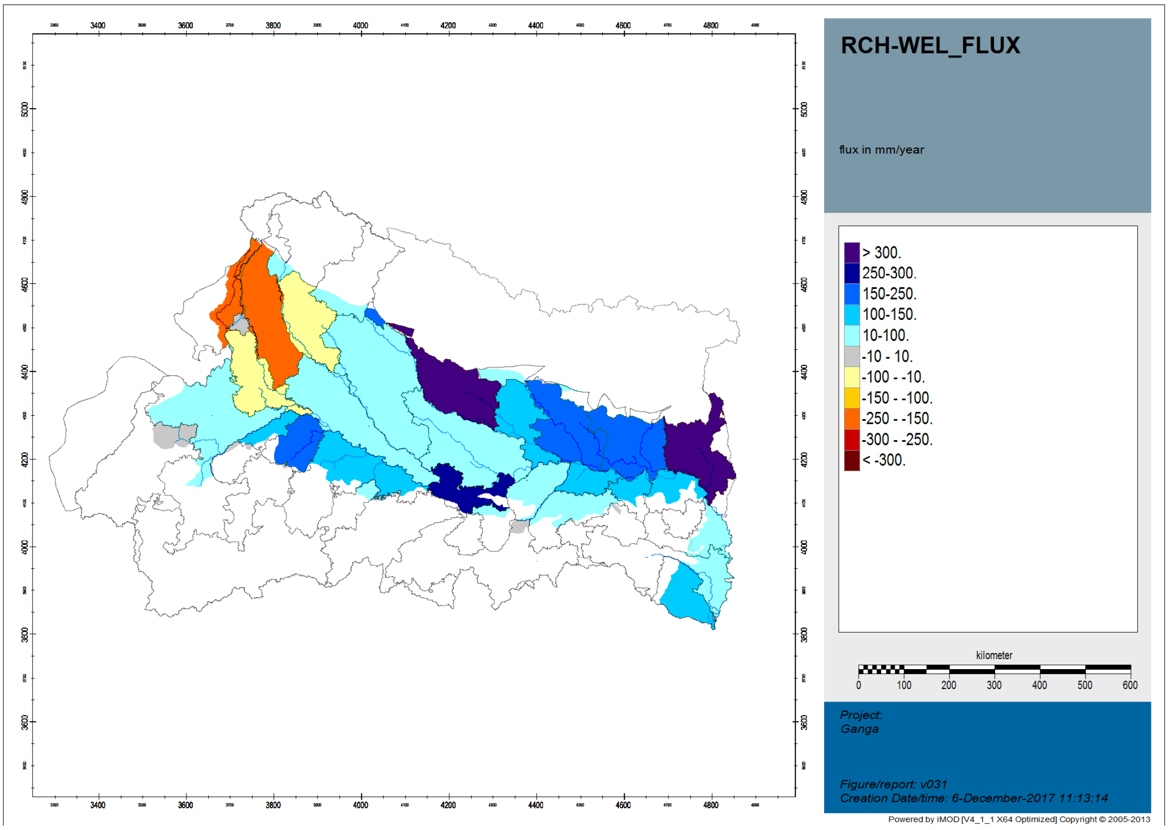

Figure 4.11: Difference between average recharge (RCH) and average draft (WEL) per irrigation area in mm/year

4.5.5 Validation and Conclusion

The final calibrated model is validated against the heads measured at the 50 percent arbitrary selected locations not used in the calibration. The differences between observed and calculated heads are plotted in a histogram and a scatterplot (see Figure 4.12).

Comparison of the validation and calibration results in Figure 4.12 shows that the model behaves consistently for both observation sets:

- Both the average and median values of the histogram are almost equal for both datasets. The median difference for the validation set is -72 cm against a value of -87 cm for the calibration set;
- In the validation data set extreme values occur in the histogram. As for the calibration dataset, these extreme values are most likely caused by scaling issues of the surface level in hilly areas.

In the major area of the model, head deviations are both positive and negative within a range that is explainable from the local variation in the head, e.g. by local wells or streams, and the surface variation. A sensitivity analysis of the groundwater model is described in Chapter 10.

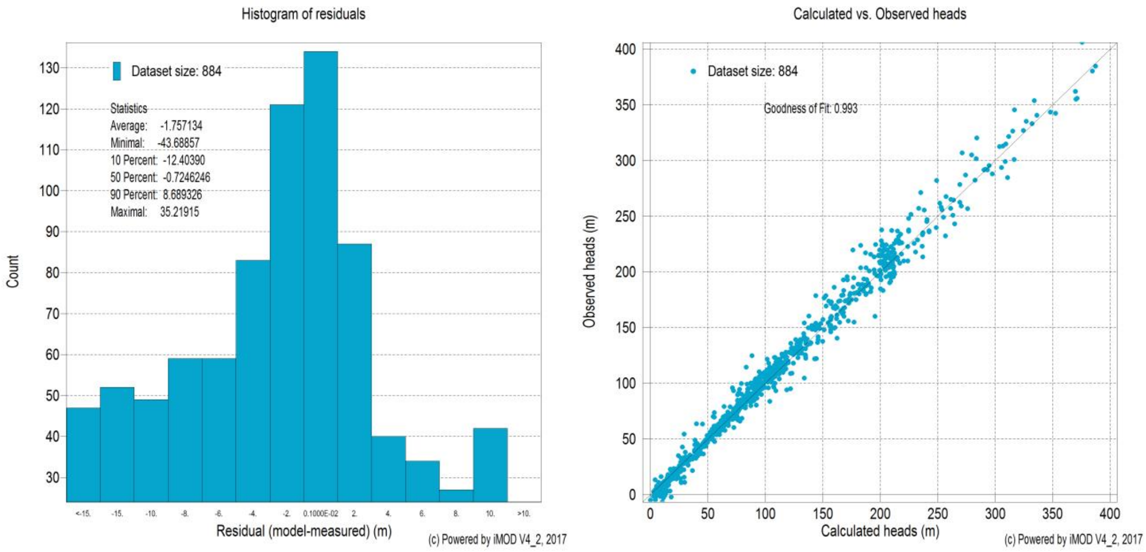

Figure 4.12 : Histogram and scatterplot based on time series in the validation data set (outliers are removed)

5 Water Resources Model RIBASIM

5.1 Concepts

The water resources model RIBASIM simulates water demand, allocation of water, operation of water infrastructure, such as dams, barrages and pumps, and ultimately water shortage for the different water users. The aim of the RIBASIM model is to provide insight into the impact of different what-if scenarios, such as socio-economic development, climate change and the construction of new reservoirs.

RIBASIM takes a central position in the workflow of the entire river basin model, as indicated in Figure 5.1. User input on climate and water use and management is combined with the flows simulated by SPHY and Wflow (see Chapter 3). Data on groundwater extraction and the interaction between surface and groundwater are exchanged with the iMOD model. The flows and water supply calculated by RIBASIM become input for the water quality model, the ecology module and the dashboard. See Section 5.4 for a more detailed description of the links with other model components.

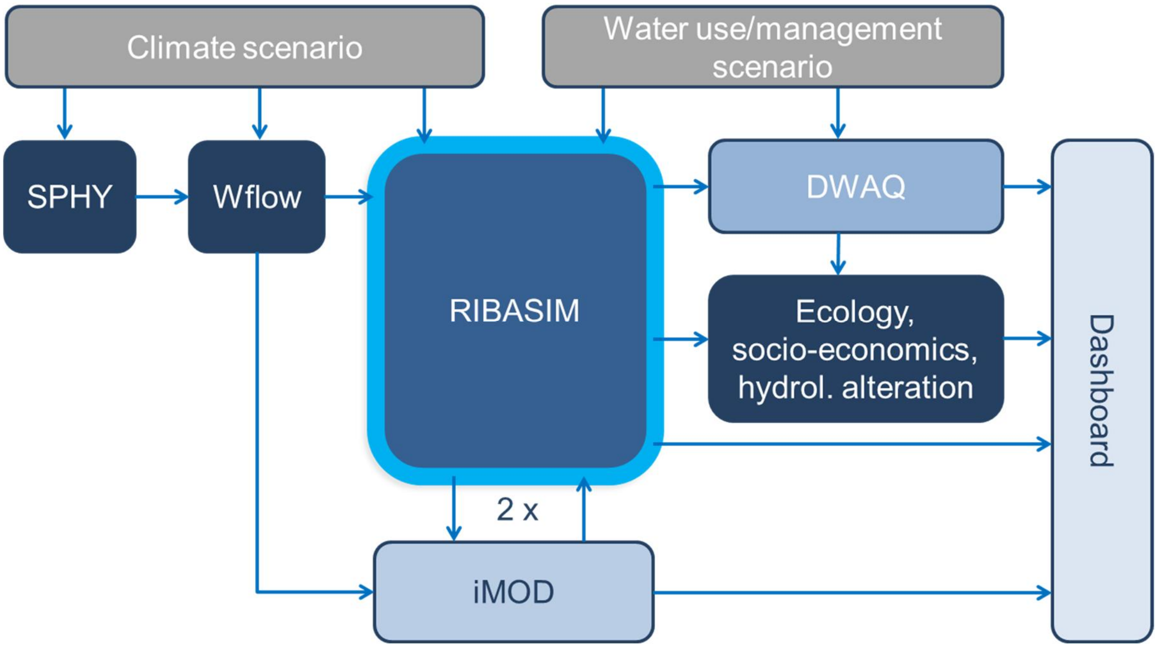

Figure 5.1: The position of RIBASIM in the workflow for the Ganga river basin model

One month is the time step in the RIBASIM application for the Ganga basin. For each time step in the simulation period a steady-state water balance is calculated. No hydraulic simulation is performed and the flows in rivers and canals are assumed to be constant during the time step. This approach is ideal for the assessment of water resources and shortage over a longer time period, such as the meteorological variation observed over a time series of several decades. Calculation times remain limited and for most types of water use, monthly temporal detail is sufficient. However, assessment of variation within the time step of one month is not possible in this approach. Such an assessment would be required for detailed analysis of hydropower generation during peak demand hours and for detailed flood risk analysis, which are outside the scope of strategic planning at the basin scale.

The monthly water balance is simulated for a network consisting of links and nodes. The nodes represent the inflow of water, different types of water demands and different types of water infrastructure. The links represent the transport of water through rivers, canals and tube wells. Water demands in RIBASIM can be supplied by both surface and groundwater, allowing for so called conjunctive use, which is an important feature of the water resources management of the Ganga basin. The impact on the groundwater is not simulated with RIBASIM, but with the iMOD model (see Chapter 4).

Each time step begins with the calculation of the flow through the network without any water use or operation of infrastructure. Then the water demand is calculated and supplied based on the availability. Water infrastructure is operated to satisfy water demand not met by the direct availability of water. If all demands cannot be met in times of water shortage, the allocation of water is based on a user defined prioritization of demands and on a user defined list of sources.

Water demand for low flows and industry is input data. Water demand for domestic supply is calculated from the number of inhabitants, per capita water use, and supply efficiency. RIBASIM uses a module similar to FAO's CROPWAT to calculate the irrigation water demand based on monthly crop area, monthly crop transpiration coefficients, reference evapo-transpiration and efficiencies for conveyance and field application.

The data for water demand and infrastructure are the most recent in order to approximate the actual situation. The hydrometeorological input covers the period 1959–2014. This means that the results for 1959 from the RIBASIM model do not represent the water resources situation of the year 1959, but that they represent a combination of the actual water demand and infrastructure with the hydrometeorology of 1959. The advantage of applying a long time series is that a large variation of different degrees of wet and dry years is included, as well as some variation in the sequence of wet and dry years. Model simulations have mostly been limited to the period 1985–2014 in order to ensure that the simulations represent the current climate and to limit the possible impact of historic climate change.

A complete description of the concepts behind the RIBASIM model, including equations for all calculations and a description of all input files and user interaction, can be found in the RIBASIM Technical Reference Manual (Van der Krogt, 2008) and the accompanying User Manual (Van der Krogt and Boccalon, 2013, and Deltares, 2015b). Version 7.01.15 of the RIBASIM software package has been implemented in the Ganga river basin model.

5.2 Set-up

The schematization of the Ganga river basin in RIBASIM is presented in Figure 5.2. It covers the Ganga basin in India, Nepal and China ending at the boundary with Bangladesh; it also includes the Hoogly branch that flows through the Indian state of West-Bengal to the Bay of Bengal. The focus of RIBASIM is on that part of the basin in India.

To describe the inflow of water resulting from rainfall-runoff and melting of snow and glaciers, modelled by SPHY and Wflow (see Chapter 3), the basin has been divided into 314 subbasins. See Figure 5.3 for the subbasins and Table 5.1 for the number of each type of node and link used in the schematization. The subbasins are generated from the same Digital Terrain Model used for the hydrological models. A new subbasin is distinguished above each reservoir, barrage, recording node and low flow node in the schematization to calculate the flow at that specific location.

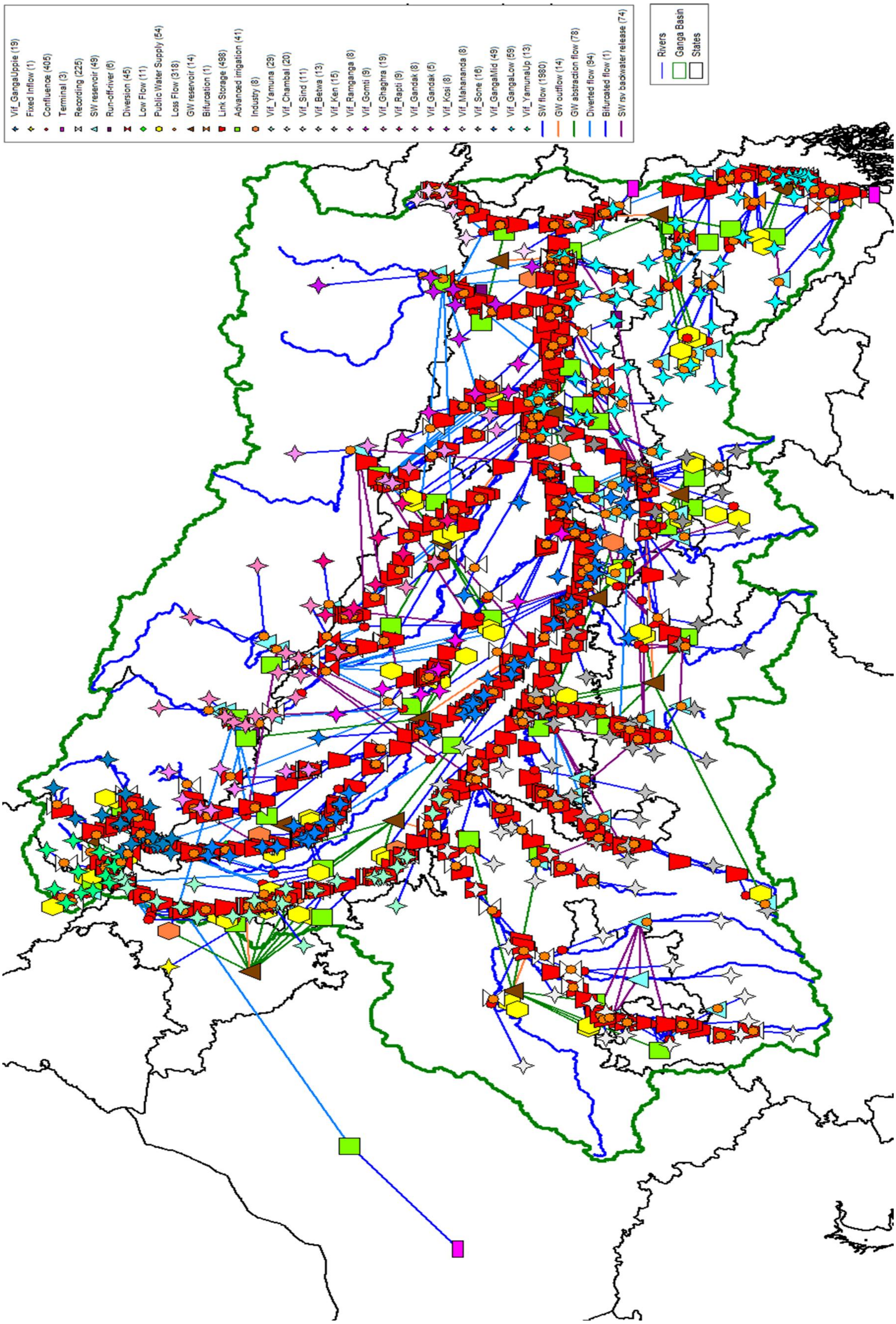

Figure 5.2: Schematization of the Ganga river basin in RIBASIM

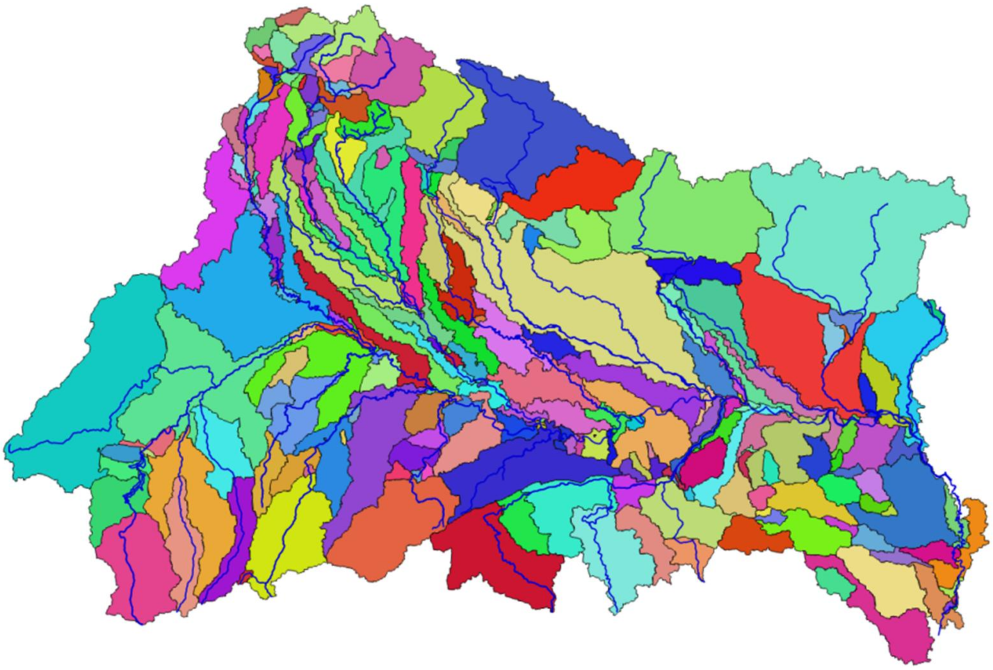

Figure 5.3: The 314 subbasins identified in the Ganga river basin

In a strategic river basin model it is not possible to include all details of reality, such as each individual dam, canal and irrigation block. Therefore, only the largest 34 surface water reservoirs have been included and the irrigation areas have been aggregated to 41 nodes. See Figure 5.4 for a map of the areas corresponding to these 41 nodes.

For domestic water supply the basin has been divided into 22 regions for which urban and rural water supply have been handled separately. Nine major cities have been included individually. The distinction between urban and rural domestic water use is necessary to be able to include the differences in the per capita water use, the source of water and the fate of waste water.

Table 5.1: Number of nodes and links in the RIBASIM schematization divided by type

Node type	Number
Variable inflow nodes representing subbasins	314
Surface water reservoirs	49
Irrigation areas	41
Public water supply nodes for domestic use	48
Public water supply nodes for industry	6
Confluences	405
Terminal nodes	3
Recording nodes	225
Diversion nodes	45
Low flow nodes	11
Loss flow nodes for exchange with the groundwater	318
Link-storage nodes to describe stage-discharge-width relations	498
Surface water flow links	1980
Groundwater abstraction flow links	78
Diverted flow links	94
Surface water reservoir backwater release links	74

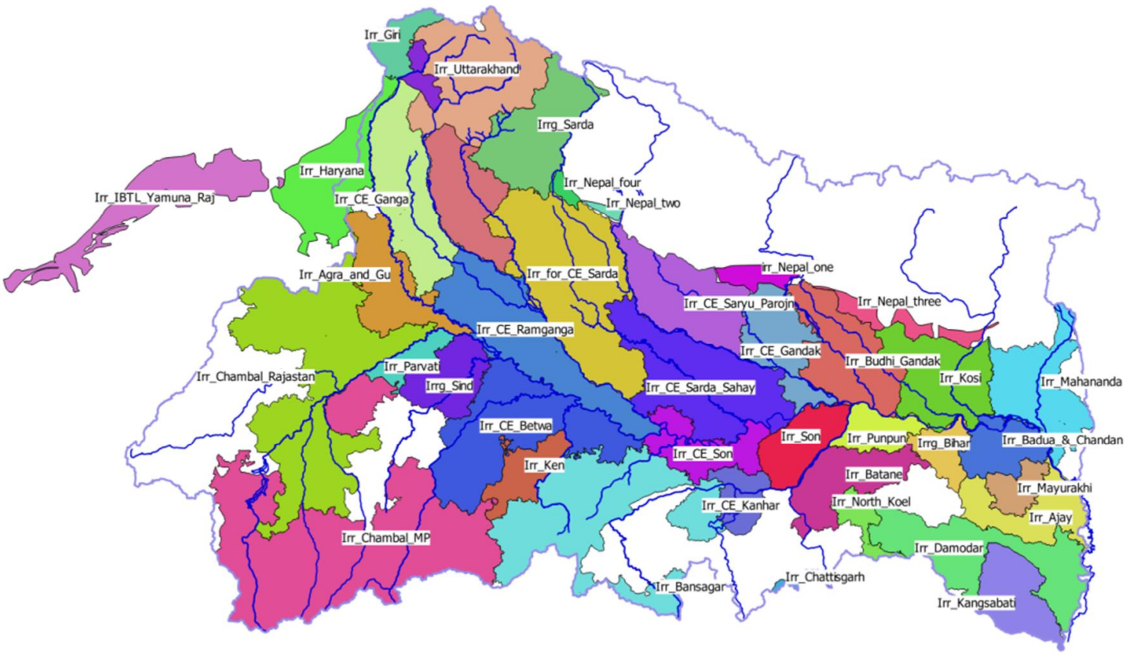

Figure 5.4: The areas corresponding with the 41 irrigation nodes in the Ganga river basin model with the names of the nodes

Hydropower has not been included in the RIBASIM model, although the model software includes the option to do so for dams and run-of-the river hydropower stations. However, the required input data on dam and turbine characteristics and peak and firm energy demand are not available.

5.3 Input Data

The input data for the RIBASIM model aim to describe the actual situation around 2015 with respect to water demand and water resources management. In reality data have been collected for the most recent year for which they are available, which might be some years earlier.

The location and data regarding water infrastructure such as barrages, dams and canals has mainly been derived from the Ganga basin Report (CWC and NRSC, 2014) and India WRIS (the Water Resources Information System of India[2]). The schematization has been adapted based on the input from the first round of state level and basin wide workshops. Data are missing regarding the life storage capacity of three of the reservoirs included: Bhalubangi Dam, Chandwa Dam, and the reservoir in Bhopal. Estimates based on the average capacity of the other reservoirs have been used for the moment.

The information on irrigated area per crop has been derived from the Land Use Statistics Information System of the Ministry of Agriculture and Farmers Welfare[3]. Data per district have been aggregated to data per irrigation node. The cropping calendar, when which crop is planted, has been derived from information provided by Crop Science Division of the Indian Council of Agricultural Research[4].

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[2] *http://www.india-wris.nrsc.gov.in/wris.html*

[3] *http://aps.dac.gov.in/LUS/Public/Reports.aspx*

[4] *http://eands.dacnet.nic.in/At_A_Glance-2011/Appendix-IV.xls*

Estimates for irrigation efficiencies and fractions return flow from irrigated areas have been taken from Gupta and Deshpande (2004). Because of the importance of irrigation efficiency and return flow fractions for water demand and river discharges, these values are presented in Table 5.2. 40 percent of the surface water abstracted for irrigation is transpired by the irrigated crops. The rest is lost mainly due to leakage of canals and evaporation of open water. The efficiency of irrigation with groundwater is much higher with 70 percent of the abstracted water transpired by the crops. The difference is due to the large amount of leakages from canals used to convey surface water from the rivers to the irrigated areas. Conveyance of groundwater leads too much less leakage because the distributed nature of groundwater abstraction limits the length of which groundwater needs to be transported. The largest part of the water not used for transpiration by crops drains to the groundwater, 54 percent; 6 percent drains to the surface water and the remaining 40 percent evaporates to the atmosphere.

Table 5.2: Irrigation efficiency and return flow percentages (from Gupta and Deshpande, 2004)

	Surface water	***Groundwater***
Efficiency as a percentage of gross water supply	*40%*	*70%*
Return flow as a percentage of total gross demand not transpired by the crop[1]	*6%*	*54%*

[1] – Does not sum to 100 percent since the remaining part evaporates to the atmosphere

State-wise data on monthly average reference evapotranspiration have been taken from Nag et al. (2014). The monthly crop transpiration coefficients for most crops are India specific values from Hajare et al. (2007). For maize and rapeseed, coefficients are used from Shankar et al. (2012). For sugarcane, tobacco and fodder crops no information specific for India could be found and data have been used from the FAO database[5].

For domestic water supply population data per district are based on 2011 census data (Office of the Registrar General & Census Commissioner, India, 2011[6]). These values have been corrected for population growth and urbanization as observed in the period 2001–2011. District data have been aggregated to correspond with the 54 public water supply nodes for domestic demand. Data on water sources, leakage and return flow for major cities have been obtained from Naran and Srinavasan (2012). Data on industrial water demand are from CPCB (2013).

The public water supply and irrigation nodes are supplied by water from both the surface and the groundwater to simulate conjunctive use. The capacity of the surface water supply for irrigation is determined by the canal capacity, mostly obtained from WRIS. The capacity of groundwater supply for both has been tuned to yield results that are comparable to the estimates presented in CGWB (2014).

During periods of water shortage, RIBASIM allocates water based on priorities, with 1 the highest priority. The following order of priorities has been used in the Ganga basin Model:

- Drinking water supply;
- Industrial water supply;
- Irrigation water supply; and
- Low flow requirements for spiritual use, bathing and environmental flows.

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[5] *http://www.fao.org/nr/water/cropinfo.html*

[6] *http://censusindia.gov.in/*

A complete description of the input data for RIBASIM, their origin and their storage location in the system can be found in Appendix D.

5.4 Link with Other Components of the Ganga River Basin Model

The water flow from each subbasin is simulated with the Wflow model (Section 3.2). These results incorporate the results of the SPHY model for the Himalaya (Section 3.1). The Wflow results provide daily discharges on a 1x1 km grid. These data are aggregated in the GangaWIS to monthly values per subbasin, when the input for RIBASIM is prepared. There is a two-way exchange of data with the geohydrological model iMOD (Chapter 4). The following input for iMOD is obtained from results of the RIBASIM simulation:

- Recharge of groundwater from irrigation areas;
- Recharge of groundwater from public water supply;
- Discharge in the main rivers, used for calculation of river water level; and
- Abstraction of groundwater for irrigation areas and public water supply.

iMOD simulates the exchange flux between the rivers and the groundwater. The result is used as input for RIBASIM. The flow of water from the river to the groundwater is incorporated in the loss flow nodes for each of the subbasins. The flow from the groundwater to the river is added to the inflow per subbasin, as simulated by Wflow (see Figure 5.5).

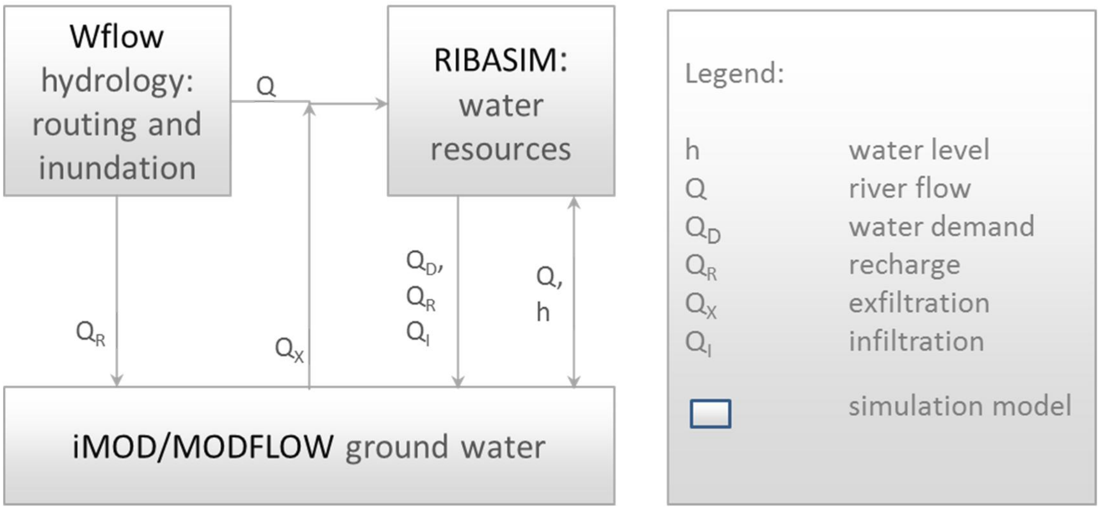


Figure 5.5: Schematic representation of the exchange fluxes between the model components Wflow, RIBASIM and iMOD

Because of the two-way nature of the exchange of data between RIBASIM and iMOD, both models are run twice (see Figure 10.1):

- RIBASIM is run with input from Wflow with no loss flow from the rivers to the groundwater;
- iMOD is run with the input from Wflow and RIBASIM and calculates the exchange between the rivers and the groundwater;
- RIBASIM is run again with the same input from Wflow, but now with the exchange fluxes between river and groundwater calculated by iMOD; and
- If necessary, iMOD can be run again with the same input from Wflow and the results of the second run of RIBASIM. This is only required if the exchange between river and groundwater has a very large impact on the river discharge.

The surface water flows calculated by RIBASIM for the river and canals are used as input for the water quality module DWAQ and the ecological knowledge rules module.

5.5 Calibration and Validation Results

The calibration of RIBASIM has taken place in three steps:

1. Calibration of the pumping capacities (in m^3/s) for irrigation and public water supply on the estimates of the annual amount pumped in 2011 (in million m^3) provided by CGWB (2014) and calibration of canal capacities, where data are not available, on the assumption that there will be no major water shortages for public water supply and irrigation in years not drier than the average;
2. Combined calibration with Wflow on the measured discharges in the rivers under the assumption that there will be no major water shortages for public water supply and irrigation in years not drier than the average; and
3. Combined calibration with Wflow and iMOD on the measured discharges in the rivers after incorporation of the exchange between the rivers and the groundwater resulting from the first step simulation of iMOD and on the measured groundwater level.

Step 1 has been performed on the input data reflecting the actual situation comparing with measurements of the year 2011. For steps 2 and 3, a difference has been made between the calibration and the validation period. Modification of model input has taken place based on the results for the calibration period 1995 – 2009 The results of the validation period 1985–1995 are compared to the calibration results to verify that there are no major deviations in model performance between the two periods. When interpreting results for the validation period it is important to consider that the situation in the simulation with respect to water demand and infrastructure represents the 2015 situation, which might deviate significantly from the situation during the validation period.

Step 1 of the calibration outlined above has resulted in the set of pumping and canal capacities as described in Appendix E. The result of this step of the calibration is presented in Figure 5.6. It appears that the simulation estimates slightly higher groundwater abstractions for irrigation and public water supply, compared to the assessment (CGWB, 2014). This is deemed to be within the acceptable margin, since the estimates of the assessment by CGWB (2014) are not based on direct measurements, but on water balance calculations similar to those included in this calibration with a fairly large margin of error.

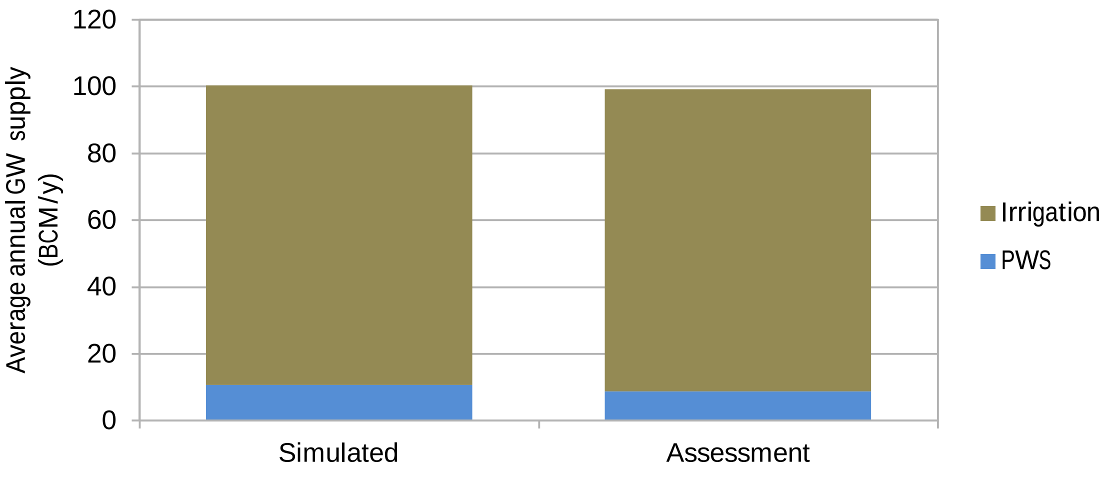


Figure 5.6: Calibration results comparing the average annual groundwater abstraction simulated with the value estimated by CGWB (2014)

Step 2 showed that the non-monsoon flow simulated by SPHY/Wflow was initially too low compared to measurements and water demands for irrigation. The settings of Wflow have been adapted to generate more flow in the non-monsoon season (see Section 3.2.5 for more details on these settings). During step 2 no modifications have been made to the input of RIBASIM.

In step 3 the conductivity of the riverbed in iMOD has been calibrated to get exchange fluxes between the river and groundwater in the expected order of magnitude, since no measurements of these fluxes are available. During step 3, the iMOD results initially showed that the recharge calculated from irrigation areas in the eastern part of the basin resulted in groundwater levels above the ground level. Therefore, extra drainage has been added to lead the excess groundwater to the surface water system of rivers and canals. See Chapter 4 for further details.

The evapotranspiration (ET) simulated by RIBASIM has been validated by comparison with a remote sensing based assessment of evapotranspiration. The ETensemble product of UNESCO-IHE's Water Accounting Group[7] has been used for this. ETensemble combines six different remote sensing derived ET products namely, ALEXI, CMRSET, SSEBop, MOD16, GLEAM and ETMonitor. It is available globally for the period 2003–2014 with a time step of one month and a spatial resolution of 0.00025º x 0.00025º. It can be downloaded using the Water Accounting Plus toolbox[8].

The result of this comparison is shown in Figure 5.7. The simulated and ETensemble evapotranspiration rates are very similar for the period where irrigation is concentrated, between June and November. The simulated ET is much lower during the rest of the year.

This is most likely due to the fact that RIBASIM only simulates ET from irrigated crops, while ETensemble measures total ET with additional contributions from vegetation and rainfed crops. However, additional irrigation in the period December to May could also contribute to the observed difference.

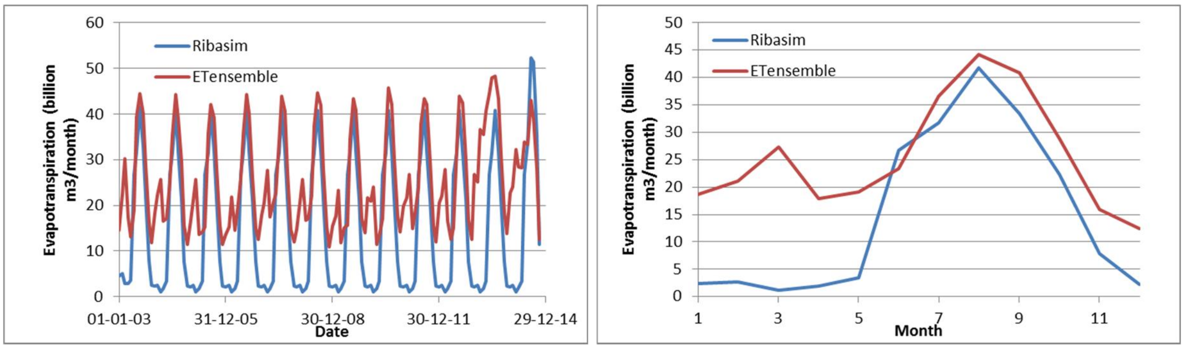


Figure 5.7: Comparison of monthly evapotranspiration simulated by RIBASIM and derived from the ETensemble remote sensing product for the period 2003–2014 (left) and monthly average values over this period (right) accumulated over all irrigated areas as shown in Figure 5.4

This comparison shows that the irrigation related ET flux is simulated quite accurately by RIBASIM, but that further investigation of the cropping pattern especially in the period December to May could possibly improve the results.

[7] *http://www.wateraccounting.org/*

[8] *https://github.com/wateraccounting/wa*

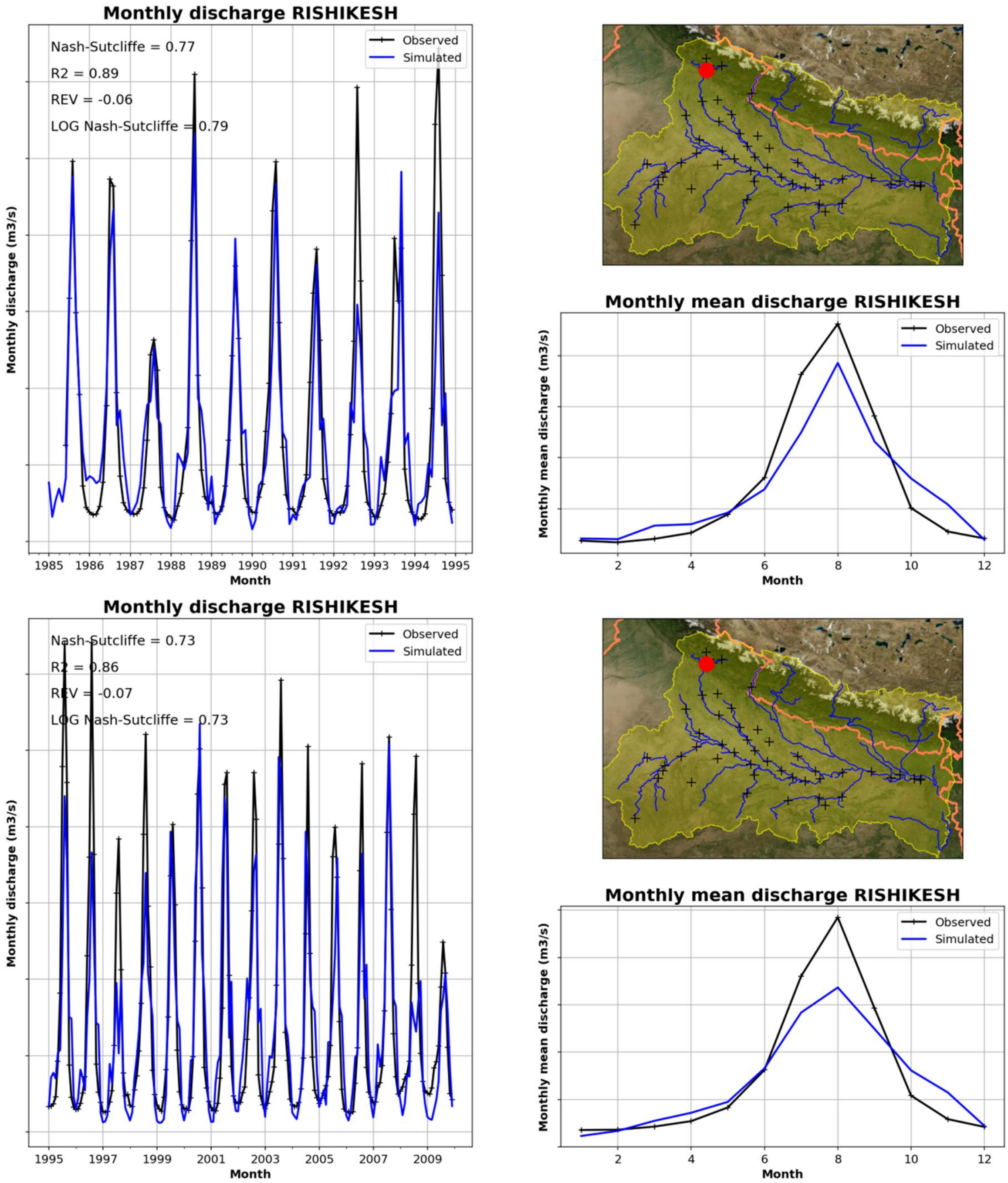


Figure 5.8: Validation (1985–1994, top) and calibration (1995–2009, bottom) results for the Ganga river at Rishikesh with the monthly discharges (left), mean monthly discharges (right bottom) and location of the station (red dot on map right top)

Simulated and measured river discharges for the calibration and validation period are shown below for some of the locations where data are available (Figure 5.8). More graphs are presented in Appendix D. The graphs have no values on the Y-axes, because the discharge measurements in the Indian part of the Ganga basin are classified. The statistics in the left upper corner of the graphs with monthly discharges show different coefficients of the similarity between simulated and measured discharges. The meaning of these coefficients is explained in Section 3.1.5. The discharges show very large seasonal fluctuations due to the monsoon character of the climate. This makes it difficult to see differences between simulation and measurement when several years are shown together. Therefore, graphs of the simulated and measured average monthly discharges are presented as well. These clearly demonstrate any significant deviations of model results from actual measurements.

The graphs in Figure 5.8 present results for the monitoring location Rishikesh on the Ganga in the foothills of the Himalaya and downstream of the large Tehri Dam. The graphs in Figure 5.9 present results for the Ganga river at Varanasi, the most downstream point at which discharge measurements were sufficiently available. The first location is indicative for the performance of the SPHY model to reproduce the runoff in the Himalaya and of the RIBASIM model to reproduce the operation of the Tehri dam.
The second location combines the influence of runoff simulated by SPHY and Wflow with the water demand and operation of infrastructure simulated by RIBASIM. More results of the calibration and validation are shown in Appendix D.

Nash-Sutcliffe values mostly vary between 0.5 and 0.8, showing that the models are very capable of describing the seasonal and annual fluctuations in flow. The non-monsoon periods are more important than the peak monsoon flows for water resources planning, since water shortage will be concentrated during the low flows. No systematic difference between the calibration and validation periods is observed. Timing of flows seems to be accurate, at the monthly scale, for upstream stations, like Rishikesh. At more downstream stations like Varanasi, the simulation results seem to precede the measurements by 0.5–1 month. At Rishikesh the simulation underestimates the flow volume during the monsoon slightly. At Varanasi the simulation on average overestimates the flow volume during the low flow period. More detailed study of the results (Appendix D) show that this phenomenon is not present on the main stem of the Ganga upstream of the confluence with the Yamuna. The explanation can be found in the too slow release of groundwater to the river mainly in the catchment of the Chambal. Further improvement of calibration proved not possible due to the lack of monitoring data on the Chambal and the Yamuna.

Overall, the results of the calibration and validation of discharges provide enough confidence for the use of the model results to assess the impact of what-if scenarios by analyzing the difference in model results.

However, improvement of the model is very possible. Adding more detail is, in itself, not necessarily an improvement for a strategic basin model. Therefore, it is advised to focus on improvement of input data before considering a data expansion in the schematization.

Points of attention for improvement include:

- Improved calibration of the discharge of the Chambal river, especially based on the release of groundwater;
- Missing data on storage capacity of three reservoirs;
- Missing data on hydropower generation and demand;
- Missing data on operation rules for dams and barrages;
- Calibration of the groundwater extraction on the inventory of installed pumping capacity and depth; and
- Improve data on the cropping calendar.

It is advised to avoid adding more detail to the model, since this would increase the complexity and the interpretation of its results. However, additional detail that improves the evaluation of measures that could be part of strategic basin plans would be valuable.

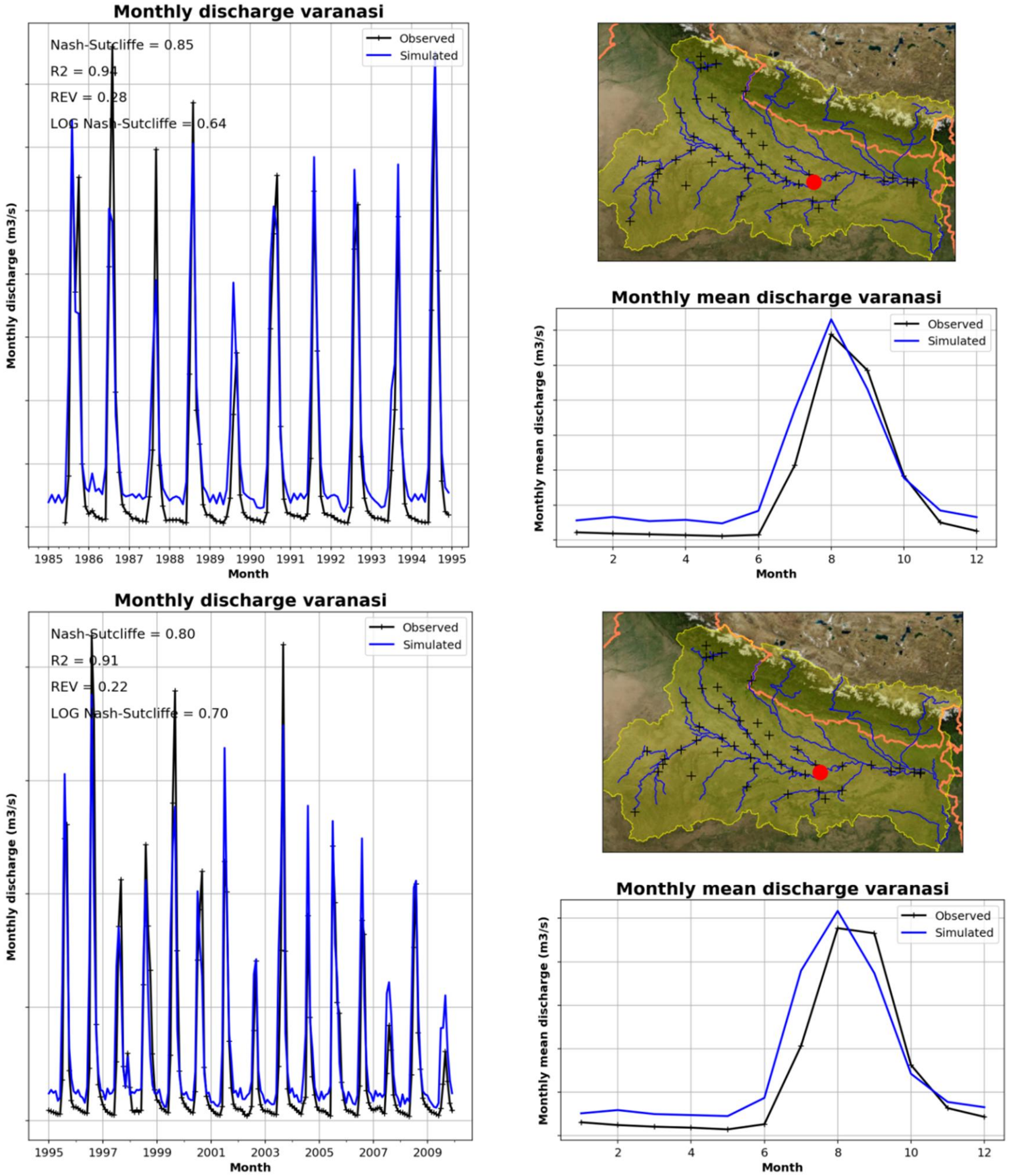


Figure 5.9: Validation (1985–1994, top) and calibration (1995–2009,bottom) results for the Ganga river at Varanasi with the monthly discharges (left), mean monthly discharges (right bottom) and location of the station (red dot on map right top)

5.6 Indicators on the Dashboard

The indicators on the dashboard are derived from the results of the RIBASIM model:

The term 1/10 dry year in the descriptions of the dashboard indicators refers to a year where 90 percent of the simulated years are wetter and 10 percent of the simulated years are drier, i.e. the value of the 10 percentile driest year. For discharge this will be the 10 percent lowest value and for deficits the 10 percent highest values. Year refers here to a hydrological year, which is defined for India as starting in June and ending in May next year.

Table 5.3: Dashboard indicators obtained from RIBASIM

INDICATOR	DESCRIPTION
Minimum discharge main river (m^3/s)	The minimum monthly simulated discharge of the Ganga river and its main tributaries are shown for a 1/10 dry year. For the Ganga basin the simulated inflow above Farakka Barrage is shown. For the states the outflow from the selected state is shown.
Volume of water stored in reservoirs (Billion m^3)	The total sum of simulated water stored in the main reservoirs in the basin or the selected state at the end of the monsoon period, October, for a 1/10 dry year.
Deficit drinking water (%)	The difference between simulated drinking water supply and simulated demand as a percentage of the simulated demand for a 1/10 dry year.
Deficit irrigation water (%)	The difference between simulated irrigation water supply and simulated demand as a percentage of the simulated demand for a 1/10 dry year.
Area with reduced agricultural production due to water shortage (%)	Percentage of the total irrigated area with severely reduced productivity due to water shortage as expressed by a simulated irrigation deficit exceeding 20% in a 1/10 dry year.
Volume of groundwater abstracted (Billion m^3/year)	Total simulated volume of groundwater abstracted for public water supply and irrigation during the 1/10 driest hydrological year, the year with the 1/10 highest abstraction.
Area with critical groundwater development (%)	Percentage of the area where the simulated groundwater abstraction amounts to 90% or more of the simulated recharge.

6 Pollution Load and Water Quality Model DWAQ

6.1 Concepts

DWAQ simulates water quality in the complete RIBASIM network for substances indicative of pollution such as Biochemical Oxygen Demand (BOD), Faecal Coliform (FColi), and Total Coliform bacteria (TColi). Pollution sources included in the model are population, industry and agriculture. The DWAQ model provides quantitative insight into the impact of different what-if scenarios, such as socio-economic development and wastewater treatment plans to improve water quality by reducing pollution.

Water quality models simulate the fate and transport of substances in water; substances are characterized by their concentration C (in mg/L) as a function of space and time. DWAQ is an open source numerical water quality model (https://oss.deltares.nl/web/delft3d/delwaq), which calculates C(t) for a series of water volumes or segments, which can be aligned in 1, 2 or 3 spatial dimensions. It has been linked to various hydrological, hydrodynamic and water allocation models and has >100 licensees worldwide and over 1000 model applications of rivers, lakes, seas, lagoons, urban water systems, and deltas and associated canal systems, e.g. polders and irrigation systems. This chapter and Appendix E describe the implementation of DWAQ as the water quality model within RIBASIM.

For the application of DWAQ, the RIBASIM network of nodes and links is translated into a network of connected finite volumes each with its concentration and with geometric characteristics e.g. length, volume, horizontal surface area and depth. The geometric characteristics are required to simulate pollutant processes, i.e. reaeration of oxygen. As most RIBASIM links and nodes, except Link Storage nodes, do not have a defined geometry (see Table 5.1), these are estimated without intervention from the user.

DWAQ takes the water flows in the study area, calculated by RIBASIM, and accounts for the transport of pollutants, i.e. dilution, within the water courses and accounts for pollutant processes, e.g. decay and transformation. The DWAQ time step of 0.5 day is smaller than the RIBASIM time step of 10 days which is required to calculate the resulting concentrations of pollutants in the water, i.e. water quality, without numerical problems. Although water quality is simulated in all RIBASIM links, the simulated concentrations are only presented for the areas of interest in the water quality model, viz. Yamuna and Ganga main branch. Figure 6.1 portrays the water quality model concept.

The water quality model requires information on the pollution loads entering the water system. For this purpose, a separate emissions model is used and coupled to the water quality model. Emissions were calculated using the Waste Load Module (WLM) software developed and maintained by Deltares (Deltares, 2017). WLM uses the unit load approach, which is based on emission variables or emission sources and emission factors for each source (see Figure 6.1) to estimate waste produced by various sources of pollution. The WLM is integrated with RIBASIM and estimates emissions for three different node types, viz.:

- public water supply (PWS) nodes;
- public water supply nodes representing industry (IND);
- advanced irrigation (AIR) nodes.

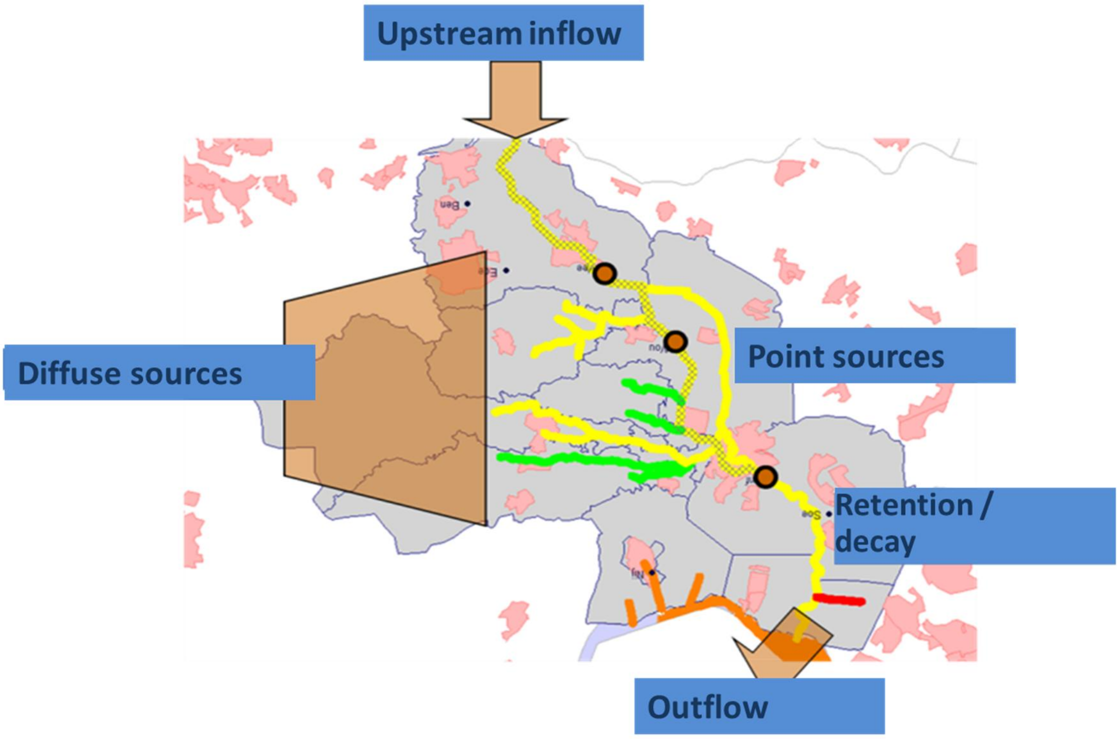


Figure 6.1: Conceptual schematization of a basin in DWAQ (sub catchments in grey polygons, dots are points where emissions enter the river network).

The definition of emissions according to the unit load approach is user defined. Table 6.1 presents the definition used in this study.

Table 6.1: Emission factors and emission explaining variables used for waste load estimation

	Public Water Supply	Industry	Irrigation
Emission Variable	Population number	Return flow (m^3/s), subdivided over sectors: • chemical • food etc.	Cultivated areas for various crops (ha)
Emission Factor	Per capita load in waste water	Concentration (g/m^3) in return flow, per sector	Emission in kg/ha/year per crop

The generated emission (W) is calculated as follows:

$$W_{i,j} = \sum_k EV_{i,k} \cdot EF_{i,j,k}$$

W = emission (g/s)
EV = emission variable (X)
EF = emission factor (g/s/X)
i indicates individual node
j indicates individual substance
k indicates individual EV's

The generated emission (W) can be treated before it reaches the network, e.g. by a sewage treatment plant (STP). Per individual node one or more treatment types, e.g. individual STPs, can be defined plus the share of the return flows treated, or as an option, the maximum amount of water treated, the volumetric treatment capacity, ψ. For each of the treatment types, the removal efficiency for different substances is defined. This is accomplished by a transmission factor, a scale factor on the emission W as defined above; this factor is different for every node, every substance and every time step. It is calculated as follows:

$$T_{i,j}(t) = 1 - \sum_{m} \left(\phi_{j,m} \cdot \frac{\min\left(Fr_{i,m} Q_i(t), \psi_m \right)}{Q_i(t)} \right)$$

T	=	fraction of emission transferred to water quality network (-)
Φ	=	the removed fraction due to treatment (-)
Fr	=	fraction of return flow treated by a certain treatment type (-)
Q	=	return flow (m^3/s)
ψ	=	capacity of a certain treatment type (m^3/s)
m		indicates individual treatment types

Per node the non-treated part of the emission (W x T) is transferred partly to surface and partly to groundwater. The emission load “follows”, i.e. is carried by the return flows from surface and groundwater as defined in RIBASIM. The return flows are time variable, e.g. monthly, values and defined as a percentage; surface and groundwater percentages sum to 100 percent.

The temporal distribution of the emissions is thus dictated by the variation over time, if any, of the emission variables, and by the variation over time of the carrier discharge, viz. the return flows from the AIR, IND and PWS nodes. The mathematical description is provided in Appendix B of WLM (2007).

The route the emissions follow in the network determines the catchment retention. The concept of the emission routing is shown in Figure 6.2. Retention in a subcatchment is modelled by (1) loss to groundwater and (2) loss processes in channels and links simulated by DWAQ.

Loss processes in channels and other links are simulated by DWAQ. The residence time is the most important factor determining the retention of pollution. The residence time is proportional to the ratio of the volume and the flow rate from the simulation. Larger volumes and smaller flow rates increase residence time and retention is enhanced by sedimentation and decay processes.

The volumes of reservoirs and the main rivers Yamuna and Ganga (see Figure 7.3) are mostly available in RIBASIM. These are time variable and based on stage-discharge-width relationships. Volumes of most other links representing smaller surface water flows, tributaries and canals are not known and were estimated for DWAQ using an estimation procedure described in Appendix E.1. The volume estimator uses the length of the RIBASIM link and thus the distance between the emission nodes (PWS, AIR, IND), and the river network influences the catchment retention.

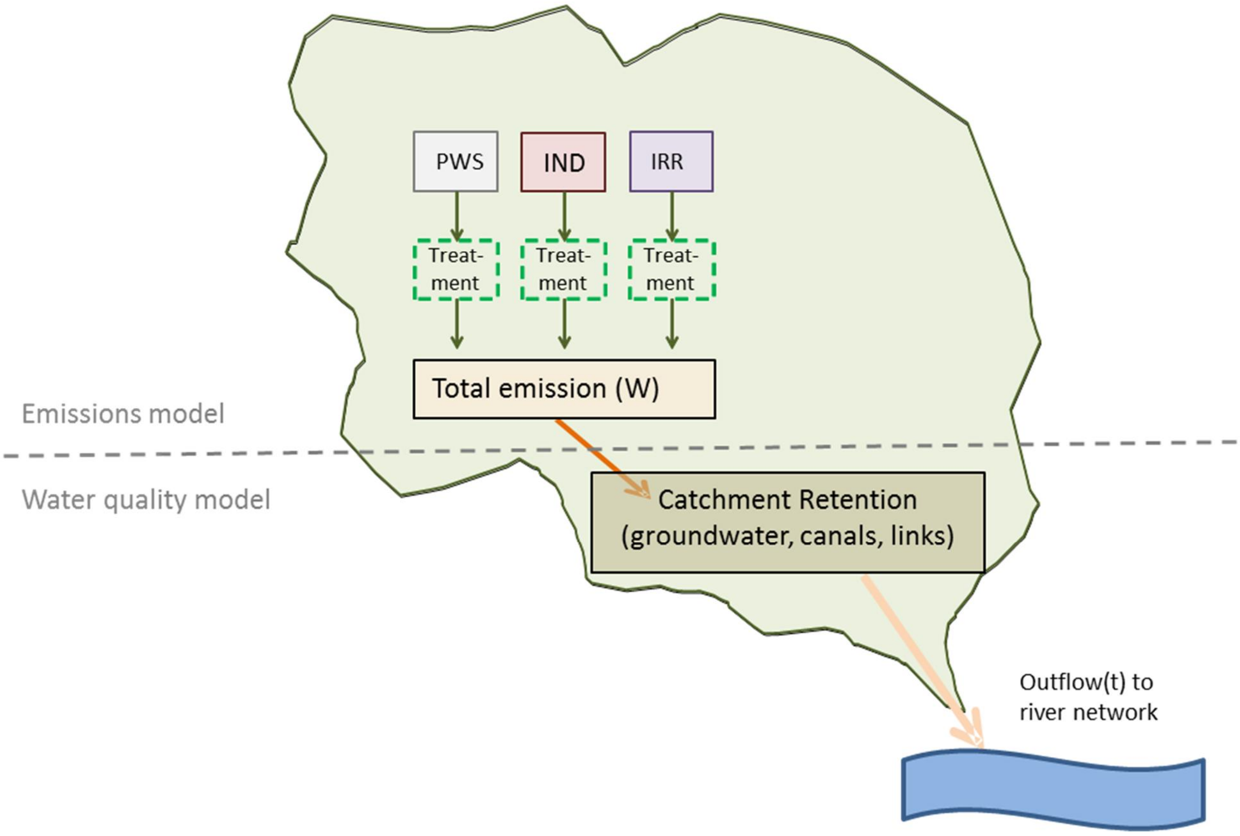


Figure 6.2 Conceptual schematization of the Emission Model

A complete description of the DWAQ model concepts, including equations for all calculations and a description of all input files and user interaction, can be found in:

- D-Water_Quality_User_Manual.pdf;
- D-Water_Quality_Description_Input_File.pdf;
- D-Water_Quality_Processes_Technical_Reference_Manual.pdf;
- WLM, 2017. Water quality simulations with DWAQ in RIBASIM.

Relevant publications are:

- about DWAQ processes: Smits and van Beek, 2013;
- about the system setup: Postma et. al, 2003.

6.2 Set-up

The DWAQ schematization of the Ganga river basin is the same as the RIBASIM schematization presented in Figure 5.2. It covers the Ganga river basin with focus on that part of the basin in India. DWAQ simulates water quality in all RIBASIM links and in that way makes use of its administrative capabilities, which keep the mass balance of the substances in the system. However, for some RIBASIM links that represent schematized canals or groundwater abstraction there is no volume information available. To allow a DWAQ simulation, a segment volume is estimated. An error in the volume estimation is linearly propagated to the simulated concentrations.

Concentrations in segments without volume information are considered less accurate, which is the case for the brown colored links in Figure 6.3. Figure 6.4 shows the DWAQ river and drainage water segments together with all boundary inflow points for DWAQ.

Figure 6.5 shows Public water supply (PWS) nodes, industrial (IND) nodes and irrigation (AIR) nodes. The emissions calculated by WLM at these nodes enter the water quality model. At the nodes the supply flow is going out of the network, while a smaller return flow is coming back from the node carrying the emission from the node. As the substances present in the supply water do not come back via the return flow, the emissions from PWS, IND and AIR nodes are net emissions representing the total waste load generated in the node.

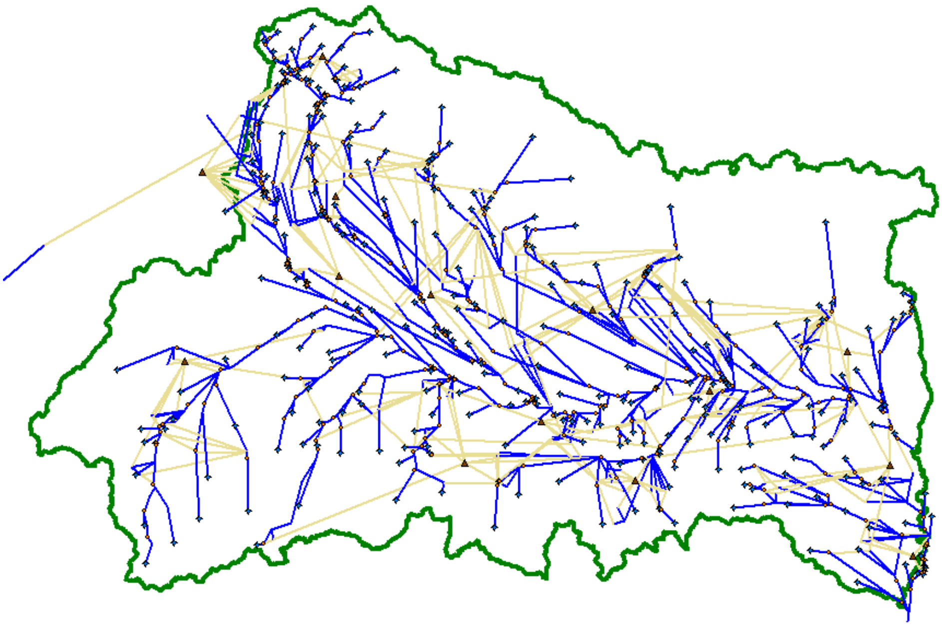


Figure 6.3 Schematization of the Ganga river basin RIBASIM: 1930 river and drainage links (blue) and 262 canal and abstraction links (brown) together with inflow nodes (boundary conditions)

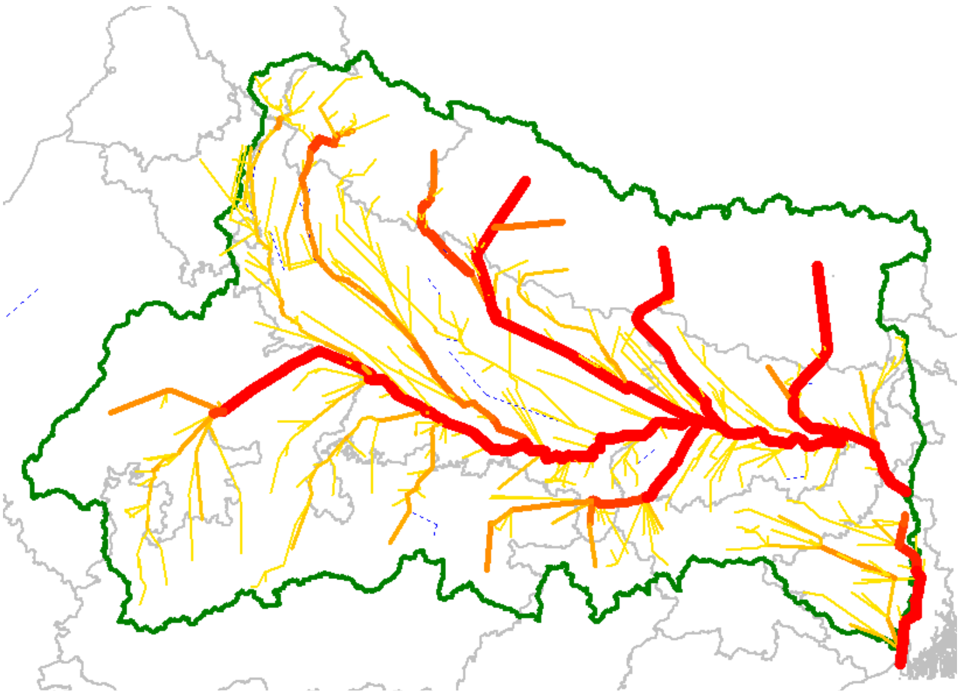


Figure 6.4 DWAQ schematization of surface water (1930 links) of the Ganga river basin. In the graph the width of the segment is proportional to the RIBASIM simulated average flow (1999–2014)

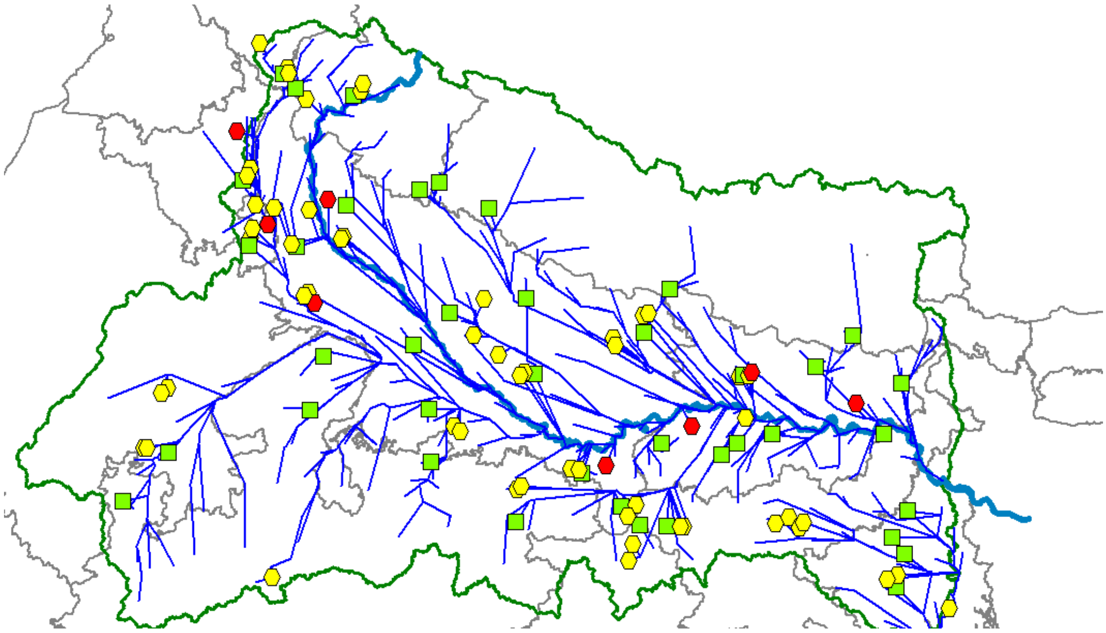


Figure 6.5 DWAQ schematization of surface water with sources of pollution indicated: 53 public water supply nodes (yellow), 8 industrial nodes (red), and 41 irrigation nodes (green).

6.3 Input Data

The input data for the DWAQ model describe the situation with respect to water quality. As the main reference report for emissions is a report published in 2011, based on data from 2001, the model is considered representative for the period 2001–2011. DWAQ is 1:1 coupled to RIBASIM and copies relevant inputs such as population numbers, agricultural and industrial data from RIBASIM, which are considered representative for 2015 (see Section 5.3), although in reality data have been collected in earlier years.

Population data per district have been aggregated in the 54 public water supply nodes (Figure 6.5) for domestic demand as described in Section 5.3. Emission factors determining waste production are derived from various literature sources (Metcalf & Eddy (1979), CSE (2012) and CPCB (2013)) and presented in Table 6.2. Treatment of sewage is applied separately based predominantly on an inventory (CPCB, 2013) for all major cities (class I and class II, total 49), which provide waste water generation and treatment capacity, in terms of MLD volume (census 2001). From this information the percentage treatment per treatment facility is derived and used as input to the waste load model (“Fr”, in 2nd equation Section 6.1).

Table 6.2: Emission factors for population

	BOD (g/cap/d)	NH4 (g/cap/d)	NO3 (g/cap/d)	TN g/cap/d)	TP (g/cap/d)	TColi (#/cap/d)	FColi (#/cap/d)
Untreated sewage	40 (27–41)	3	1	4 (8–14)	1.8 (0.4–2.0)	2.0e6	2.0e5

Treatment efficiency in terms of removal fraction due to treatment (“Φ”, in 2nd equation Section 6.1) is based on the same inventory (CPBC, 2013) of 51 sewage treatment plants with total installed capacity of 1009 MLD and actual utilization of 59 percent. Performance is evaluated by inspecting concentrations of influent and effluent for BOD and COD.

Removal efficiencies for variables other than BOD and COD were estimated based on typical values for the treatment technology applied in the STP. Information on common treatment technologies in India, mostly the activated sludge process, is based on Tare, V. and Bose, P (2009).

Pollution by industry is based on CPCB, 2013 (Appendix E) in which 764 individual industries (Figure 6.6) are listed with information on 'water consumption' in m^3/d and 'waste generation' also in m^3/d. RIBASIM defines water consumption as explicit use. For the pollution assessment, the waste generation in m^3/d is combined with typical effluent concentrations per type of industry, which were derived from the literature (see Appendix E). Waste generation differs by type of industry. The following types are distinguished: chemical, distillery, dying textile & bleaching, food, dairy & beverages, pulp and paper, sugar, tannery. The remainder is categorized as 'others'. Spatial aggregation of the individual industries to river stretches within a state resulted in the 8 industrial nodes shown in Figure 6.5).

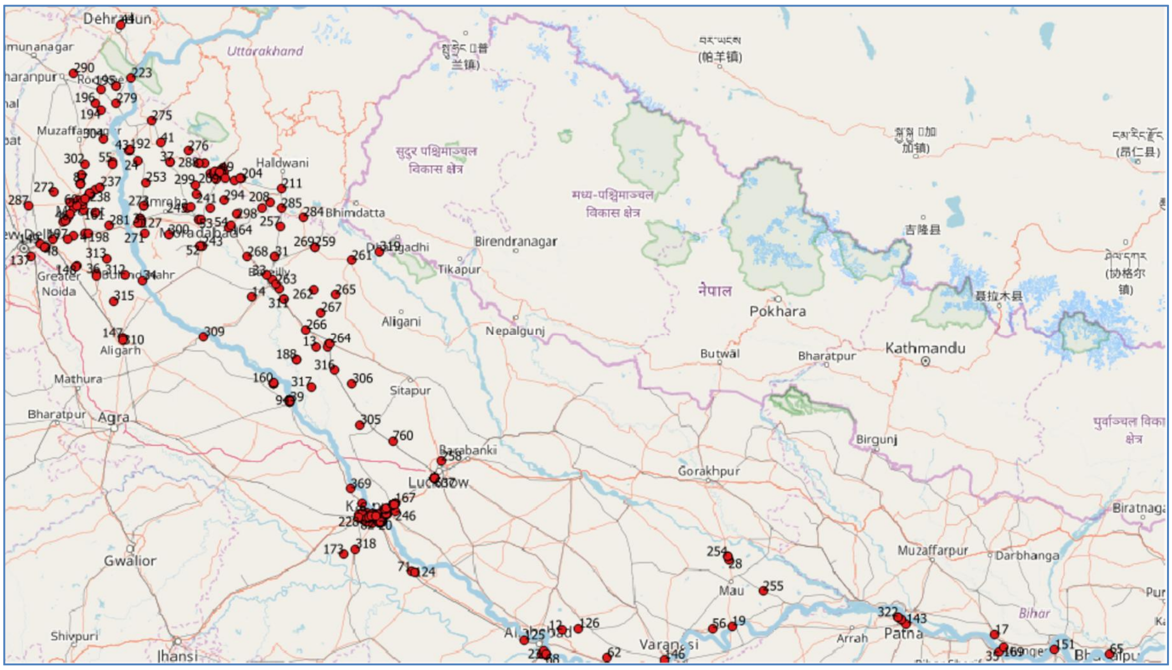


Figure 6.6 Map showing most polluting industries in the basin (CPCB,2013).

Loads from irrigation are derived by multiplying the total irrigated area per irrigation node and per crop type with a specific emission factor that quantifies the loss by leaching from soil in g/ha/year. Extents of N, P, and K loss depend on various factors such as fertilizer use, soil type, climate, and crop type. Loss of N through leaching from Indian soils is 10–20 kg N ha (Pathak et al, 2009). Based on this study estimates for crop specific emissions from irrigated areas were made using data on nutrient requirement per crop type (Pathak et al, 2009) and the assumption that loss through leaching, volatilization, and denitrification accounts for 50 percent of N inputs. The cropping pattern for each node is included in the RIBASIM input (Appendix D).

A complete description of the input data for DWAQ, their origin and their storage location in the system can be found in Appendix E.

6.4 Link with Other Components of the Ganga River Basin Model

DWAQ is based on RIBASIM results. RIBASIM simulates the flows and water balance in a network consisting of links and nodes (Section 5.1). The nodes represent the inflow of water per subbasin, simulated by Wflow (see Section 3.2) and the flow from the groundwater to the river, simulated by iMOD (see Section 4.1). Nodes also account for different types of water demands.

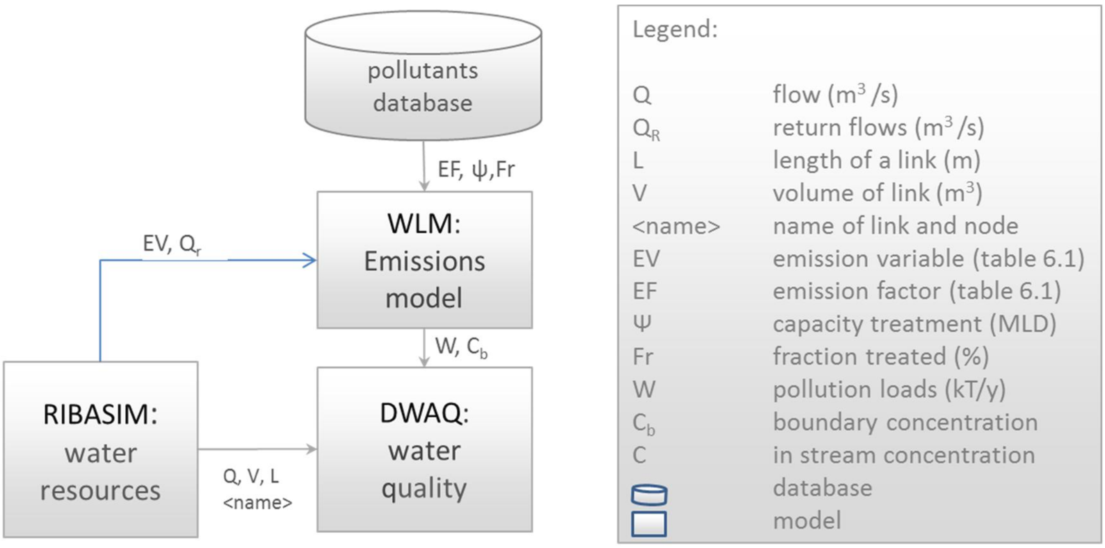


Figure 6.7 Schematic representation of the exchanges between the model components Wflow, RIBASIM and iMOD

RIBASIM links represent the transport of water through rivers, tributaries, canals and tube wells. All links in RIBASIM are transferred one-by-one to a completely mixed segment for the water quality calculation in DWAQ. Every link has its own concentration, and the flow of pollutants through the network follows the flow of water (Q in Figure 6.7).

Some of the RIBASIM nodes, e.g. Link Storage nodes and Reservoirs, are included in the segments because they hold a water volume. The volume of the DWAQ segment is then based upon the volume of the RIBASIM node (V in Figure 6.7).

For RIBASIM links lacking volume, the volume is estimated using the length of the link (L in Figure 6.7) and a representative low flow in the link, 10 percent mean flow, with a minimum of 0.5 m^3/s. This yields a static segment volume. Furthermore, a fixed depth to width ratio for these segments is assumed (see Appendix E). DWAQ segments adopt their naming from links and node names in RIBASIM according to principles explained in WLM (2017).

The emission model WLM receives emission variables from water demanding nodes in RIBASIM, viz. public water supply nodes, industry nodes and irrigation nodes. The population number, the return flows and the cultivated areas for various crops are communicated to the waste load module (see EV and Qr in Figure 6.7). The pollution database contains the relevant emission factors to convert this information to emissions (W) which are fed to DWAQ.

The concentrations simulated by DWAQ are used for presentation in the dashboard (Section 6.6) and a selection of variables, e.g. dissolved oxygen, is used in the environmental impact assessment. Concentrations are available in all DWAQ model segments.

6.5 Calibration and Validation Results

WLM and DWAQ are both calibrated on the measured instream water quality recordings in the main branch of the rivers Ganga and Yamuna in a tiered approach adjusting (1) the instream decay rates in DWAQ and (2) the catchment retention for non-point rural emissions from population by increasing the share of groundwater return flows.

All available water quality measurements from water quality monitoring stations on the Ganga and Yamuna rivers by CPCB and CWC (±40) are used for the calibration. The time series for the calibration period (1999–2014) are statistically summarized to a 15-year average. Longitudinal plots for Ganga and Yamuna (Figure 6.8 to Figure 6.10, legend explained in Table 6.3). By following this procedure, the impact of occasional less reliable data points is reduced.

The number of data points in the measurements is considered insufficient to use in an independent calibration and validation period. In addition to the validation presented here, the yearly variation in observed and simulated water quality using yearly box-whisker plots is compared for a number of representative water quality stations (see Appendix E).

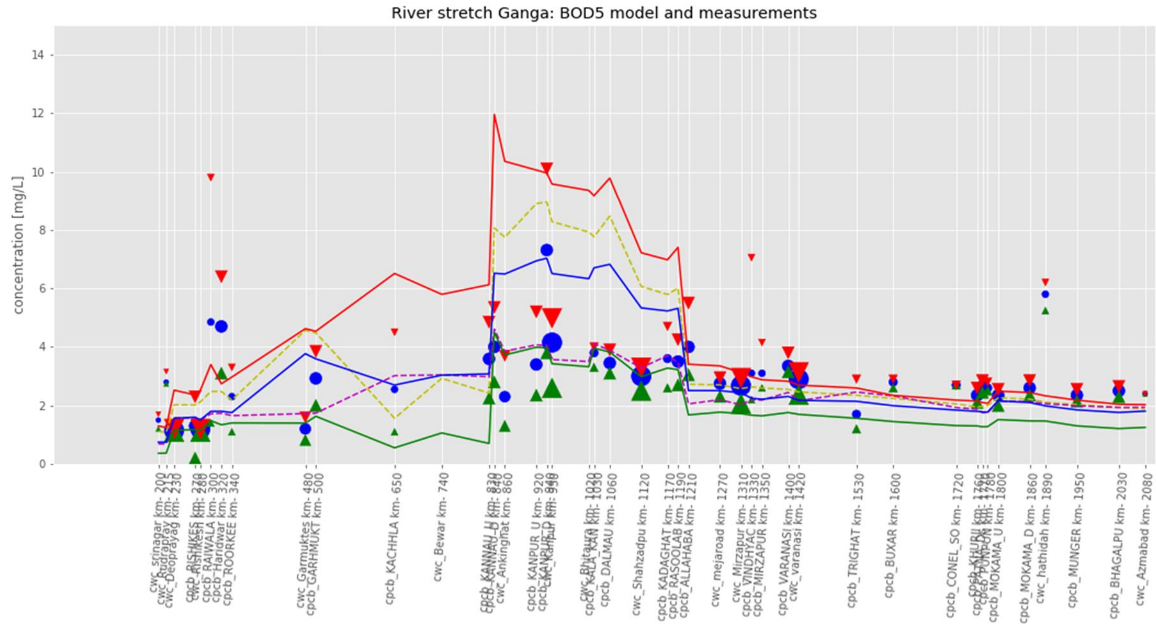
Table 6.3: Explanation of longitudinal plots (Figure 6 8–Figure 6 13)

	Model result	Measurement result
	10-percentile yearly value	▲
	50-percentile value monsoon	na
	50-percentile yearly value	●
	50-percentile value winter	na
	90-percentile yearly value	▼
In the longitudinal plots, the model and measurement statistic are kept similar: for each calendar year the minimum value, 10-percentle value, the median, and 90-percentile, are determined based on 10-day output frequency of the model. The 15-year (1990–2014) model simulation statistics are summarized using their median value for those calendar years where measurements are available. Model results for the dry winter season of December, January, and February and for the wet monsoon period of July, August and September are presented. This information is not available for the CPCB measurements as they only report annual minimum, median and maximum values.		

Results show that the dry season values are close to the maximum yearly values and the monsoon values approximate the yearly minimum values. This is expected as the highest monsoon river flows heavily dilute the waste loads giving the lowest concentrations, while the opposite holds for the dry winter season flows.

Given the uncertainties in discharge and river volumes, emissions and water quality measurements and the rather crude DWAQ schematization the model shows an acceptable degree of agreement with the measurements (
Table 6.4):

- Predicted longitudinal patterns match the pattern in the measurements: there is an unpolluted upstream river section, a section with heavy pollution in the middle parts of the river as a result of low flows or strong abstractions followed by a section with better water quality downstream, notably in the Ganga, where despite a strong pollution load, water quality improves by dilution and self-purification;
- Yamuna concentrations for polluting substances exceed Ganga concentrations, both in the data and in the model;
- Yearly averaged simulated concentrations are in agreement with measured levels for BOD, DO, Coliforms;



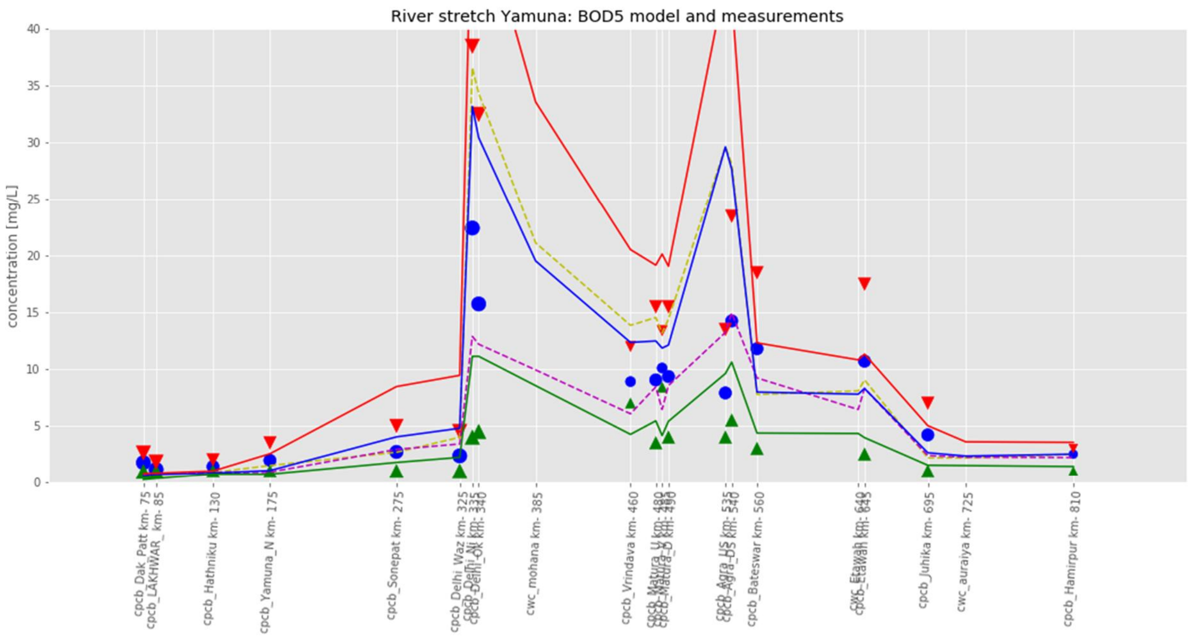
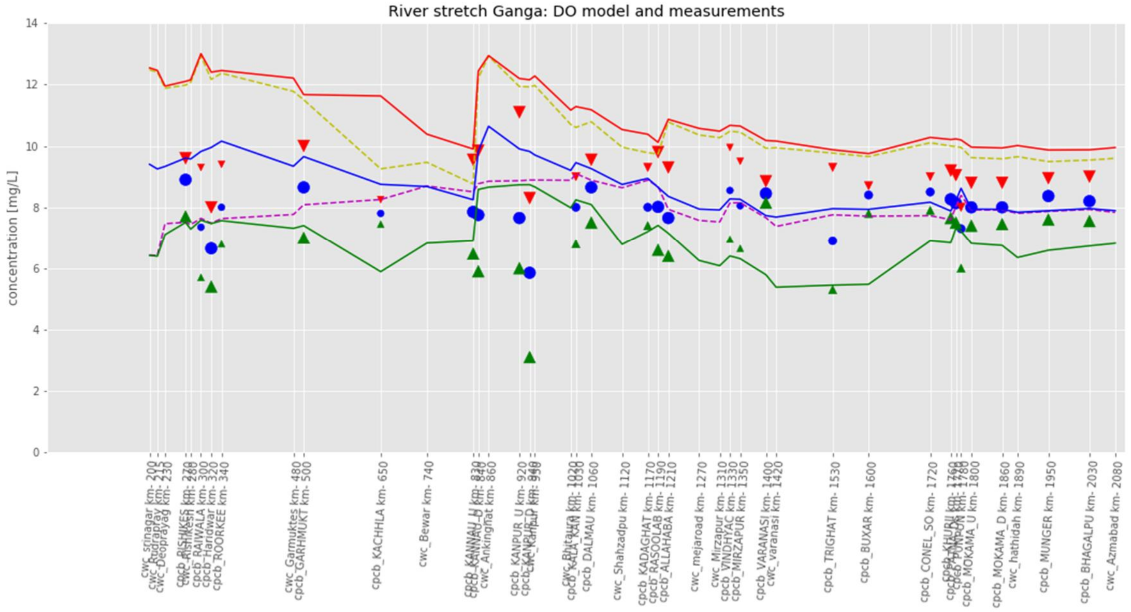


Figure 6.8: Longitudinal profile of measured (symbols) and simulated (lines) biochemical oxygen demand (BOD5, mg/L) for river Ganga(top) and Yamuna (bottom). Table 6 3 provides the legend. Symbol size is dependent on number of years represented.



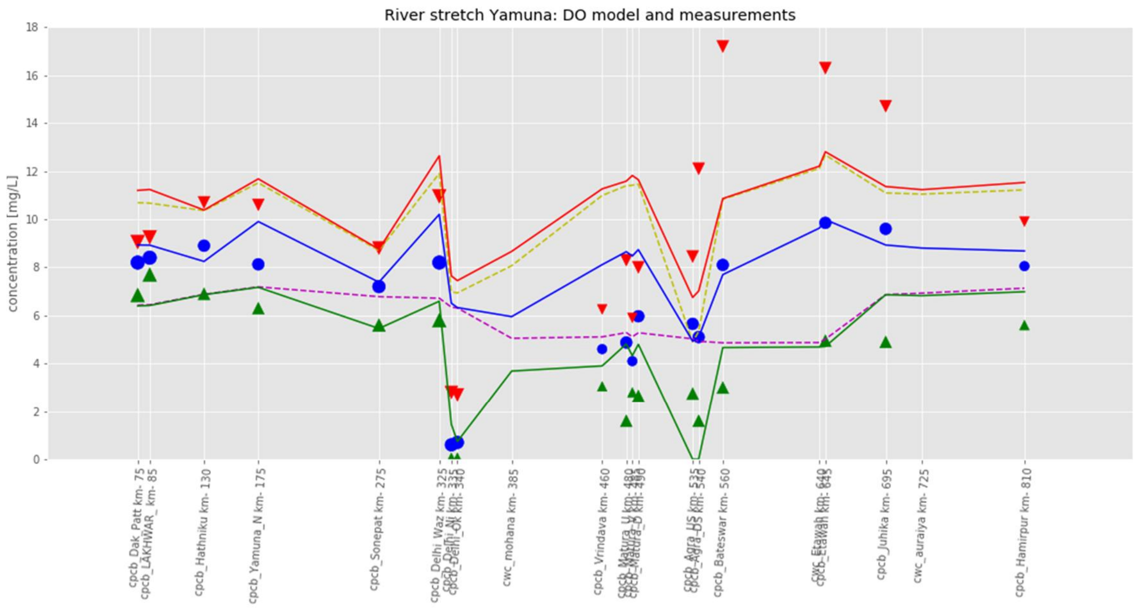
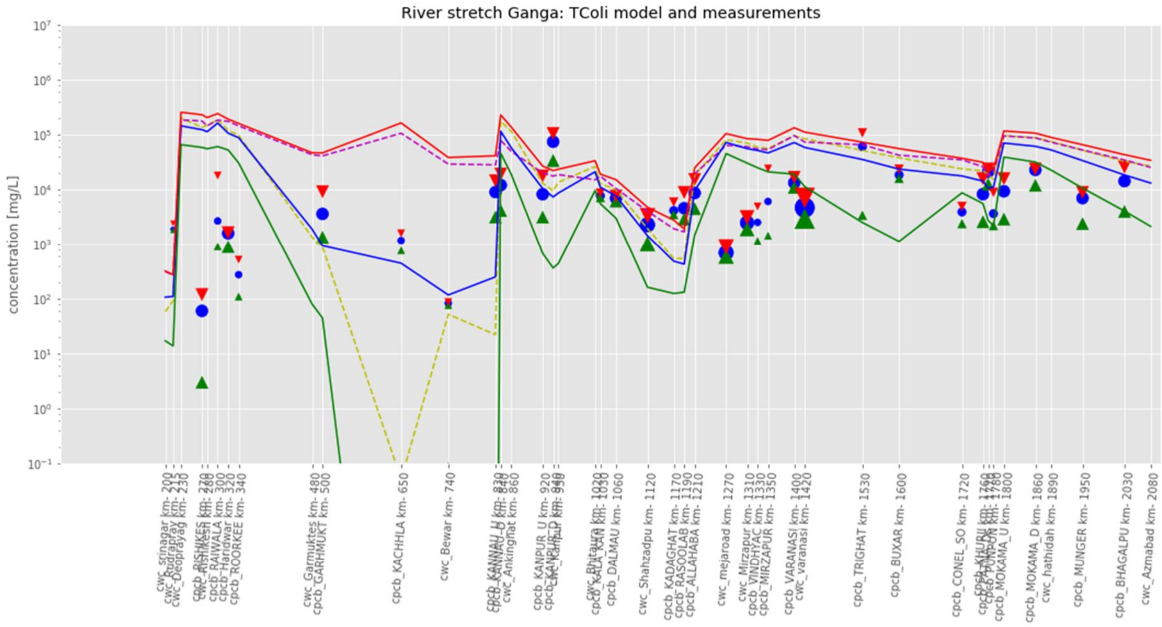


Figure 6.9 : Longitudinal profile of measured (symbols) and simulated (lines) dissolved oxygen (DO) for river Ganga (top) and river Yamuna (bottom). Table 6.3 provides the legend. Symbol size is dependent on number of years represented.



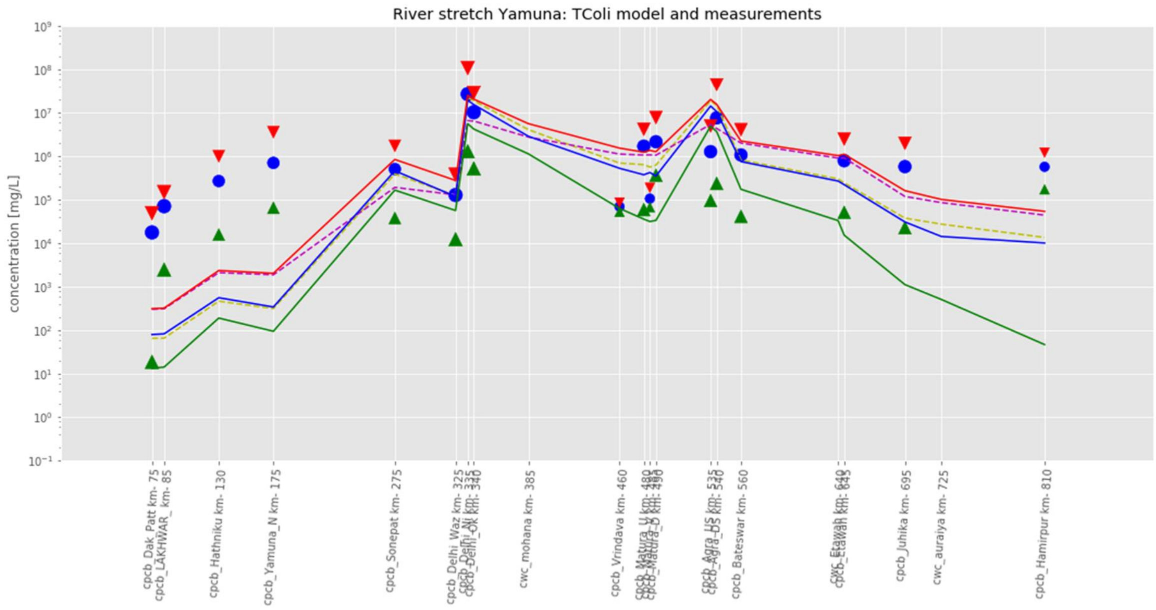


Figure 6.10 : Longitudinal profile of measured (symbols) and simulated (lines) total coliforms for river Ganga (top) and river Yamuna (bottom). Table 6.3 provides the legend. Symbol size is dependent on number of years represented.

- Occasionally significant deviations between the model and the measurements may be expected in the dry season, as the simulated low flows are less accurate. Therefore, the seasonal variation in the model may deviate from that in the measurements.

Table 6.4 Index of agreement for Ganges and Yamuna water quality variables.*

River	BOD5	DO	TColi§	FColi§	Water temperature
Ganga	0.49	0.45	0.33	0.30	0.74
Yamuna	0.68	0.58	0.53	0.52	0.79

§ after log transformation

* McCuen et al. (2006) showed that the outliers can significantly influence sample values of the Nash–Sutcliffe efficiency index. We therefore use the index of agreement, d, varying from 0 to 1 with higher values indicating a better fit of the model as proposed by Legates D.R. and McCabe (1999):

$$d = 1.0 - \frac{\sum_{i=1}^{N} |O_i - P_i|}{\sum_{i=1}^{N} (|P_i - \bar{O}| + |O_i - \bar{O}|)}$$

N is the number of pairs of model predictions (Pi) and field observations (Oi). The advantage of this index of agreement is that the errors and differences are given more appropriate weighting, and are not inflated by their squared values.

6.6 Indicators on the Dashboard

The "surface water quality index" is the only dashboard indicator derived from the results of the water quality model. The indicator is derived from the CPCB classification for designated best use in which the CPCB classifies inland surface waters into five categories (A to E) on the basis of criteria for designated best use (Table 6.5). The classification is such that the water quality requirement becomes progressively lower from A (drinking water source) to E (irrigation and industrial cooling). The water quality of any one of the five categories also satisfies the requirements of the lower categories. Waters may fall below the lowest class E when quality fails to meet the class E criteria.

The water quality model does not include all the parameters required in the CPCB classification. For classes A, B and C, pH is missing; for class D, free ammonia is missing; for class E, none of the required irrigation parameters (EC, SAR and Boron) are modelled. The surface water quality classification in the dashboard is based on simulation results of Total Coliform bacteria, Dissolved Oxygen and Biochemical Oxygen Demand only.

Interpretation of the dashboard indicator shown in Table 6.6 implies:

- Classes A, B, C are not based on pH. As pH is normally not the most critical parameter for these classes this is considered not a severe limitation;
- Class D is based on dissolved oxygen whereas ammonia should be evaluated too. This is considered a limitation which cannot easily be solved as ammonia is not modelled, for lack of validation data and not available in the measurements;
- Class E should be interpreted as "not suitable for designated uses under classes A to D". Its suitability for irrigation or industrial cooling cannot be evaluated by the model.

The surface water indicator is presented in the dashboard per location as a stacked, up to 100 percent, color bar which shows the distribution of the water quality classes (A–E) over the simulated years. The vertical size of the bars indicates which percentage of the time this water quality class is available at this location. The indicator is calculated from monthly averaged model results.

Table 6.5: CPCB Water Quality Classification based on Criteria for designated best use of surface water (http://cpcb.nic.in/water-quality-criteria)

Designated Best Use	Class of water	Criteria
Drinking Water Source without conventional treatment but after disinfection	A	• Total Coliforms Organism MPN/100ml shall be 50 or less • pH between 6.5 and 8.5 • Dissolved Oxygen 6mg/l or more • Biochemical Oxygen Demand 5 days 20°C 2mg/l or less
Outdoor bathing (Organized)	B	• Total Coliforms Organism MPN/100ml shall be 500 or less • pH between 6.5 and 8.5 • Dissolved Oxygen 5mg/l or more • Biochemical Oxygen Demand 5 days 20°C 3mg/l or less
Drinking water source after conventional treatment and disinfection	C	• Total Coliforms Organism MPN/100ml shall be 5000 or less • pH between 6 to 9 • Dissolved Oxygen 4mg/l or more • Biochemical Oxygen Demand 5 days 20°C 3mg/l or less
Propagation of Wild life and Fisheries	D	• pH between 6.5 to 8.5 • Dissolved Oxygen 4mg/l or more • Free Ammonia (as N) 1.2 mg/l or less
Irrigation, Industrial Cooling, Controlled Waste disposal	E	• pH between 6.0 to 8.5 • Electrical Conductivity at 25C micro mhos/cm Max.2250 • Sodium absorption Ratio Max. 26 • Boron Max. 2mg/l

Table 6.6: Water Quality classification criteria based on variables available in the water quality model.

	A	B	C	D	E
Total Coliforms	**≤50**	**≤500**	**≤5000**	**-**	**-**
Biochemical oxygen demand	**≤2**	**≤3**	**≤3**	**-**	**-**
Dissolved oxygen	**≥6**	**≥5**	**≥4**	**≥4**	**-**
pH	**nc**	**nc**	**nc**	**nc**	**nc**
Ammonia	**-**	**-**	**-**	**nc**	**-**
Irrigation parameters (SAR, Boron, EC)	**-**	**-**	**-**	**-**	**nc**
nc = not checked, - not a variable for this class					

7 Indicators for Environmental Flow Analysis

7.1 Concepts

To assess the impact of alterations in discharge and water quality on the Ganga ecosystem and services, three main Dashboard indicators are calculated within the Ganga river basin model: hydrological alteration, species habitat suitability and ecosystem service availability (Figure 7.1). Each main indicator is an aggregation of several underlying sub-indicators. Both main and sub-indicators were selected for ecological and social relevance and together cover the main valued features of the Ganga river system (details in Appendix F). To account for spatial variation, the Ganga main stem and parts of major tributaries are divided into zones with relatively homogeneous geomorphological, anthropogenic, hydrological and ecological characteristics. Indicators are calculated for each of these 'ecozones'. This chapter describes the creation of the river zonation and how the main indicators and sub-indicators are calculated, aggregated and presented on the dashboard.

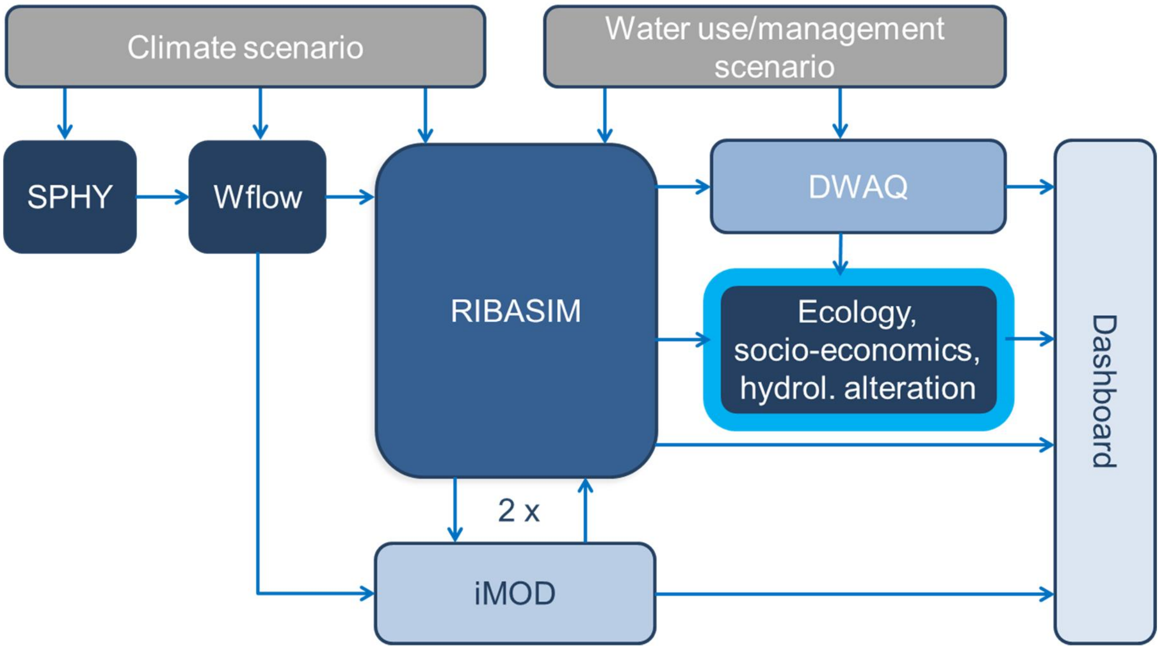


Figure 7.1: The position of hydrological-, ecological- and socio economic calculations in the workflow for the Ganga river basin model

7.2 Overall Approach to Assess Impacts on Ganga Ecosystem and Services

Three types of indicators are considered for Dashboard presentation by the Ganga Information System:

- Indicators that describe alteration in ecologically-relevant flow characteristics;
- Indicators that show the habitat suitability for key species; and
- Indicators that show the extent of the ecosystem services offered to society.

Figure 7.2 shows the main lines through which model output is processed into the main indicators. As input, the indicators use a 30-year time series of monthly discharge and water quality, dissolved oxygen (DO), Biological Oxygen Demand (BOD) and temperature data calculated by the hydrological and water quality models from the Ganga river basin model.

For some indicators the discharge is converted into water depth. For these conversion rules, additional analysis was carried out as discussed in Section 7.4.2.

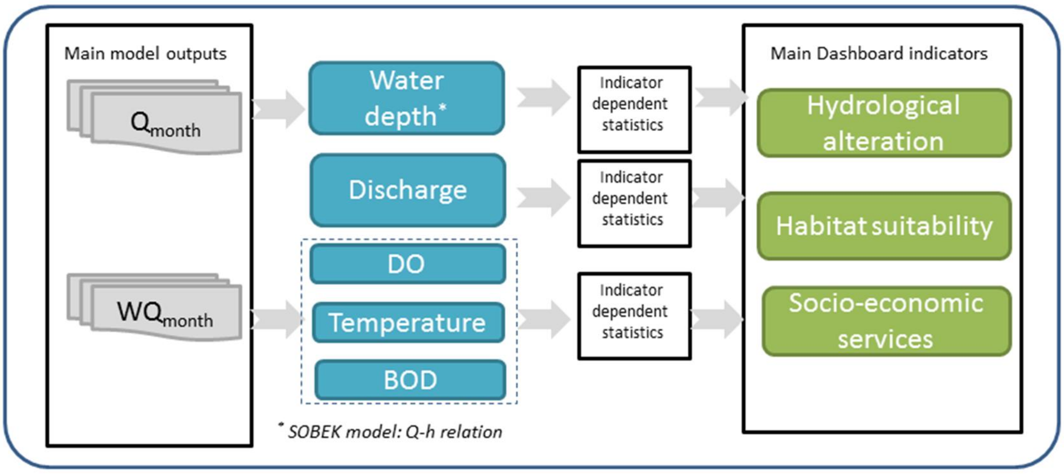


Figure 7.2: Flow diagram for the calculation of indicators for the environmental flow analysis.

All indicators will be computed as deviations from a reference situation, which is a situation without human influence or a 'pristine' situation. The pristine situation excludes all human interferences by returning the natural vegetation cover for natural ecohydrological processes, removing irrigation, public water supplies and dams from the RIBASIM model and removing anthropogenic emissions. Although this situation may not be achievable, it provides the best reference. In analysis of the results, it should however be kept in mind that deviations, and even large deviations in certain zones, may be societally acceptable. The indicators will be evaluated as a deviation class that refers to percentages of agreement with the reference situation (Table 7.1).

Table 7.1: Classes to depict deviation from reference

Description	**Class**	**Agreement (%)**
	Reference	100 (no deviation)
Very good	Class A	80 – 100
Good	Class B	60 – 80
Moderate	Class C	40 – 60
Poor	Class D	20 – 40
Very poor	Class E	0 – 20

Results are presented in three ways: in a river chart, a map and the main scorecard. The river chart visualizes the class distribution of a specified indicator over time per zone for ecology and socio-economics. The map represents a weighted average value for the main indicators for each eco zone. The Main Scorecard, which will be presented on the Dashboard, contains an average of the weighted average values for all ecozones per indicator. The detailed approach per indicator is described in Section 7.4, Figure 7.8 and Appendix F.1.

7.3 River Zonation into 'Ecozones'

The Ganga river and its major tributaries were subdivided into ecozones (Figure 7.3 and Appendix F.2). Indicators are calculated separately for each ecozone. In the river basin model, each zone contains one output location that provides the water quality and flow results that form input for the computation of the indicators (see also Appendix F.3 for model nodes corresponding to ecozones).

The upper reaches of several rivers, the Burhi-Gandak, the Chambal, the Gomti, the Sind and the Sone, were not included in the river basin model due to their smaller scale and limited impact on the total Ganga river catchment. This makes it impossible to model these reaches with sufficient level of detail within the spatial resolution of a strategic river basin model. Therefore, these ecozones were dismissed from the final zonation.

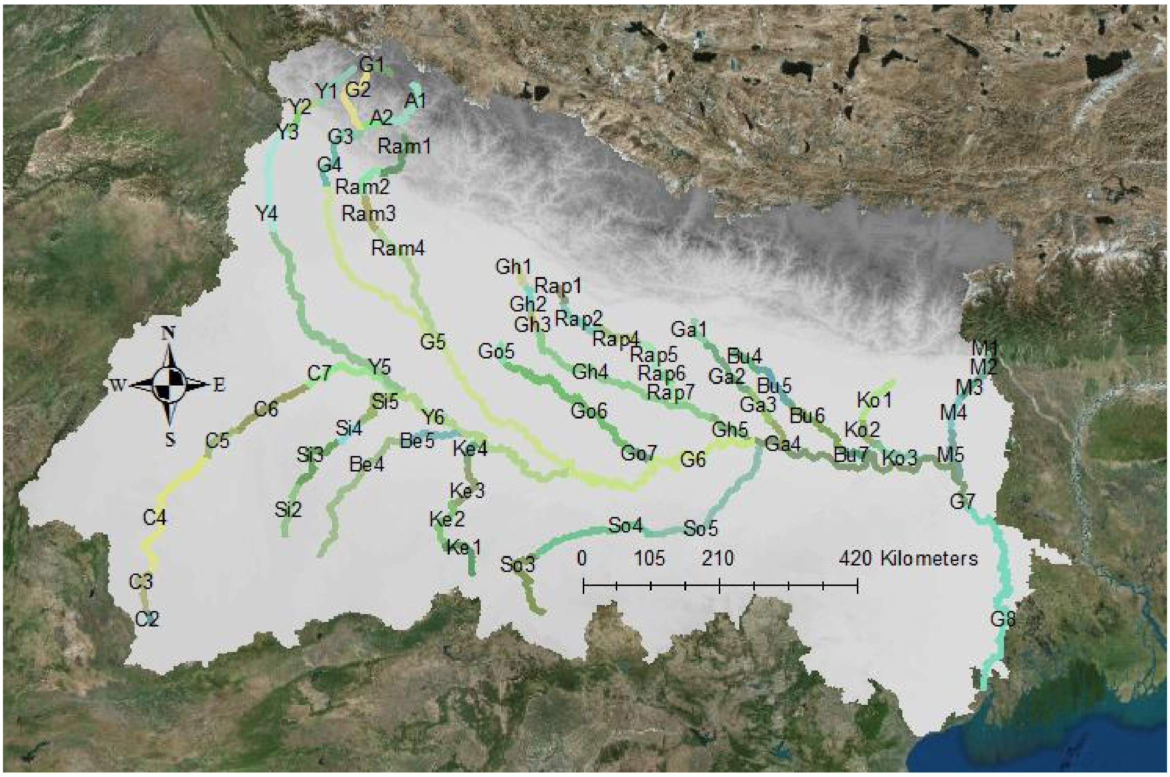


Figure 7.3: Division of the Ganga River and its tributaries into 'ecozones'.

The Need for Zonation

Assessment of environmental flows for the Ganga river basin requires a division into ecologically and socio-economically distinct riverine stretches to effectively capture this large and complex river system. For this purpose, a representative group of rivers, strategically selected from the Ganga river system, was subjected to systematic zonation. The zonation process was designed to identify each riverine stretch characterized by a unique set of ecological and socioeconomic traits, which distinguishes it from all the other riverine stretches in the zonation scope.

7.3.1 Scope of the Zonation

The scope of the zonation exercise comprised the following 16 rivers of the Ganga river basin: Ganga, the Ganga main stem, considered from Gomukh to Ganga Sagar; ten primary tributaries, namely Alaknanda, Ramganga, Yamuna, Gomti, Ghaghra, Sone, Gandak, Burhi-Gandak, Kosi and Mahananda, that drain directly into the Ganga main stem; and five secondary tributaries, namely Chambal, Sind, Betwa, Ken and Rapti, that drain into one of the primary tributaries. The selection of these particular rivers for inclusion in the zonation was based on hydrological considerations and their relative contribution to the Ganga river. For each of these rivers, the zonation process considered primarily the river channel and banks and secondarily the overall catchment.

7.3.2 The Zonation Methodology

The following steps were followed for zoning each river:

1. Construction of a longitudinal profile of the river channel to derive a slope graph of the river. This leads to a zonation on the basis of significant inflections in slope;
2. Examination of the hydrogeomorphology of each slope-based zone. Identification of river stretches distinguished by distinct sets of hydrogeomorphic features. This step refines the zonation from step 1;
3. Examination of the confluences of the river with tributaries. This leads to a zonation of the river on the basis of confluences with tributaries which significantly influence the amount of water in the river downstream;
4. Examination of the riparian forest along the river. Zonation of the river on the basis of presence, extent and quality of riparian forest along different riverine stretches, leading to a riparian forest-based zonation;
5. Examination of the habitat ranges of faunal species with respect to the river, leading to a zonation based on the range limits of faunal species;
6. Comparison of the results from steps 3, 4 and 5 to identify zones reiterated by the three corresponding zonation criteria and integration of these steps into the zonation from step 2;
7. Examination of the major anthropogenic pressures on the river, leading to an anthropogenic impact-based zonation;
8. Integration of the Zonation 6 zones into the preliminary zonation to derive the final zonation.

Since hydrogeomorphology is the main driver of riverine character, relatively more weight was given to the zonation resulting from step 2, which is the product of slope inflections and hydrogeomorphic features. The zones suggested by all the other zonation criteria served to reinforce or refine the zones indicated by these initial two zonations. Additional details on the zonation process and the description for each ecozone are provided in Appendix F.2.

7.4 Indicator Post-processing

7.4.1 Indicators of Hydrological Alteration

The hydrological alteration indicator represents a set of ecologically-relevant discharge-based parameters that indicate the flow alteration compared to the pristine situation over 30 simulated meteorological years. The indicators are based on the 'IHA' (Indicators of Hydrological Alteration) method from Richter *et al.* (1997). The IHA method distinguishes 32 indicators that are to be calculated with daily discharge data. Not all indicators could be used in this study because several indicators use daily discharges as input, while the Ganga river basin model calculates with monthly time steps. Moreover, these indicators were initially developed for the United States and may not be directly applicable to the Ganga system. However, the underlying principles are suitable for rivers in many places in the world. According to these principles, the components of a river's flow regime can be described as variations in five parameters: magnitude, timing, duration, frequency and rate of change. Of these, rate of change is difficult to assess with monthly discharge results. For example, sudden changes at small time scales due to reservoir releases cannot be distinguished in the monthly averaged simulation results. For all other parameters, indicators that could be calculated using monthly simulation results were selected (Table 7.2). Some fields in the table were left blank on purpose. For example, a discharge that is exceeded only 20 percent of the time in the pristine situation is assumed to result in the present situation in undesired high damage floods in settlement/urban/cropped areas.

The timing of the minimum discharge month was considered not to provide much information since there is a very large dry season, during which small changes in discharge in one month could result in a large time shift, although the impact in reality is considered to be small. Each indicator will return a single value for the 30-year simulation period (Figure 7.4).

- *Table 7.2: Hydrological indicators used for the environmental flow assessment*

	Very low flow	**Low flows**	**Average flows**	**Intra-annual high flows**	**Inter-annual high flows**
Magnitude	Annual min discharge 20% percentile	average annual minimum discharge	average annual average discharge	average annual max discharge	annual max discharge 80% percentile
Timing				Most frequent month of annual maximum discharge	
Duration		average number of months per year with Q<Q25			
Frequency	frequency of pristine 0.8 percentile exceedance of annual minimum discharge	frequency of pristine median annual minimum discharge		frequency of pristine median annual maximum discharge	

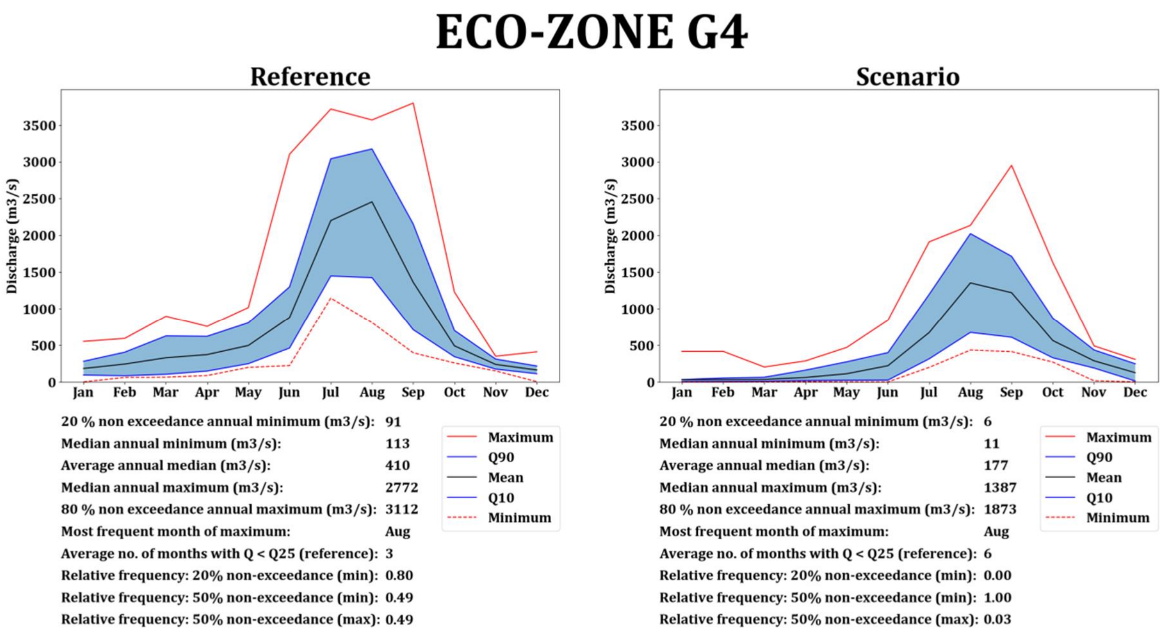


Figure 7.4: Example of hydrological indicators for a zone from one of the test runs (scenario: present climate and water use, reference: pristine situation).

Except for the two indicators of timing and duration, the value of all other indicators is processed into a level of agreement with the value for the same indicator in the pristine situation and assigned a class A, B, C, D or E accordingly (Figure 7.5). For the timing indicators, no change is assigned class A, a one-month shift class B, and a lower class for each additional month change in timing or duration. This results in a class between A and E for all 10 indicators, which are then processed into an average class of hydrological change, rounded down to the lowest class, per ecozone and subsequently to a weighted class over all ecozones. Since hydrological indicators use the variation over time as part of the calculation, this calculation results in only one class per ecozone over all simulated years, as opposed to a class distribution per ecozone as is done for the ecological- and socio-economic indicators. This class is represented on the Dashboard in the bar plot and on the map. To subsequently calculate one value for hydrological alteration for the whole river basin, a similar method for weighted aggregation over all ecozones is applied as described in step 3 of Figure 7.8.

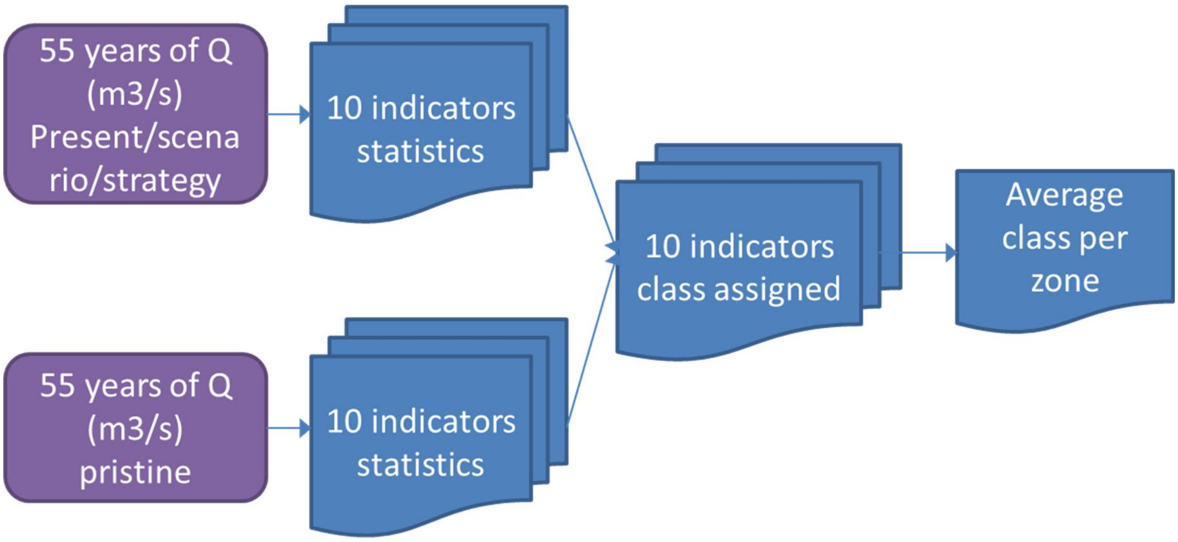


Figure 7.5: Flow diagram for the calculation of the hydrological indicators.

7.4.2 Ecological Indicators

The main ecological indicator is compiled by averaging calculated habitat suitability of several IUCN protected fluvial species, flagship species and food fish species (Table 7.3). This list was agreed upon during the environmental flow workshops with Indian experts.

Table 7.3: List of selected species for ecological indicators (see Appendix F.1 for additional information)

Common name	**Scientific name**
Mottled eel	*Anguilla bengalensis bengalensis*
Snow trout	*Schizothorax richardsonii*
Golden Mahseer	*Tor putitora*
Rohu	*Labeo rohita*
Indian major carp	*Catla catla*
Indian shad	*Tenualosa ilisha*
Indian flapshell turtle	*Lissemys punctata*
Gharial	*Gavialis gangeticus*
Ganga river Dolphin	*Platanista gangetica*

For each species, response curves were created which describe the habitat suitability for variations in water quality, discharge, and water depth parameters (Appendix F.1). These habitat suitability response curves are derived using available literature data combined with expert judgement from Indian experts acquired from two workshops and interactions with Indian experts.

The habitat suitability approach was developed by the U.S. Fish and Wildlife Service (U.S. Fish and Wildlife Service, 1980) and calculates the potential occurrence of species habitats based on a chosen set of environmental conditions ranging from 0, not suitable, to 1, high habitat quality. Higher habitat suitability values mean there is a higher chance of species occurrence due to availability of suitable habitat, but does not assume the species is present. This methodology has been applied in many scientific studies (e.g. Guisan and Zimmerman, 2000; Tomsic et al., 2007; Haasnoot and Van de Wolfshaar, 2009).

The calculation method for water quality parameters and water depth differs slightly (Figure 7.6). For water quality parameters, habitat suitability is calculated per month for the pristine scenario and case scenario and the final habitat suitability for each scenario is the minimum habitat suitability over the year. Subsequently, the absolute deviation of the tested scenario compared to the pristine scenario is calculated and expressed in a class representing the agreement with the pristine situation (Table 7.1). For water depth, the calculation depends on the meters of lateral river bank that are within the suitable depth range of that species, as determined by the response curve. Depth classes are calculated with a Q-h relation and therefore link to the predicted discharge from the Ganga river basin model. The Q-h relations are calculated per ecological zone with SOBEK using cross-sectional data, river slope and a general Manning roughness of 0.04 (SOBEK version 2.13 (Deltares, 2016; example in Figure 7.7). Cross-sectional data was supplied by local authorities and covered the main stem of the Ganga river and most of the larger tributaries to the north (Table and details provided in Appendix F.3). For ecological zones lacking cross-section data, the cross-section of a representative river reach was taken with the discharges of the reach under consideration. The slope was calculated with a Digital Elevation Model (DEM) by dividing the height difference of the river reach within the ecological zone by the length of the corresponding reach.

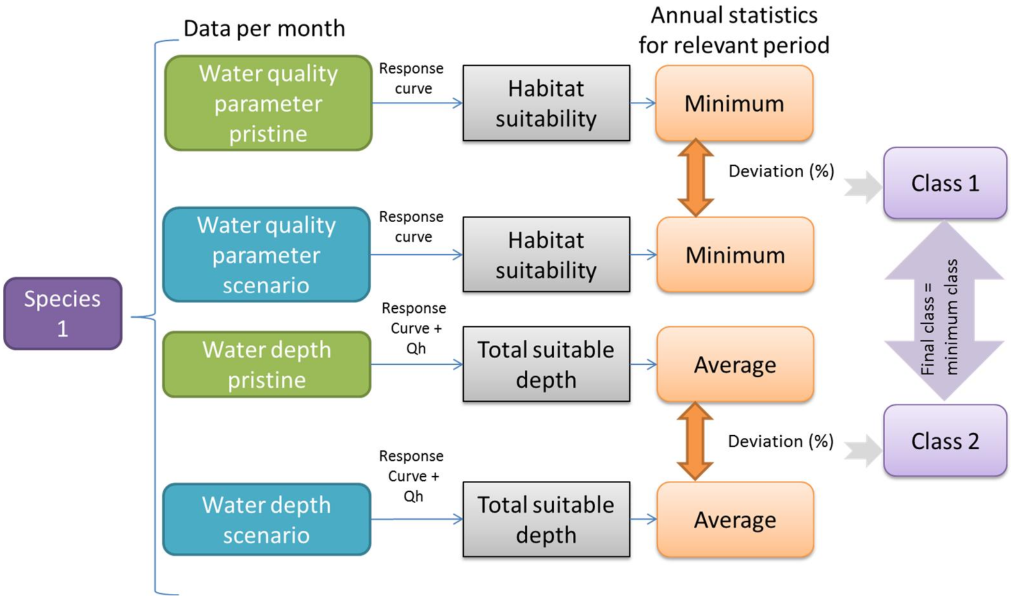


Figure 7.6: Flow diagram for the calculation of the ecological indicators.

This results in summed monthly depths per scenario which are annually averaged, taking into account relevant time periods for ecological events (details provided in Appendix F.1). Depth values were averaged instead of taking the minimum, because it is assumed that species can migrate to more suitable areas within the river reach when the water depth is less suitable in one location, contrary to water quality, which is assumed to be relatively homogeneous within one ecological zone.

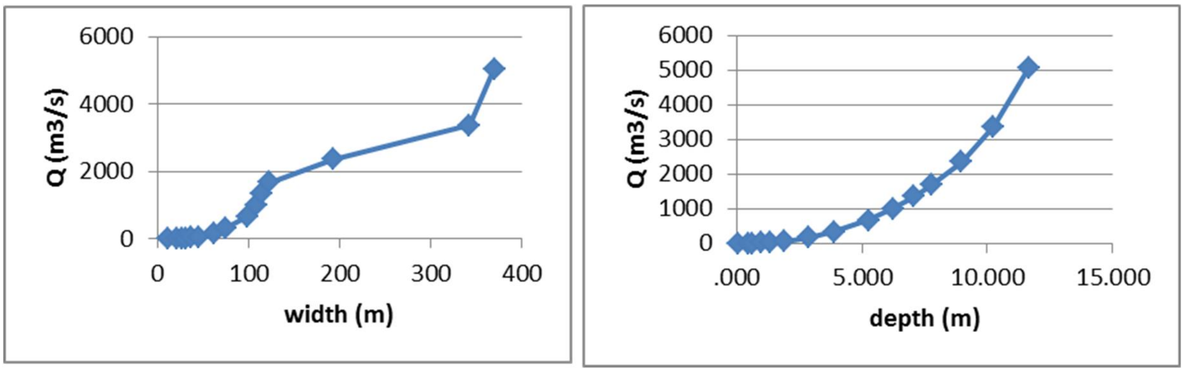


Figure 7.7: Example of the relations between discharge and river width (left) and depth (right) for the ecological zone in the middle of the Ganga river (ECO_G4).

The class is calculated as the deviation from the pristine situation, where values higher than the reference automatically have the highest class (A). For each species, the final class is the minimum class of all environmental parameters, since that is the limiting factor determining habitat suitability for that species in a specific year. For each species the relative class distribution is calculated over all meteorological years.

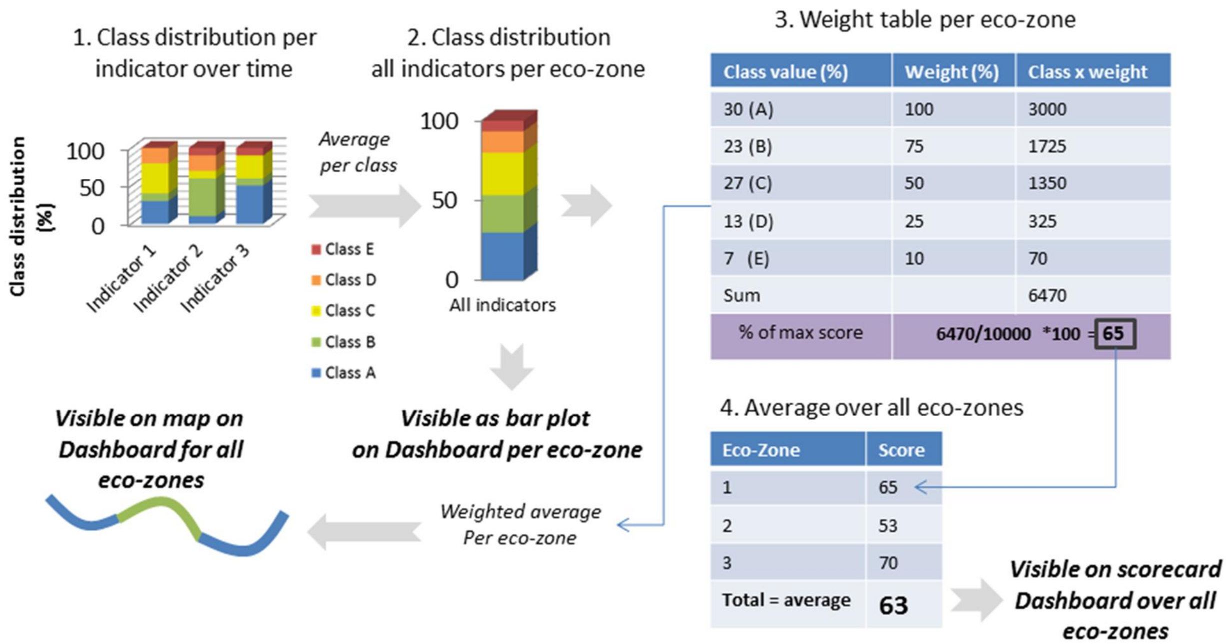


Figure 7.8: Aggregation of indicators and presentation on Dashboard.

Ecological results are depicted on the Dashboard (Figure 7.8):

- A graph calculated per ecozone as an aggregated ecological indicator over species and over time by presenting the average relative class distribution over all species as a bar plot in step 2;

- A scorecard with one ecological indicator aggregated over time, space and species as a weighted aggregation value from step 4;
- A map spatially visualizing the distribution of the weighted average score for each eco zone (result from step 3). The score is translated into a class category based on the percentage range defined on the level of agreement for each class from Table 7.1. For example, weighted average of 65 = class B.

7.4.3 Indicators for Ecosystem Services

Indicators are determined for three services: 1) fisheries, 2) agriculture in the active floodplain, and 3) religious bathing. For each of these services, response curves are developed in a way comparable to the ecological response curves. The fisheries indicator is assumed to depend on the habitat suitability of those fish species that serve as human food product. The fisheries indicator is calculated by selecting the dominant class for each year over all food fish species; this data is subsequently used to create the class distribution of this sub-indicator. When there is more than one dominant class, the lowest class is selected.

Agriculture in the active flood plain is assumed to take place in those areas of the active floodplain that were inundated during the previous year and dry during a large part of the dry season. Religious bathing requires sufficient, but not too deep, water and an acceptable water quality level. The specific response curves are included in Appendix F.1. The class is calculated in a way which slightly deviates from the hydrological and ecological indicators, because a deviation from natural can be beneficial for socio-economic use. The exact equations used are included in Appendix F1. For each service, the monthly class is the minimum class of all environmental parameters per month, since that is the limiting factor determining the service availability for that month. The monthly values are averaged into annual values. The full socio-economic indicator is the average class, rounded to the lower class if necessary, of the three socio-economic indicators.

For all services the relative class distribution is calculated over all meteorological years. Ecosystem service results are visualized on the dashboard (Figure 7.8):

- A graph calculated per ecozone as an aggregated indicator over services and over time by presenting the average relative class distribution over all services;
- A scorecard with one ecosystem services indicator aggregated over time, space and services as a weighted aggregation;
- A map spatially visualizing the distribution of the weighted average score for each service per eco zone translated into a class category resulting from step 3.

7.5 Verification Results

To verify the response curves and aggregation steps, ecological zones that show large changes in hydrology between the pristine and recent situation were selected from the main stem of the Ganga river, its largest tributary the Yamuna and several other smaller tributaries. The zones selected for testing the response curves are presented in Table 7.4.

7.5.1 Testing Ecological Response Curves

The ecological outcome is assessed in two different ways:

- Comparison of the dataset provided by the Indian Central Inland Fisheries Research Institute (CIFRI) to the predicted presence/absence values in the recent situation;
- Comparison of modeled results for the pristine and the recent situation.

Table 7.4: Selected ecozones to be used in the verification of the ecological- and socio-economic response curves. For specific locations of the ecozones see Figure 7.3.

Zone ID	River	Motivation
ECO_Y1	Yamuna	Most important tributary of Ganga river
ECO_Y2	Yamuna	Most important tributary of Ganga river
ECO_Y3	Yamuna	Most important tributary of Ganga river
ECO_Y4	Yamuna	Most important tributary of Ganga river
ECO_Y5	Yamuna	Most important tributary of Ganga river
ECO_Y6	Yamuna	Most important tributary of Ganga river
ECO_G1	Ganga	Main stem Ganga river
ECO_G2	Ganga	Main stem Ganga river
ECO_G3	Ganga	Main stem Ganga river
ECO_G4	Ganga	Main stem Ganga river
ECO_G5	Ganga	Main stem Ganga river
ECO_G6	Ganga	Main stem Ganga river
ECO_G7	Ganga	Main stem Ganga river
ECO_G8	Ganga	Main stem Ganga river
ECO_Go7	Gomti	Tributary Ganga middle reach
ECO_A2	Alaknanda	Tributary Ganga upper reach
ECO_Ram4	Ramganga	Tributary Ganga upper reach
ECO_M5	Mahanandra	Tributary Ganga lower reach

7.5.1.1 *Fish Absence/Presence Prediction*

A fish dataset from CIFRI from 2013 was used to compare the predicted habitat suitability for fish species with the recorded presence data. Fish were assumed present when the predicted habitat suitability was higher than 0 for all parameters. Results are presented in Table 7.5. Since monitoring data was only available for the middle and lower reach of the main stem of the Ganga river, ecozones G4–G8, only these reaches were assessed. It is important to note that the response curves were not constructed with the goal to predict absolute habitat suitability, but only to give an indication of change compared to a pristine situation. This is due to a lack of data to construct refined response curves and therefore these curves should not be used to predict detailed habitat suitability. However, this comparison provides a broad indication of how the modelled data compares to the thresholds of species and the species observations and therefore provides insights in both the quality of the modelled parameters and the sensitivity of the species to certain model parameters.

Table 7.5: Comparison of observed and predicted values for fish presence in the main stem of the Ganga. Colors visualize the outcome of the comparison: true positives and true negatives in green, false positives in orange and false negatives in red. O = observed, present in the dataset and P = predicted by the model.

Species	**Eco G4**		**Eco G5**		**Eco G6**		**Eco G7**		**Eco G8**	
	O	P	O	P	O	P	O	P	O	P
T. putitora	+	-	-	-	-	-	-	-	-	-
T. ilisha	-	+	-	-*	-	+	-	+	+	+
S. richardsonii	+	+	-	-	-	-	-	-	-	-
C. catla	-	-	+	+	+	+	+	+	+	+
A. bengalensis	-	+	+	+	+	+	-	+	+	+
L. rohita	+	-	+	+	+	+	+	+	+	+

For most species and most zones there is generally an agreement between observed and predicted data. *T. putitora* and *S. richardsonii* are both fish that prefer colder headwaters and also contain response curves for temperature, DO and water depth (Table 7.6). In the model, the occurrence of these fish species is restricted to the headwaters based on elevation boundaries (Appendix F.1.2 and F 1.3), where *T. putitora* is able to occur until ECO_G5 and *S. richardsonii* only until ECO_G3. For *S. richardsonii* this matches the response curves for temperature, where the species thresholds for temperature fall within the predicted minimum and maximum temperatures, while the other ecozones are not suitable due to temperatures that fall outside the thresholds (Appendix F.4). This is in line with the observed data. However, for *T. putitora* the predicted temperatures are outside the species thresholds in ECO_G4 and ECO_G5, while the species is observed in ECO_G4. This can be due to the predicted temperature and the thresholds used in the response curve. The temperature in the river basin model is air temperature with a correction to predict water temperature. This results in a relatively large spread in data and, especially in the upper reaches of the Ganga, modeled temperatures that are lower than measurements. This might explain the discrepancy between observed and predicted *T. putitora* in ECO_G4.

However, since all results are presented as a percentage of agreement with the pristine situation, and the temperature is not expected to change much between the present and pristine situations and future scenarios/strategies, temperature is not expected to have an effect on the habitat suitability. Therefore, this parameter is relatively unimportant compared to the other parameters.

C. catla has a relatively wide temperature tolerance and falls consistently inside the modeled temperatures and also contains suitable water depths and oxygen values, resulting in a good fit between observed and predicted.

Table 7.6: List of response curves available for species and services

Species	**Parameters in response curve**			
	Temperature	DO	BOD	Water depth
T. putitora	x	x		x
T. ilisha				x
S. richardsonii	x	x		x
C. catla	x	x		x
A. bengalensis		x		x
L. rohita	x	x		x
P. gangetica				x
G. gangeticus				x
L. punctate				x
Agriculture				x
Bathing			x	x

Occurrence of *A. bengalensis* is dependent on water depth and oxygen. Suitable depth is always available, although very variable between different ecozones (Appendix F.4) and also oxygen is above the critical threshold value. Therefore, *A. bengalensis* is predicted to occur in all ecozones, while it has not been observed in ECO_G4 and ECO_G7. This is probably due to other parameters that were not included in the response curves, e.g. migration. However, since there are large variations in suitable water depth, this parameter is potentially sensitive for changes in discharge. *T. Ilisha* contains only response curves for water depth that indicate this species is better predicted than observed. However, for this species the habitat suitability for water depth in ECO_G5 is very low, which is in line with the observed data (Table 7.5, Appendix F.4). Finally, *L. rohita* is well predicted in all zones based on temperature and water depth, except for ECO_G4, where the temperatures are too low for reasons explained above.

To summarize, the predicted presence/absence values compare relatively well to the observed values; however, the response curves should not be used to predict absolute habitat suitability values. The false negatives can be explained by deviations in predicted temperatures that fall outside the response curves of several species, while the false positives may be explained by the limited number of parameters to restrict occurrence in some ecozones. However, this will most likely have little effect on the difference between pristine and present and therefore will not lead to large deviations in classes. The only risk might be insufficient sensitivity in the response to altered situations for some species that have a limited number of response curves, e.g. *T. Ilisha*.

7.5.1.2 Pristine Versus Present Ecology

The main verification to assess the method for the calculation of ecological response is to check if the trends in predicted agreement classes correspond to the trends in the steering variables, discharge, DO, temperature and water depth. In this way the sensitivity of the indicators for changes in discharge and water quality are assessed.

For each of the selected ecozones, the dynamics in temperature, DO and discharge for the selected zones (Figure 7.9 – Figure 7.11) and water depth (Appendix F 5.3) are compared to the total relative class distribution for all indicators per zone (Figure 7.12).

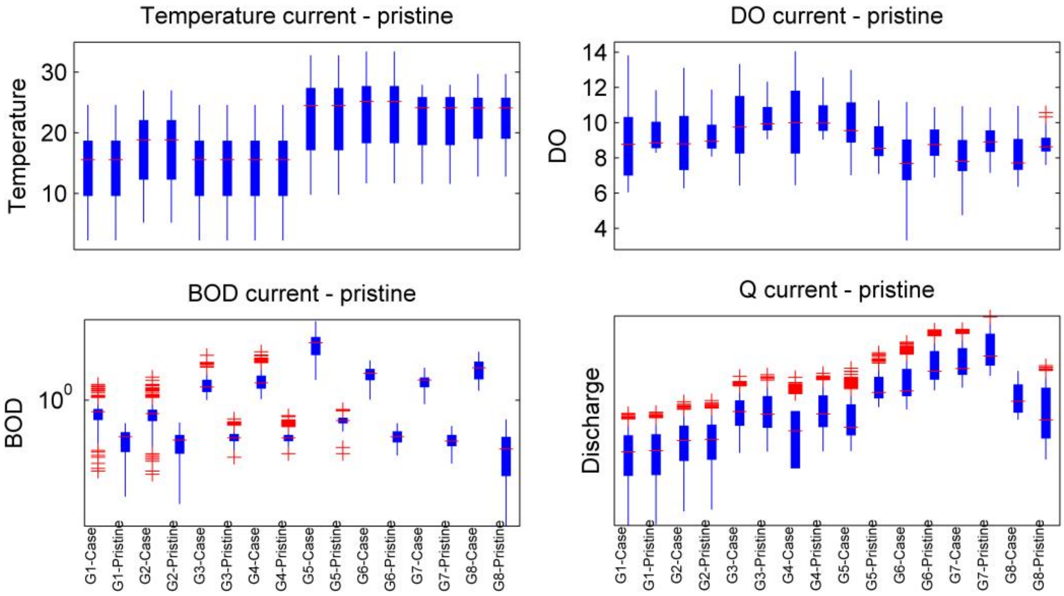


Figure 7.9: Overview of dynamics in water quality and discharge in the pristine versus current situation of the Ganga river. Vertical blue lines represent minimum and maximum range of the data set, not considering outlines (red stripes). Blue boxes represent 25-75 percentile values, red line in the box 50 percentile/median.

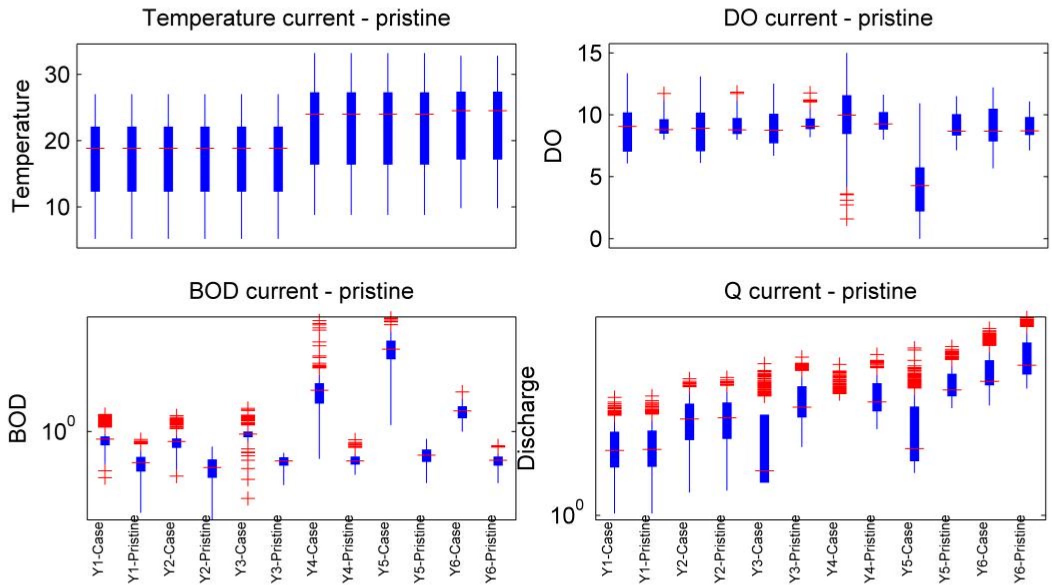


Figure 7.10 : Overview of dynamics in water quality and discharge in the pristine versus current situation of the Yamuna river. Vertical blue lines represent minimum and maximum range of the data set, not considering outlines (red stripes). Blue boxes represent 25-75 percentile values, red line in the box 50 percentile/median.

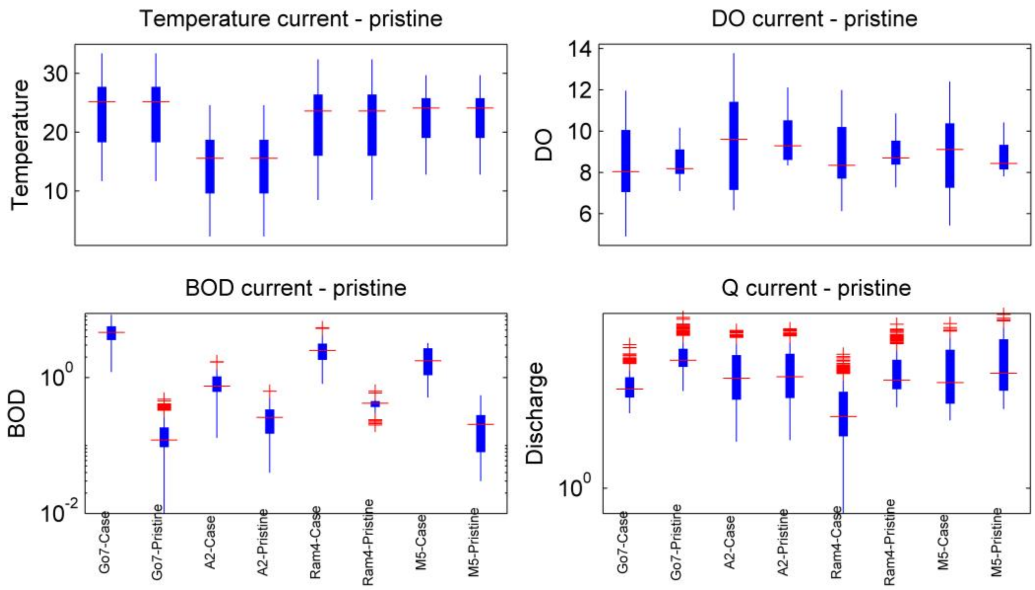


Figure 7.11: Overview of dynamics in water quality and discharge in the pristine versus current situation of the selected tributaries. Vertical blue lines represent minimum and maximum range of the data set, not considering outlines (red stripes). Blue boxes represent 25-75 percentile values, red line in the box 50 percentile/median.

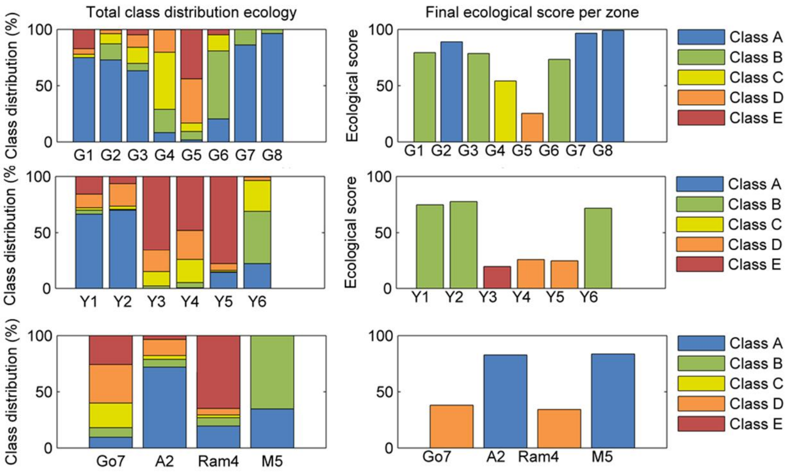


Figure 7.12 : Class distribution of all ecological indicators per selected ecozone (left panels) and the final weighted ecological score (right panels) for Ganga zone (top), Yamuna zone (middle) and tributary zone (bottom).

Results show there are clear class differences between the zones in the selected rivers. In the Ganga river, zones G4 and G5 clearly have a lower class distribution than the other zones (Figure 7.12). This is to be expected since the changes in discharge, DO (Figure 7.9) and corresponding water depths (Appendix F.5.3) are the largest in these zones. A similar result is found in the Yamuna, where ecozones Y3–Y5 clearly have a lower class distribution. For the other tributaries lower classes are found in the lower reaches of the Gomti and Ramganga and higher classes in the Alaknanda and Mahanandra rivers. These results are dominantly influenced by fluctuations in suitable water depth since that is the parameter that is included for most species and is also the only parameter for several species (Table 7.6).

Temperature varies only slightly between pristine and present (Figure 7.9 – Figure 7.11). Thus, temperature is not a discriminating factor. Dissolved oxygen is only included for two fish species that mostly occur in the upper reaches of the Ganga basin which negatively influences the quality in ecozones Ram4 and Y3–Y5. But since the ecological score represents multiple sub-indicators, the relative contribution of DO to the total ecological score is relatively low in this case.

The ecological score correctly reflects changes in discharge and dissolved oxygen, but it is dominantly influenced by changes in suitable water depth. Each species responds differently depending on their sensitivity to specific parameters and the number of parameters that are included in the response curves (Appendix F.5.1). When additional response curves are added for species, the ecological score will decrease because these parameters will most likely restrict the occurrence of this species in some ecozones. This means that adding more species and parameters or refining response curves will improve the realism of the ecological prediction, but it will also change the class distributions of species and hence the total ecological scores.

7.5.2 Testing Socio-Economic Response Curves

7.5.2.1 Pristine Versus Present Socio-Economics

The overall socio-economic result is determined by averaging three indicators: fisheries, agriculture and bathing quality (see Figure 7-13, with detailed results for these three indicators presented in Appendix F.5). The socio-economic score is constructed with a limited number of indicators, so realism of the calculations can be improved by adding more indicators and more response curves, but this will also change the class distributions of services and hence the total socio-economic scores. Also, it was difficult to collect data on actual fish catches, use of the floodplain for agriculture and use of the Ganga for bathing. The indicators therefore need to be considered as a logical approach to further process the model results. Should additional data become available the response curves can be tested and updated.

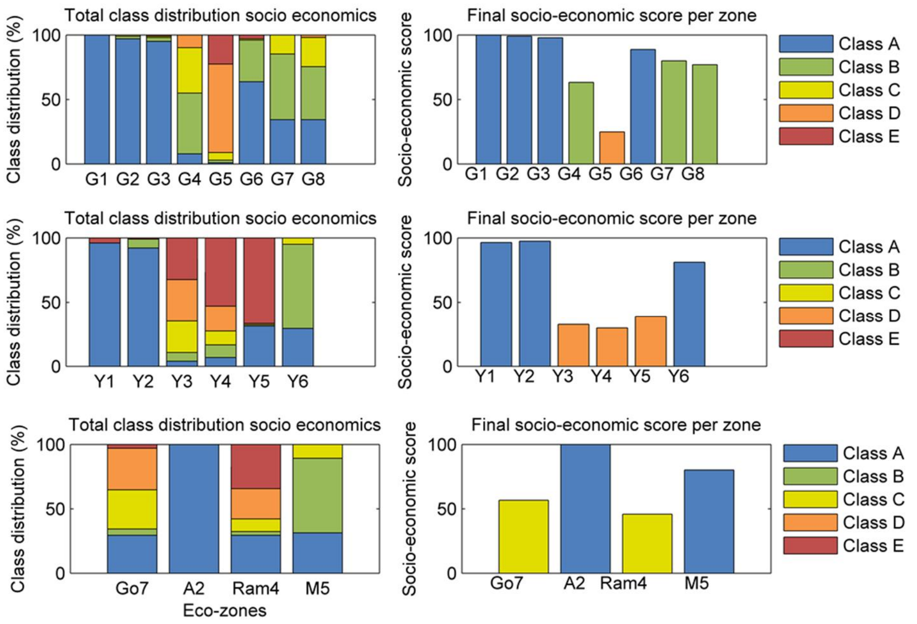


Figure 7.13: Class distribution (left) and weighted combined score for the socio-economic indicator (right) for selected zones in the Ganga (top), Yamuna (middle) and tributaries (bottom)

The current results demonstrate that most zones show a variation in classes over the years. This shows that the indicator responds to variations in model output. This is important for comparing the consequences of different scenarios and strategies.

The results also show a variation in service availability along the Ganga and Yamuna. The results for the upper reaches in the current situation are close to the reference situation. Further downstream the service availability goes down, while in the lowest reaches the availability increases again. This decrease in availability can be explained by large scale abstraction and waste water discharges in these reaches. The increase in availability further downstream can be explained by additional inflows of water of relatively good quality.

The results for religious bathing can be verified in a similar way as the ecological results by comparing spatial trends in agreement classes with variations in the underlying variables. Religious bathing is determined by both BOD and water depth. Since fisheries follow directly from the ecological analysis, the verification of this indicator at the level of correspondence with underlying variables is already carried out in Sections 7.5.1.1 and 7.5.1.2. Agriculture does not follow directly from the water depth indicator, but from differences in water depth between the lean season in a certain year and the monsoon season from the previous year. Since this difference directly determines the indicator score, there is no need to further investigate the underlying variable. The indicator is the underlying variable, recoded into classes.

Variations in BOD for Ganga, Yamuna and a selection of other zones are depicted in Figure 7.9 – Figure 7.11. In addition, variations in river width with a suitable depth for bathing are presented in Figure 7.14. These results show that the variations in BOD between the pristine and current situations are rather large except for the upper reaches, while variations in suitable water depth are small between these situations. Nevertheless, it turns out that the overall results are in most zones limited by water depth requirements.

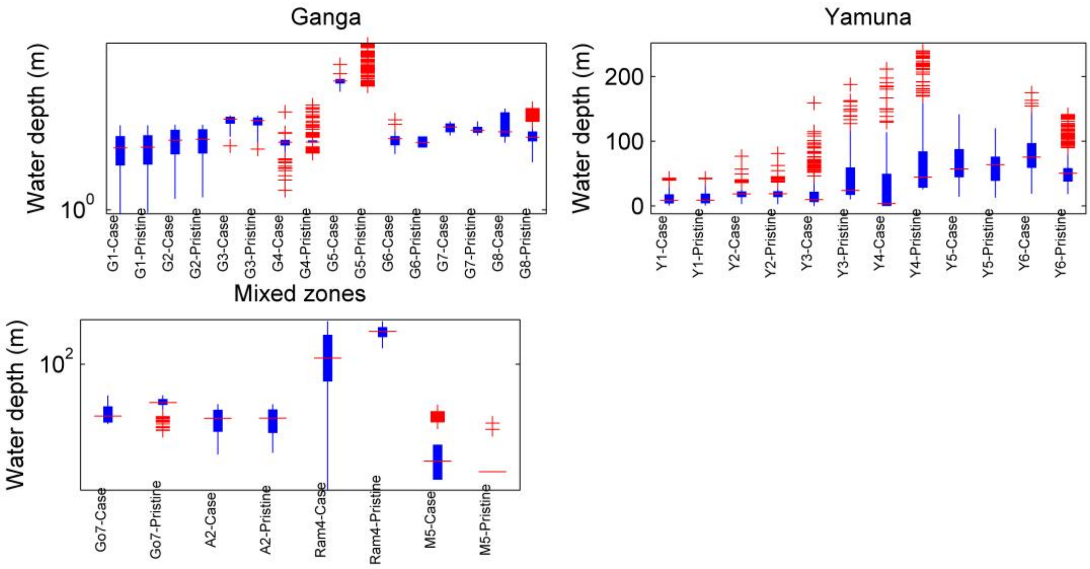


Figure 7.14: Variations in river width with a water depth suitable for bathing for selected zones for both the pristine and the current (case) situation. Vertical blue lines represent minimum and maximum range of the data set, not considering outlines (red stripes). Blue boxes represent 25-75 percentile values, red line in the box 50 percentile/median.

8 GangaWIS

8.1 Introduction

The Ganga water information system (GangaWIS) is designed to enhance understanding of the natural and social systems of the Ganga River Basin. It forms a central repository of relevant, measured and modeled information and data for various users, e.g. data managers, modelers, policy makers and decision makers from different organizations within the Ganga basin. This has major consequences for data management and dissemination, in particular, the definition of several levels of access.

GangaWIS is based on global standards for exchange of data. Model results for various scenarios will be made available to the general public via OGC services[9]. Data from model studies performed in GangaWIS can be disseminated through IndiaWRIS; conversely IndiaWRIS data can be imported manually into GangaWIS to serve as input and background data.

Various information systems currently exist. The most important for the Ganga project is IndiaWRIS[10], which was the product of a joint venture project between the Central Water Commission (CWC), Ministry of Water Resources and the Indian Space Research Organization (ISRO), Department of Space. The project, *"Generation of Database and Implementation of Web Enabled Water Resources Information System in the Country",* was governed by a Memorandum of Understanding (MOU) between the two departments signed on December 3, 2008, for a period of four years, and subsequently extended through December, 2015. IndiaWRIS is an information system that disseminates earth science related data on web pages and via OGC WMS services. It is not designed to allow linking of models and data that are essential for basin management of the Ganga and are therefore also central to the design of GangaWIS. GangaWis has been designed such that information from GangaWIS is easily made available in IndiaWRIS. Data from model studies performed in GangaWIS can be disseminated through IndiaWRIS and conversely IndiaWRIS data can be imported manually into GangaWIS to serve as input and background data.

The Ganga water information system (GangaWIS) will enable users across the basin to:

- Analyze all input data of the modelling system, both static, land use and soil maps, and dynamic, time series of temperature and precipitation in graphs and maps. GangaWIS will provide access and visualization of all the data elements: temporal and spatial, hydrogeology, water quality, hydraulic infrastructure, ecology, DEM/land use. Both a local option and a web-based version will be available to all users;
- Import new input data and run one model or several models in sequence. This option is only available for local computer systems;
- Analyze the output for individual model runs or comprehensive strategies or scenarios which are a product of models run in sequence. Both a local option and a web-based version will be available to all users;

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[9] OGC services are a set of services described by the OpenGeospatial Consortium (http://www.opengeospatial.org/) which is an organisation committed to making quality open standards for the global geospatial consortium. The open standards are widely used for geospatial content and services, sensor web and Internet of Things, GIS data processing and data sharing.

[10] http://www.india-wris.nrsc.gov.in/wris.html

- Present a high level summary of model results on stakeholder defined indicators, varying by state, on a dashboard. Both a local option and a web-based version will be available to all users.

The system can be installed as a stand-alone system on a PC or laptop. Users have access and control over the data and model runs of a stand-alone system; the web based version is served from one centrally maintained system. Individual or state users can upload interesting model runs or strategies to the central system to be shared with all users in the basin. The management of the central system is still a topic of discussion with the central organizations of MoWR, RD&GR and the states.

8.2 Description

The design of any information system is largely influenced by the demands of the users, the stakeholders:
- Which data are important and in what volume will they be collected?
- How will the data be used and what are the data set relationships?
- What is the end product and how will it be presented to the stakeholders?

The size of the Ganga river basin was an important consideration in the system design. Data volumes would soon become too large to be redundant; therefore, reducing the data growth was a priority issue. GangaWIS addressed these issues by incorporating software capable of handling open data via open standards, while at the same time centralizing data and avoiding redundancy. All elements of the system can openly communicate through the central data medium. GangaWIS is a system developed within the framework of OpenEarth. OpenEarth promotes the use of open source software, international standards for interoperability and exchange of knowledge via open source software and capacity building.

The OpenEarth concept is to share tools, data, and knowledge to promote efficiency and transparency. OpenEarth promotes the reuse of techniques developed within projects. This facilitates an easy transfer of the knowledge gained in previous projects and continues the benefits of prior work. This open and flexible structure has significant benefits over proprietary software packages:
- Scalability in size;
- Scalability in functionality;
- Easy ingestion of new modules, e.g. geographic information systems, within the same domain;
- Portability;
- Large communities that share knowledge and contribute software fixes and improvements;
- Service Level Agreements with private companies are not required.

Many of these OpenEarth techniques have been incorporated into GangaWIS. The GangaWIS is schematized in Figure 8.1. The various components are described in detail in the following paragraphs.

More information on OpenEarth can be found on the following reference.

Component	Link
OpenEarth	http://openearth.eu

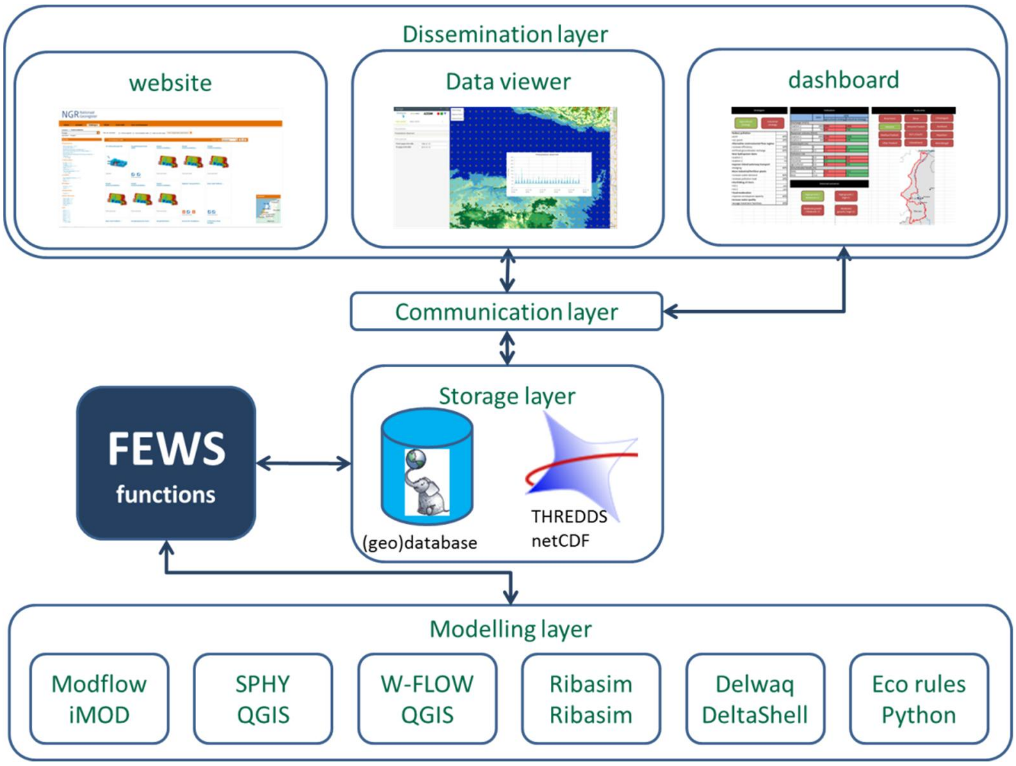


Figure 8.1: Schematized structure of GANGAWIS

8.3 System Overview

GangaWIS consists of several components:

- Storage layer;
- Communication layer;
- Dissemination layer;
- Modelling layer;
- Delft-FEWS.

These components consist of open source and freeware software adhering to international standards for communicating and interoperability. The different components are loosely coupled. Communication between the different components is based on open standards for data and information exchange, the OGC standards as described at www.opengeospatial.org. Full descriptions can be found in the Ganga river basin model and WIS Report and Documentation Appendices (Chapter P.3 to P.5).

Delft-FEWS is the intermediary between raw and validated data sources, the central database and models. Delft-FEWS serves as workflow manager, in both directions, between data sources, central storage, and models. The knowledge made available by Delft-FEWS can easily be processed in GangaWIS. Delft-FEWS has a robust international user community, and the system has been successfully implemented in international water management projects on every continent with the exception of Antarctica.

The forecasting capability of Delft-FEWS can be implemented as a stand-alone freeware product or as part of an operational system. In GangaWIS, a stand-alone version of Delft-FEWS has a direct connection to a central data storage facility.

Component	Link
Delft-FEWS	http://oss.deltares.nl/web/delft-fews/

8.4 Dissemination Layer

The dissemination layer consists of various elements with distinctive means of dissemination and audience:

- Data viewer;
- Website;
- Dashboard.

8.4.1 Data Viewer

The Delta Data Viewer (DDV) is a tool that facilitates placing georeferenced data on a map. The DDV concept is simple: features are implemented when needed, and are shared through a DDV core update.

The DDV is a portal that requires an Apache webserver with PHP and is primarily using HTML5 and JavaScript standards.

The DDV is easy to configure via a limited set of configuration files. In GangaWIS, the DDV is configured such that the data tab in the web portal displays the contents of a preconfigured GeoServer, meaning that every layer made available through that GeoServer is directly visible in the web portal. The web portal includes standard interactions like zooming and panning, and it enables the switching of preconfigured background maps, i.e. satellite images versus more standard graphical maps.

Ganga Data Viewer is an easy to use portal for viewing all modelling data and for visualizing the outcomes of various planned studies. The web portal is not a full GIS in the sense that spatial operations cannot be carried out. The web portal allows the user to view various thematic layers to analyze the resulting time series. Figure 8.2 provides an example of various map layers available in GangaWIS.

Time series management is carried out by Delft-FEWS in such a way that time series data is stored in a specific schema of GangaWIS (see Appendix Q.7 for the Delft-FEWS data model). GangaWIS portal has built-in procedures to connect with the database to graphically present time series. This is a dynamic operation; if data is added or deleted the result is immediately visible on the web portal. To graphically portray time series for a specific location the portal gets the time series data directly from the database. Figure 8.3 displays time series for a specified location.

Component	Link
Apache	https://httpd.apache.org/
PhP	http://php.net/
JavaScript	https://www.javascript.com/
HTML5	https://www.w3.org/TR/html5/

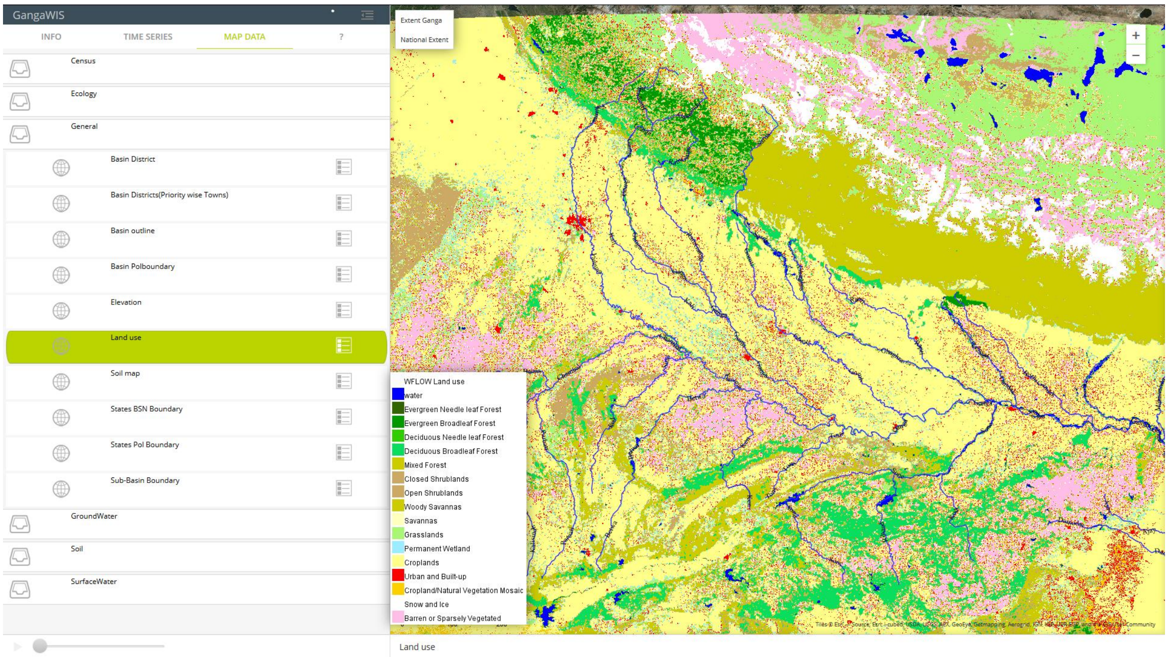


Figure 8.2: GangaWIS, (March 2018 status) display of land use and major rivers as available from the portal.

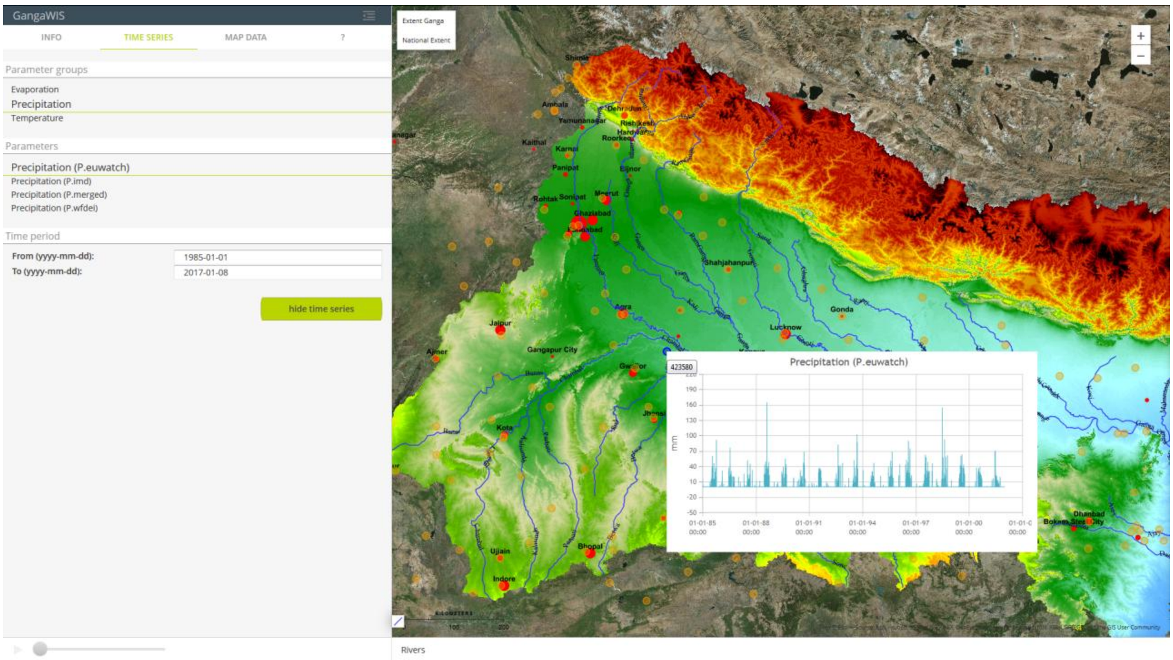


Figure 8.3: Time series in GangaWIS data portal.

8.4.2 Website

The main objective of the project website http://www.gangariverbasinplanning.com is to disseminate global information on the progress of the project. The project website facilitates:

- Active communication with a broad group of stakeholders.
- Sharing of publicly available high-quality reports as products of all project tasks.
- Viewing or downloading publicly available tabular or geographical information used in modelling and analysis.

Figure 8.4 shows the first page of the project website with its main tabs.

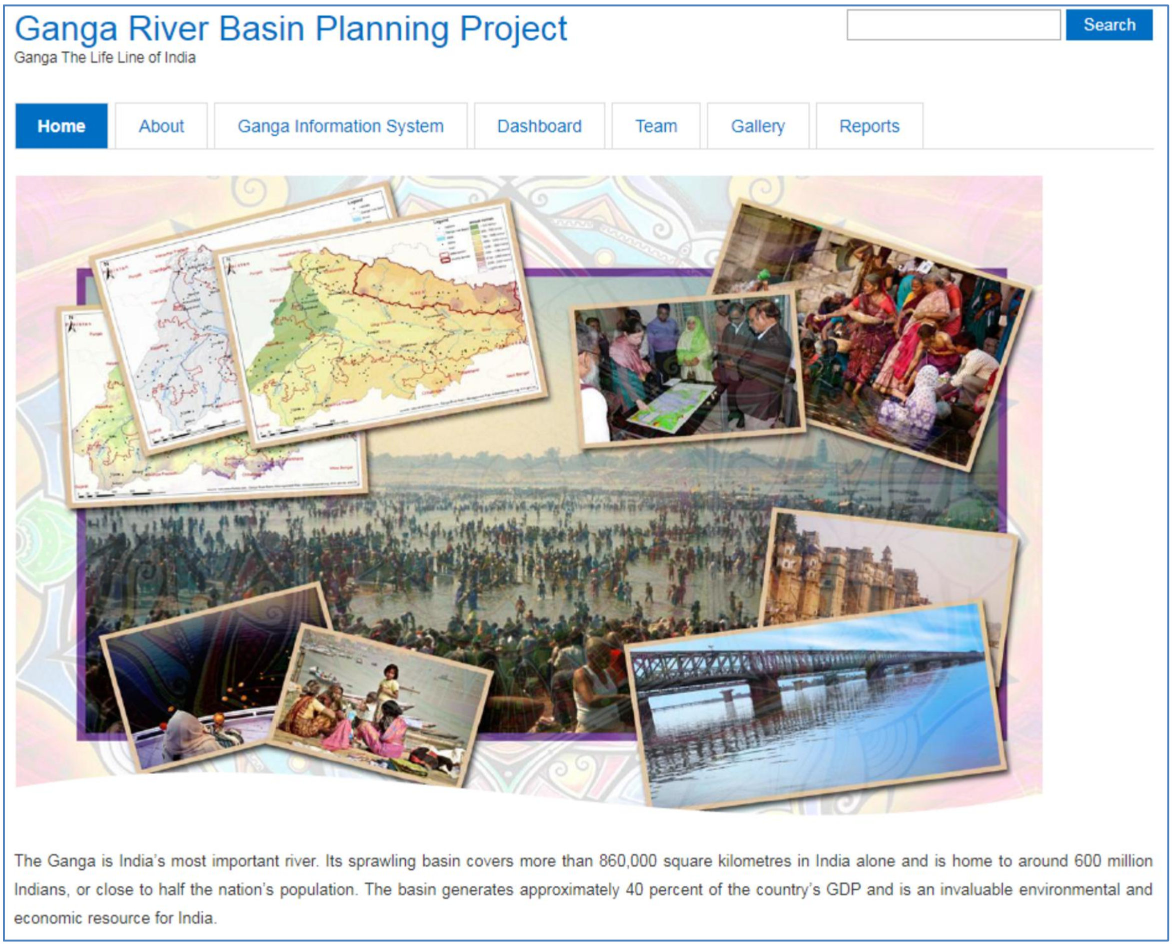


Figure 8.4: First page of project website http://www.gangariverbasinplanning.com.

The key elements of the project website are described in Table 8.1.

Table 8.1: The key elements of the project website.

Home	General introduction to the Ganga and the project
About	More information on the project and its objectives
Ganga Information System	Compilation of existing data and information on the pollution sources, water quality, hydrogeology, groundwater resources and groundwater use in the Ganga basin in a GIS-based information system: GangaWIS.
Dashboard	The Ganga dashboard provides the users and policy makers with information on the possible combined impacts of different technical measures or strategies on the Ganga river basin water system.
Team	Contact information
Gallery	Gallery of pictures from project activities
Reports	Download links of project reports

8.4.3 Dashboard

The dashboard is the element in the dissemination layer that enables a traditional planning kit approach. In a structured way, it provides the user or policy maker with information on the possible combined impacts of different technical measures or strategies on the Ganga basin water system. This information is available for the basin as a whole or for individual states. The dashboard is described in detail in Chapter 9.

8.5 GangaWIS, Delft-FEWS and Time Series Data

Delft-FEWS is the software used to input time series data, e.g. discharge data or precipitation data, into the database and to transfer this data to the models. It runs in stand-alone mode in GangaWIS. With Delft-FEWS it is possible to import data from different sources and types, to perform data transformations, e.g. from hourly to daily data or from grid to point, and to export the data in standardized formats, e.g. *.csv. Delft-FEWS contains model adapters for many types of models; this facilitates using the GangaWIS database to run different models, e.g. Wflow or RIBASIM.

As Delft-FEWS was developed as a Flood Early Warning System, it also has the capability to act as a fully operational forecasting system with automatic data imports and model running. Within GangaWIS only the basic functionalities of Delft-FEWS are employed:

- Data import;
- Model execution, including preparation of input files and storing of output in the database;
- Conversion of data to easily understood output formats.

Delft-FEWS also has a Graphical User Interface (GUI) which can be used by trained experts.

Within GangaWIS Delft-FEWS plays an important role in the data and workflow management. All external time series datasets, both scalar and gridded data, are put into the system using the import functionalities of Delft-FEWS. The data, both external and model results, can be visualized and analyzed within the Delft-FEWS GUI. For this, different displays are available. In the time series display, the user can visualize scalar time series for all available locations and parameters, perform some basic statistical functions on these time series and export the data easily for further analysis, e.g. to Excel. In the grid display, the user can display the gridded time series, e.g. rainfall.

As stated, Delft-FEWS is also used as workflow manager of the system. This means that for each step of running the models, Delft-FEWS is used to perform these steps. A user can therefore run all models, i.e. SPHY, Wflow, RIBASIM, iMOD, from the same GUI. The data to be transferred from one model to the other is configured and arranged by Delft-FEWS. The user does not have to think about copying the correct files from one model to the other.

8.6 Information System Maintenance

8.6.1 Maintenance

Daily maintenance of the server consists of normal computer maintenance:

- Backups;
- Installing updates of various types of software:
  - Operating system (Windows server 2012 R1);
  - Virus scanner;
  - Model software;
  - Additional software, e.g. GeoServer, PostgreSQL/PostGIS;
- User access rights:
  - Various types of roles to be assigned;
- Handling user requests:
  - Login requests (repository, VPN connection);

- o Data requests;
- o Modelling requests;
- o Troubleshooting login and other user questions.

8.6.2 Installation of Software

The complete GangaWIS system consists of a collection of software components. Appendix P covers the complete setup, installation and also brief manuals on how to work with the software. The complete GangaWIS system is made available on a portable virtual machine (VM). This portal VM is built using common technology and can be made available in every virtualization environment, licensed as well as open source virtualization software. Complete description can be found in Appendix R.

8.6.3 Roles and Responsibilities

Data Collection

GangaWIS will be transferred to the central organization that will have responsibility for all collected data used for system setup. This central organization is the focal point for all data used to set up the models, as well as the model code.

Data Preprocessing, Conversion and Transfer to Central Storage

Although data is collected in various formats, all data is converted into generic formats, i.e. imported into the database or converted to NetCDF or GTiff. As model extensions and data changes occur, care should be taken that any new data is transformed into the generic formats.

All data is stored on accessible parts of the central storage. This central storage is accessible via Geoserver. This is middleware between data storage (i.e. database or files) and ‘end users’. One of the ‘end users’ is the web portal as described in Section 8.4.1 (Data Viewer). Restricted data is store on non-shared parts of the Ganga server and are only accessible by authorized project members.

Data Styling

GangaWIS disseminates styled datasets. Common cartographic procedures are followed. Styling is done via the communication layer. Tutorials are available for the process of styling the data, as well as for specific software (see Appendix P.3.).

8.6.4 Key Partners and Users

Key partner in establishing the database is the IndiaWRIS team. The system was the product of a joint venture project between the Central Water Commission (CWC), Ministry of Water Resources and the Indian Space Research Organization (ISRO), Department of Space. The project, *“Generation of Database and Implementation of Web Enabled Water Resources Information System in the Country”,* sought to establish a “Single Window” solution for comprehensive, authoritative and consistent data and information of India’s water resources. The water resources and allied natural resources would be housed in a standardized national GIS framework using WGS-84 datum and LCC projection.
Tools would be developed to search, access, visualize, understand and analyze the data for assessment, monitoring, planning, and development; the ultimate goal was Integrated Water Resources Management (IWRM) of the Ganga basin.

8.6.5 Capacity Building

As previously discussed, GangaWIS consists of several components or modules, of which each is associated with specific software packages. Knowledge transfer is an important element of this project. Technical specialists have been assigned to the various components; they serve as mentors to project team members, who have also been assigned to specific components as counterparts. On missions to India these specialists concentrate on knowledge transfer: overall understanding of the information system, importance of data definition and collection, rudiments of modelling and the interaction of GangaWIS models.

Without valid information, even a well-designed modelling system will not gain credibility with the user community. Therefore, data definition and model validation and calibration receive extra attention, especially during the missions of Deltares specialists.

Because data is the critical element for success, data managers have added responsibility. They must understand how data are used by modelers and stakeholders. They must be familiar with a range of techniques, e.g. from the basic spreadsheet application Excel to the more sophisticated scripting languages R and Python. The data managers must also understand the basics of the storage layer and how data moves through the system, through the models and eventually to the presentation on the dashboard. These topics are important for knowledge transfer during the missions of the Deltares specialists.

8.6.6 Access to Data and Information

There are a variety of methods available for accessing information and data of the Ganga basin:

- Run case comparison via GangaWIS dashboard;
- Geographic and time series information via GangaWIS web viewer;
- Data via the technical interfaces of OGC services;
- Access via modelling tools.

GangaWIS Dashboard provides the highest level of data access. A summary of the data is presented to decision makers in a format that facilitates management actions. The dashboard has been constructed with software that produces websites viewable by various devices.

Geographic and time series data are critical for understanding the strategic value of the Ganga basin planning project. The GangaWIS web portal is designed to present different thematic layers in both static and dynamic mode, i.e. datasets with a time component. The portal will provide access for PCs and mobile devices.

Direct access to data and information is available via OGC services such as WFS, WCS and OPeNDAP, a data transport architecture and protocol. Because most GIS software is not scripting software and does not run on mobile devices, access will normally be from a PC system. The system administrator can initiate security protocols by password designations.

The system provides the technical possibility to view and analyze data. However, it is the data manager and the organizations that collect and disseminate the data who have to assure that relevant data will be present in the system.

9 Dashboard

9.1 Introduction

One of the main user interfaces to the GangaWIS is the Ganga dashboard, which provides policy makers instant feedback, in a structured fashion, on the possible combined impacts of different technical measures or strategies on the water system state in the Ganga river basin and for each state separately. The Dashboard collects and presents the results of the other model components, as shown in Figure 9.1.

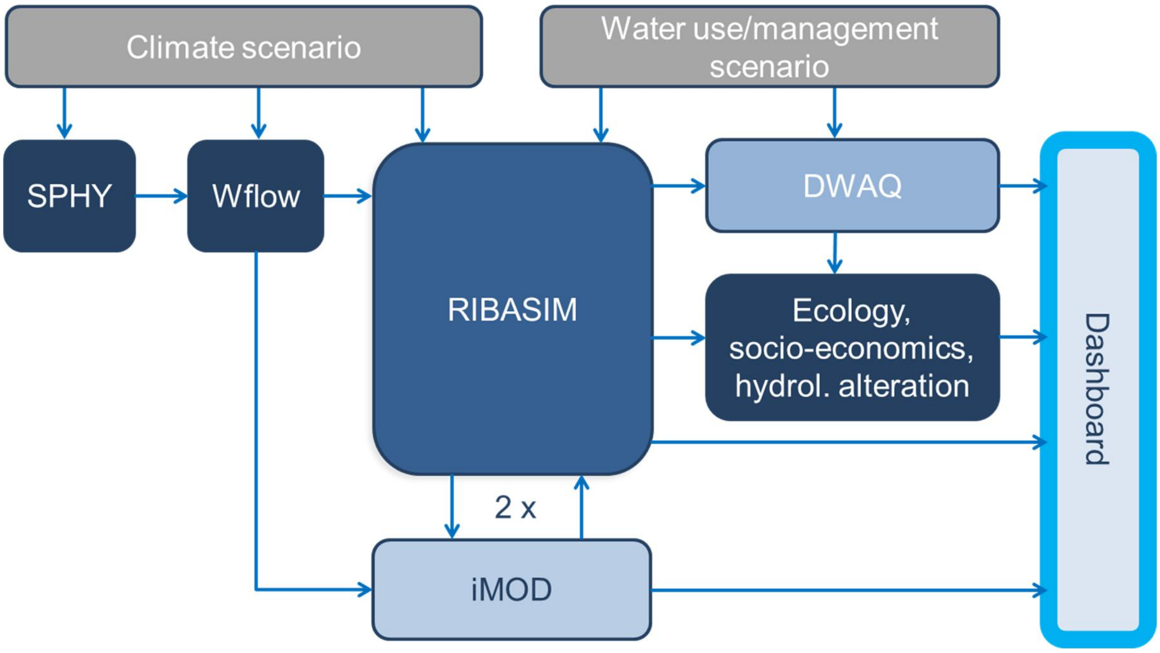


Figure 9.1: Position of the dashboard in the workflow of the whole Ganga river basin model

The Ganga dashboard is directly related to the GangaWIS, in such a way that it gives a view of data stored in the central database or local state databases. This is done for the current situation and the foreseeable future, e.g. 2050. For the future, different possible external scenarios are used; e.g. moderate/high climate change and moderate/high economic growth. The performance of the water system under different circumstances, e.g. strategies and scenarios, is analyzed through a varied set of water system state indicators, the scorecard.

The dashboard explicitly does not include functionality to configure and specify new measures or strategies. This is done through the specific modelling applications of the GangaWIS. Its main function is to import and present results from new measures and strategies, the run cases, after calculations available in the database.

The dashboard will provide basic functionality to explore the distributional effects of a strategy for different states under different future scenarios. More advanced data analysis is advised to be done with the other components in the GangaWIS that are better suited for the purpose, e.g. the central data viewer or individual model applications.

The performance of the Ganga basin under future conditions is presented through a scorecard with indicators, maps and charts, which are predefined and whose values differ for each run case and administrative state.

Each authority has its local copy of the dashboard application. As such, one is able to view and present modelling results, managed in Delft-FEWS in a preferred way. It also ensures that simulation run cases from other states or the central authority can be loaded into the dashboard application. For more technical information on the installation, configuration and use of the dashboard, see the installation manual provided in Appendix G.2.4 and the tutorial in Appendix H.4 and L.11.

9.2 Dashboard Layout

The dashboard was developed, after several iterations with end users, into the basic layout as shown in Figure 9.2.

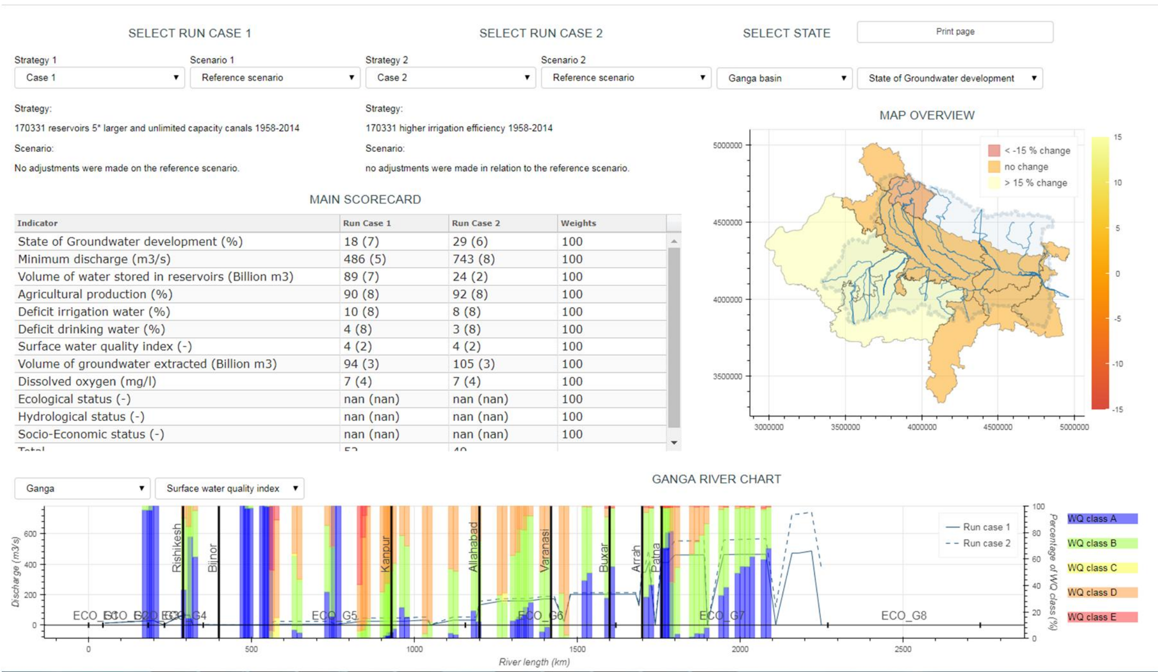


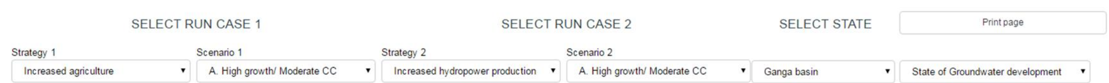
Figure 9.2: Screenshot of dashboard of GangaWIS

The dashboard consists of 4 basic components, which are described in the following paragraphs:

- Selection menu;
- Scorecard
- Map overview;
- River plot.

9.2.1 Selection Menu

The top of the dashboard shows a selection menu with six drop-down menus, two descriptive fields and Print page button:



Strategy:	Strategy:
170331 reservoirs 5* larger and unlimited capacity canals 1958-2014	170331 higher irrigation efficiency 1958-2014
Scenario:	Scenario:
No adjustments were made on the reference scenario.	no adjustments were made in relation to the reference scenario.

Figure 9.3: Screenshot of selection menu

The dashboard always works on the comparison of two run cases. A run case is a combination of a strategy, measures within the control of the water manager, e.g. higher irrigation efficiency and a reference or future scenario, external developments outside the control of the water manager; e.g. climate change. The modeler has to provide a description on the chosen strategy and scenario for each model run. These descriptions are visible in the dashboard. After the model run, the user can select at which scale level to compare the results. The performance of run cases can be compared at the level of the complete river basin and for each state separately. The various components will change in scale accordingly. With the print page button, the current selection mode can be printed to a file or a printer.

9.2.2 Scorecard Panel

The scorecard provides a list of indicators with performance values for the two selected run cases and scale level, basin or state. The list of indicators may differ, depending on the selected scale level. In the last column, one can decide to give different weights, of importance, to the different indicators. The total score will change accordingly. The weight changes are saved between comparisons, but will not be kept over various sessions. Hovering over the name of the indicator will give a pop-up window with a concise description of the indicator and the way it is calculated.

MAIN SCORECARD

Indicator	Run Case 1	Run Case 2	Weights
State of Groundwater development (%)	18	29	100
Minimum discharge (m3/s)	487	721	100
Volume of water stored in reservoirs (Billion m3)	89	24	100
Agricultural production (%)	90	92	100
Deficit irrigation water (%)	10	8	100
Deficit drinking water (%)	4	3	100
Surface water quality index (-)	1	1	100
Volume of groundwater extracted (Billion m3)	109	125	100
Total	80	73	

Figure 9.4: Screenshot of scorecard panel

9.2.3 River Plot

The river plot component shows a profile of either the Ganga main river or the Yamuna main river. The river can be selected with the left dropdown menu. From source to end of the river it shows calculated discharge values for both run cases, as well as the selected parameter from the second dropdown menu. Several parameters are available, for example, average monthly distribution of the Water Quality Index classes at several modeled stations: A = very good quality, E = very poor quality. The plot also indicates major cities along the river.

By zooming in or panning the plot, it is possible to see the data in more detail, for example, up and downstream of a confluence. When moving the cursor over the legend on the right side of the plot it will show the method that was used to determine the classes.

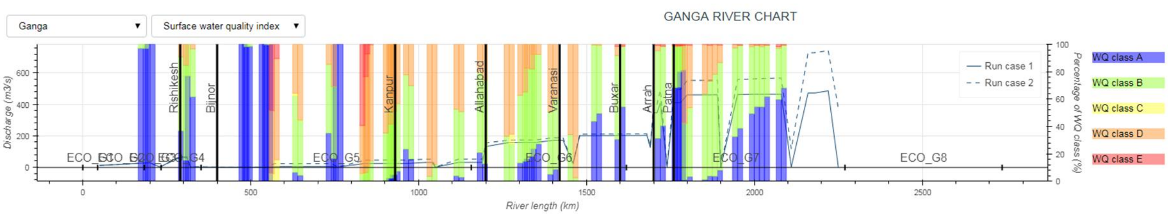


Figure 9.5: Screenshot of river plot

9.2.4 Map Overview

In the map overview panel, the user may switch between different state-dependent indicators to be shown in the choropleth map. For example, one can choose to see the difference between both run cases in the state of groundwater development, volume of water stored in reservoirs, agricultural production, deficit irrigation water, deficit drinking water, surface water quality index and volume of extracted groundwater. When hovering over the map with a mouse, a pop-up window shows the numerical difference per geographical object, e.g. district, river location, reservoirs and drinking water locations.

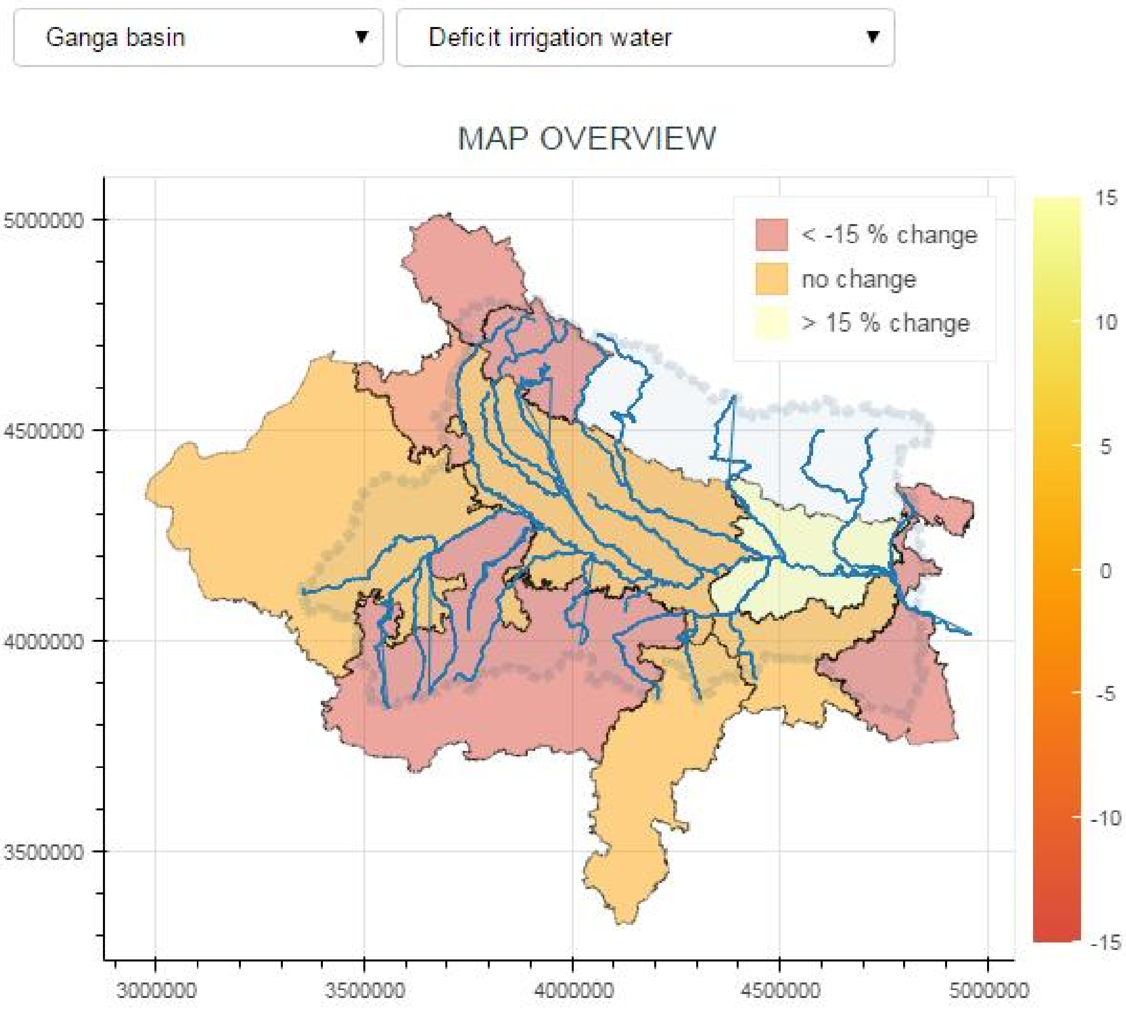


Figure 9.6: Screenshot of map overview

10 Application of the River Basin Model and Sensitivity Analysis

10.1 Application of the River Basin Model

The aim of the river basin model is to support strategic planning for the Ganga basin by enabling the impact assessment of different possible futures, such as climate change and socio-economic scenarios and possible management strategies. This report presents the concepts of the model, the set-up and input data, and the results of the calibration and validation of the model. These are necessary steps in the development of a model for strategic planning. However, the real results of the model will follow from its application to the analysis of the scenarios and strategies and the comparison of model results for different situations. The results of this scenario analysis are presented in a separate report. This chapter describes how the river basin model can be applied to support strategic basin planning. Complete tutorials for separate tasks are presented in Appendices G to P.

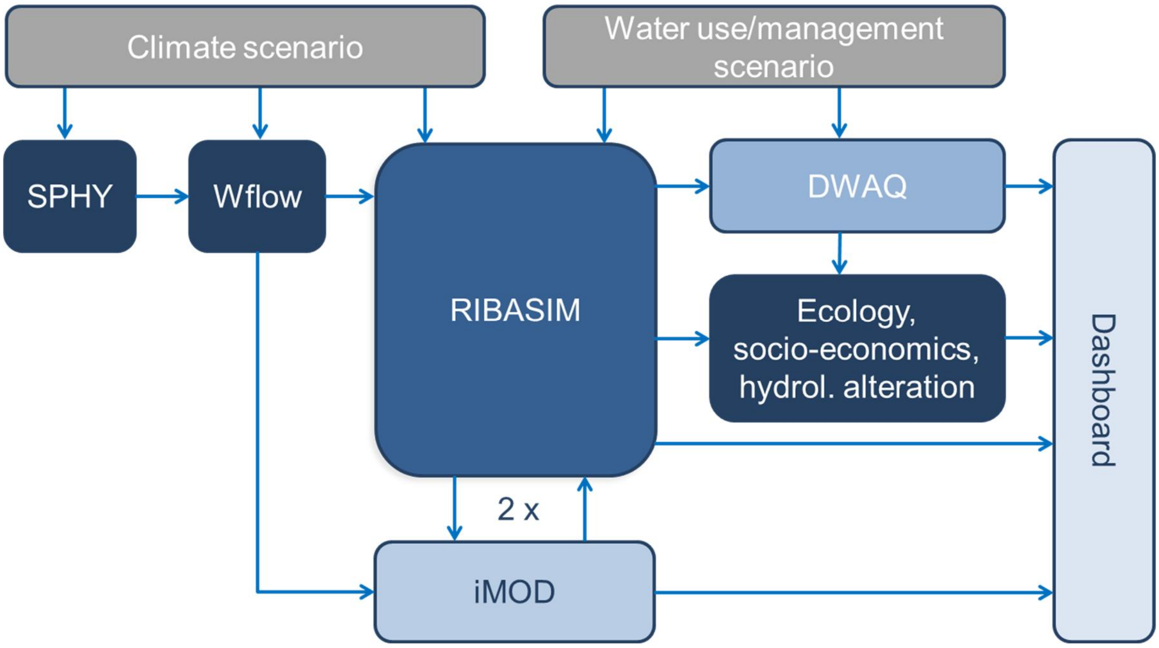


Figure 10.1 : Schematic of the total workflow of models in the GangaWIS.

Figure 10.1 presents a schematic overview of the workflow of the river basin model. Appendix K presents a tutorial on the GangaWIS user interface for workflow management. Rainfall-runoff and routing of river flow are modelled by SPHY and Wflow (see Chapter 3). RIBASIM uses the calculated flows as input to simulate water demand and allocation and the operation of water infrastructure (see Chapter 5). The recharge simulated by Wflow and the groundwater abstractions and recharges from irrigation and public water supply simulated by RIBASIM are combined to form the input to iMOD to simulate groundwater dynamics (see Chapter 4). iMOD also simulates the interaction between the surface and groundwater. A second run of the RIBASIM simulation takes account of these interactions. It might be necessary to run iMOD also for a second time, if the discharges simulated by RIBASIM show significant changes between the first and second run. It is expected that normally this will not be necessary. The discharges simulated by RIBASIM are combined with the information from the pollutants database to simulate the water quality.

All results from the previous models are used by the ecological knowledge rules to assess the state of the ecology of the Ganga river and the ecosystem services provided. Finally, all model results are aggregated to be presented as indicators on the dashboard.

The hydrological models SPHY and Wflow use meteorological data as input (see Sections 3.1.3 and 3.2.3). The actual climate is described by time series of data for the period 1959 to 2014. Such a long period is used to ensure that enough variation in conditions with respect to water resources is included. The impact of socio-economic scenarios and management strategies under the current climate can be assessed by modifying the input of the RIBASIM model. This input reflects the actual situation in the reference case which will be used for calibration and validation. To begin this will be 2015 or a close approximation. The input for the reference case can be modified to reflect the scenario and/or strategy. Appendix L presents a tutorial for water resources management and Appendix N presents a tutorial for water quality. In practical applications for scenario analysis, it is expected that the scenarios and strategies will be formed by modifying the model input with respect to water resources management and water quality.

To assess the impact of scenarios and strategies under the current climate, the results of SPHY and Wflow for the reference case can be used. The coupling of Wflow to RIBASIM describing the time series of discharges depends on the subbasin schematization presented in Section 6.2. In most cases it will not be necessary to modify this schematization. However, if new nodes to describe water demand and/or water infrastructure are added upstream of all existing nodes for demand and infrastructure, a new subbasin schematization must be constructed. Appendix M presents a tutorial how to construct a new schematization.

The impact of a climate change scenario can be assessed in two different ways. RIBASIM allows for the definition of a simple climate change scenario consisting of percentage changes for the hydrometeorological input variables inflow from Wflow, rainfall, open water evaporation and reference crop evapotranspiration. These percentage change values are applied to all model input for all years and for the whole basin. For this approach the procedure for scenario analysis outlined in Appendix L can be followed. More information on the definition of a climate change scenario is provided in Section 5.2 of *RIBASIM Version 7.01, User Manual Addendum* (Deltares, 2015b). This approach allows for a rapid assessment of the potential impact of climate changes, but no realistic climate change scenario can be implemented in this way, since realistic scenarios will show variation of the climate change in time and over the basin.

The impact of more realistic climate change scenarios can be assessed by modifying the meteorological input for the SPHY and Wflow models, consisting of time series of grid maps for temperature and precipitation. These time series of grid maps can describe variation in time and over the basin. The results of the hydrological models based on the modified input can be used as input for the rest of the workflow. Appendix O presents a tutorial on constructing realistic climate change scenarios.

The impact assessment of scenarios and strategies will be based on comparison of the results of different simulations, i.e. run cases. The comparison can be carried out on a high aggregation level using the indicators on the dashboard (see Chapter 10 for a description and Appendix I for a tutorial). This will be most attractive for non-technical users interested in policy relevant information. A further analysis is supported by the GangaWIS using non-aggregated simulation results. This is covered in the tutorial presented in Appendix J.

10.2 Sensitivity Analysis and Uncertainty of the Model Results

To draw conclusions from the application of the river basin model, it is important to have insight into the sensitivity of the model results for different values of input data and parameters and the uncertainty of model results. The calibration and validation process presented in the chapters on the different model components provides insight into the reliability and uncertainty of the model results. The following paragraphs present the results of a sensitivity analysis which can guide the interpretation of results when combined with calibration and validation information.

Table 10.1 presents an over view of the runs performed with the different components of the river basin model and the input or parameters that have been varied as part of the sensitivity analysis. The selection is based on the expectation of the most sensitive input data and parameters that are likely to be important in the definition of scenarios for strategic planning.

Table 10.1: Overview of the runs with the different components of the river basin model performed for the sensitivity analysis

		Model			
Parameter	Variation	Wflow	Ribasim	WQ	iMOD
Land-use and water demand	Pristine	x	x	x	x
Saturated hydraulic conductivity	minus 20%	x	x		
Planting time of crops	One month earlier		x		
SW irrigation efficiency	40% --> 50%		x		
GW irrigation efficiency	70% --> 75%		x		
Crop transpiration	-20%		x		
Waste load PWS	-25% and +25%			x	

10.2.1 Surface Water Models

The *Pristine* scenario describes the situation of the Ganga basin without human interference, thus, no water demand and no water infrastructure. Furthermore, the land-use and land-cover have been modified to represent the natural situation. This provides a test for the sensitivity of the model results for land-use changes. Figure 10.2 presents the results. The difference in simulated discharges is marginal for a catchment in the Himalayas upstream of current water demand and infrastructure. It shows that the vegetation modifications have a limited impact on the flow. The results for the Ganga near Kanpur and the Yamuna near Delhi show a large impact with an increase of nearly 150–170 percent of the average annual discharge in the pristine situation. This is caused by the substantial diversion of water to mainly the irrigation systems in the present situation. Finally, the result for Varanasi shows slightly less increase in discharges with nearly doubling of the average annual discharge. The impact observed at Delhi and Kanpur is attenuated further downstream somewhat by the inflow from other tributaries.

One of the most important input parameters for Wflow is the saturated hydraulic conductivity. The distribution over the basin is varied based on the soil map (see Section 3.2.3). A 20 percent reduction in the value of the saturated hydraulic conductivity has been applied to test the sensitivity of the model results. It is expected that the lower conductivity in the soil will lead to less water movement through the soil and more surface runoff, increasing peak discharges and decreasing low flow. The results are presented in Figure 10.3 Impacts are not very large and most prominent in the upstream region where groundwater contribution to river flow is relatively smaller.

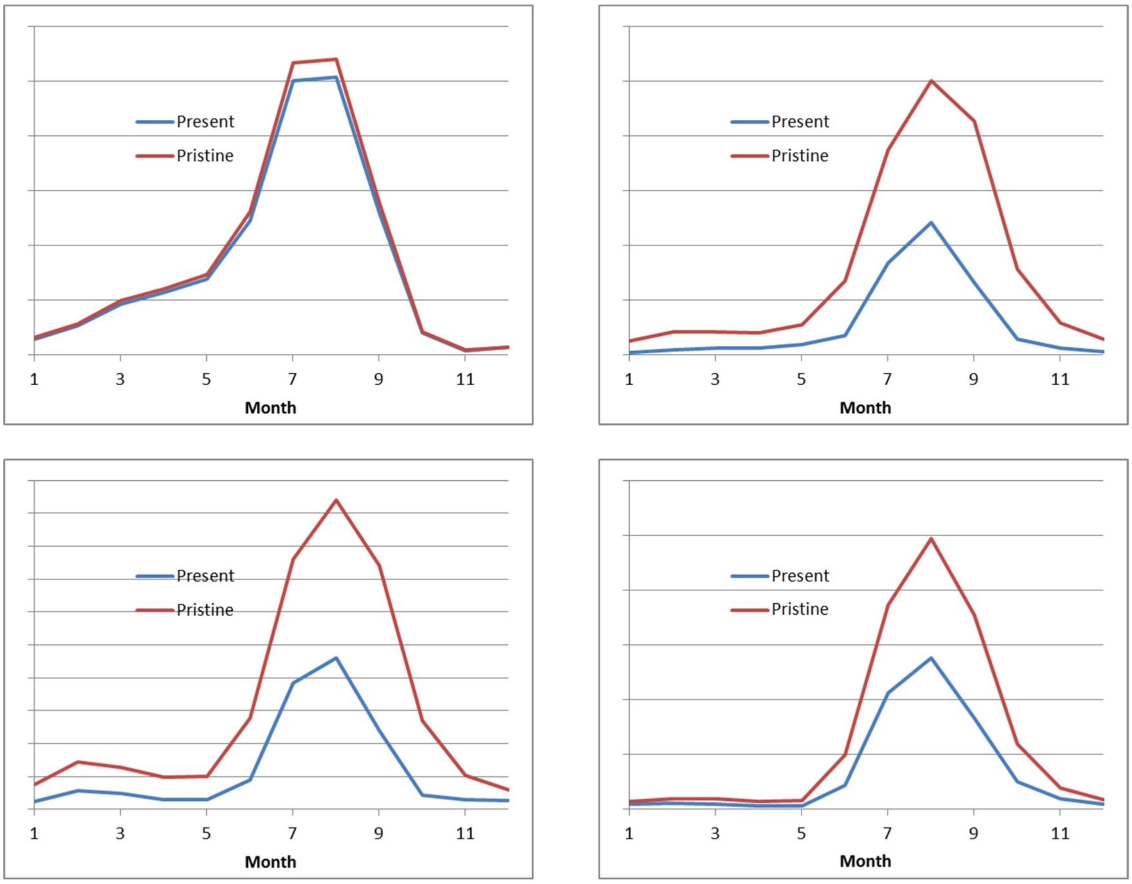


Figure 10.2 : Comparison of average monthly simulated discharges for the period 2000–2014 for the Present and the Pristine scenario for a catchment in the Himalaya (top left), the Ganga near Kanpur (top right) and near Varanasi (bottom right) and the Yamuna below Delhi (bottom left)

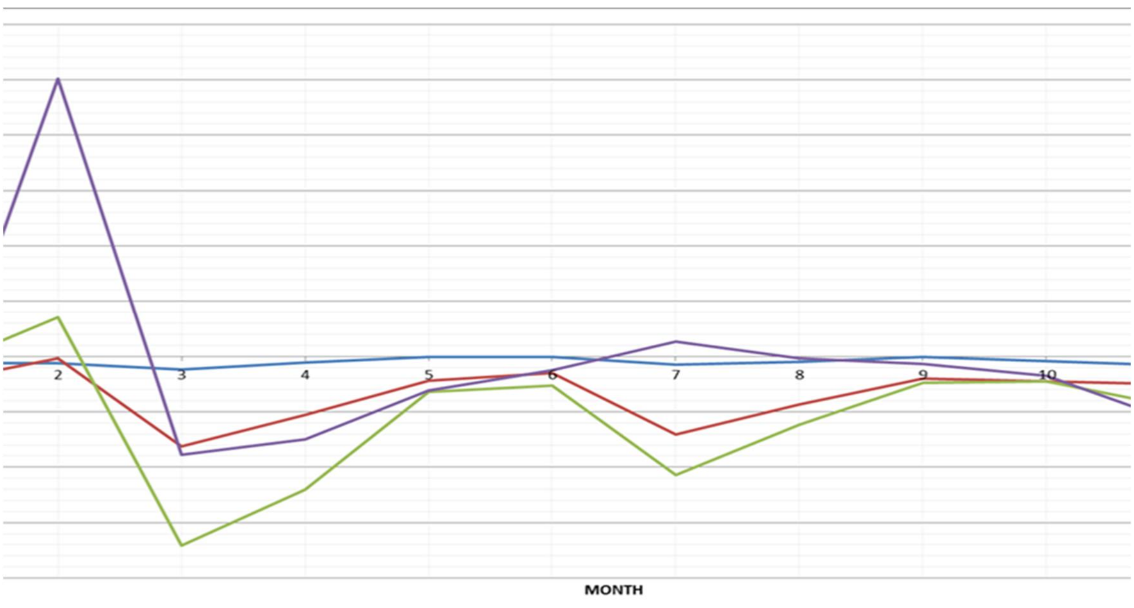


Figure 10.3: Comparison of average monthly simulated discharges for the period 2000–2014 for the Present scenario and with a 20 percent reduction in saturated hydraulic conductivity (Ksat80% - Ksat100%) / Ksat100%). for a catchment in the Himalaya, the Ganga near Kanpur and Varanasi and the Yamuna near Delhi

The timing of planting of irrigated crops in the Ganga basin is closely related to the expected availability of monsoon rain and discharge. Therefore, it can be expected that a change in planting date has a considerable impact on irrigation water demand and supply. Figure 10.4 compares the annual average water demand and supply for the reference case with a simulation where all planting dates have been decreased by one month. The results show a substantial increase in water demand and shortage. This is caused by the fact that peak water demand and monsoon water availability are no longer aligned.

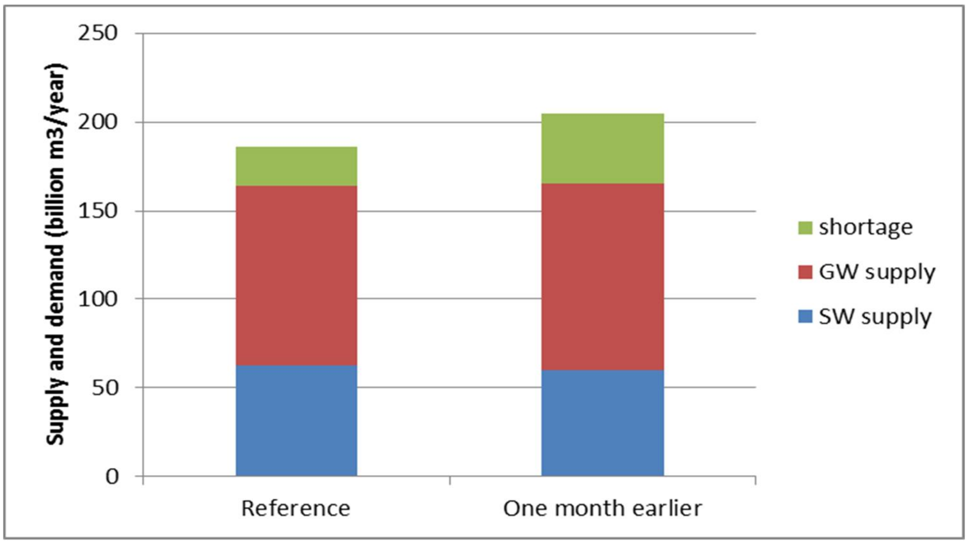


Figure 10.4 : Annual average simulated irrigation water supply and demand for the period 2000–2014 compared for the reference case and with all irrigated crops planted one month earlier

Irrigation efficiencies have been derived from Gupta and Deshpande (2004) as 40 percent from surface water irrigation and 70 percent for groundwater irrigation. However, these data can be expected to have a limited accuracy and can vary greatly within the basin. An increase of irrigation efficiency should reduce the irrigation water demand and the shortage. The impact on irrigation water demand and supply of an increase of surface water irrigation efficiency from 40 percent to 50 percent is shown in Figure 10.5 and the impact of an increase of groundwater irrigation efficiency from 70 percent to 75 percent in Figure 10.6.

Both increases of irrigation efficiency result in a decrease of the annual average irrigation water demand by some 5 percent, 10 billion cubic meters, and a more limited reduction of the simulated average annual shortage.

Crop transpiration is the basis for calculating irrigation water demand. It is based on a combination of the reference evapotranspiration and growth stage dependent crop evaporation coefficients Kc (see Chapter 5 and Appendix E). There is quite some uncertainty in the values used for the reference evapotranspiration and especially the crop coefficients.

A decrease in crop transpiration should result in a lower water demand and a smaller shortage. Figure 10.7 shows the impact of a decrease in the reference evapotranspiration by 20 percent. Since the reference evapotranspiration and the crop coefficient are multiplied to get the crop transpiration demand, a reduction by 20 percent of the crop coefficients would yield the same results. The results show indeed a strong decrease in irrigation water demand by nearly 50 percent since a larger part of the transpiration demand can now be met without irrigation. The average annual shortage is nearly eliminated. This underlines the sensitivity of the calculation to crop transpiration demand.

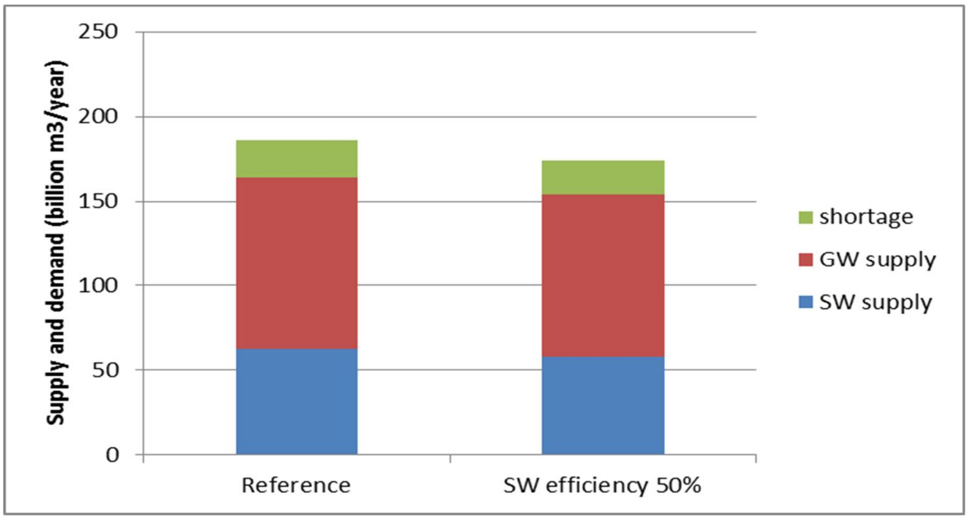


Figure 10.5: Annual average simulated irrigation water supply and demand for the period 2000–2014 compared for the reference case and with surface water irrigation efficiency increased from 40% to 50%

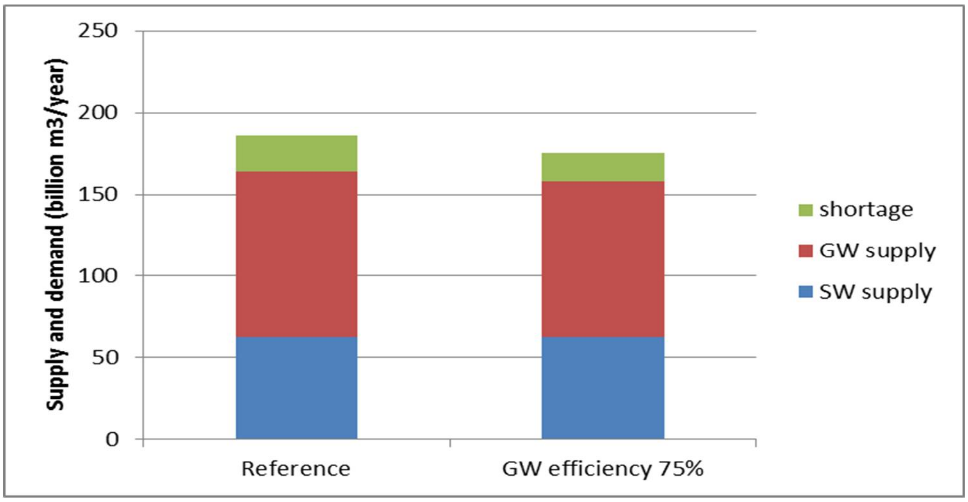


Figure 10.6 : Annual average simulated irrigation water supply and demand for the period 2000–2014 compared for the reference case and with groundwater irrigation efficiency increased from 70% to 75%

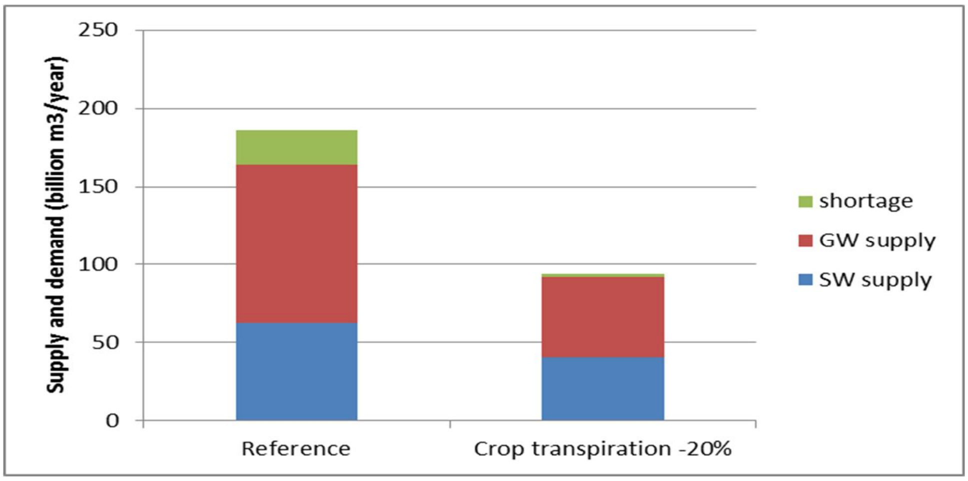


Figure 10.7 : Annual average simulated irrigation water supply and demand for the period 2000–2014 compared for the reference case and with a 20% reduction in reference evapotranspiration

10.2.2 Groundwater Model

For a general sensitivity analysis of the groundwater model, two different types of stresses are modified: 1) the levels in the main river system and 2) the abstraction rates. This will show the sensitivity of the model to major changes.

Influence Zones of Major Rivers

The major rivers are permanently in contact with groundwater and cause dampening of dynamics of the groundwater heads. Thus, the groundwater head is less sensitive to changes near the rivers than at a larger distance. Between the major rivers, the groundwater head only changes gradually; changes in heads in the model results as a result of recharge changes may only be apparent after a long period. Abstraction by wells may show up fast and strong near the wells, but at distance the lowering may continue long after the wells have been shut down.

To calculate the zone of influence of the rivers, a sensitivity run is executed by increasing the water level in the river by 2 meters. Figure 10.8 shows the widths of the influenced zones along the river are limited. As expected the rivers do not dominate the entire model area. The increase in the groundwater head in the north-west of the model area is larger than the increase of 2 meters in the surface water level. In some situations, this is possible as can be explained by situation 5 in Figure 4.3: when the river bottom is above groundwater level the increase of the groundwater level is flux based and that flux may lead to a larger increase of the groundwater level than the increase in the surface water level.

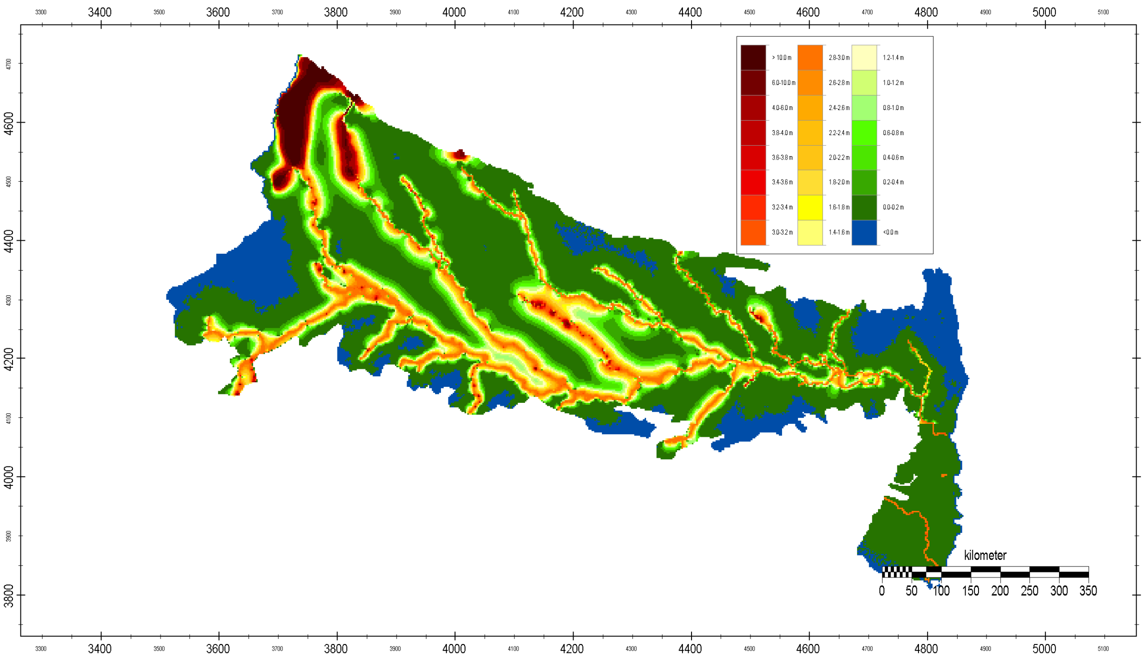


Figure 10.8: Effect of increase of riverhead by 2 meter on the groundwater head

Increase of Groundwater Abstraction.

From both studies and groundwater model simulations it is known that the relation between groundwater recharge and groundwater abstraction determines whether the groundwater is overexploited and whether levels will decrease over time. To calculate the influence of the abstraction rate, a sensitivity run is executed by increasing the abstraction rate by 200 percent. Figure 10.9 shows that the increase of abstraction rate will cause a significant drop of the groundwater head in areas where the recharge/abstraction ratio has reached a critical status at the present moment. In the areas with no significant change in the groundwater head, the abstraction rate is relative low compared to the recharge in the area. The groundwater heads are still dominated by the recharge and the model results agree with our expectations.

The model is sensitive to scale. The model parameters are derived as good as possible from the available data and the optimization at present scale. This model can only be applied for water balance studies over large domains. Local, more detailed applications should be supported by local data and should be optimized on locally measured heads.

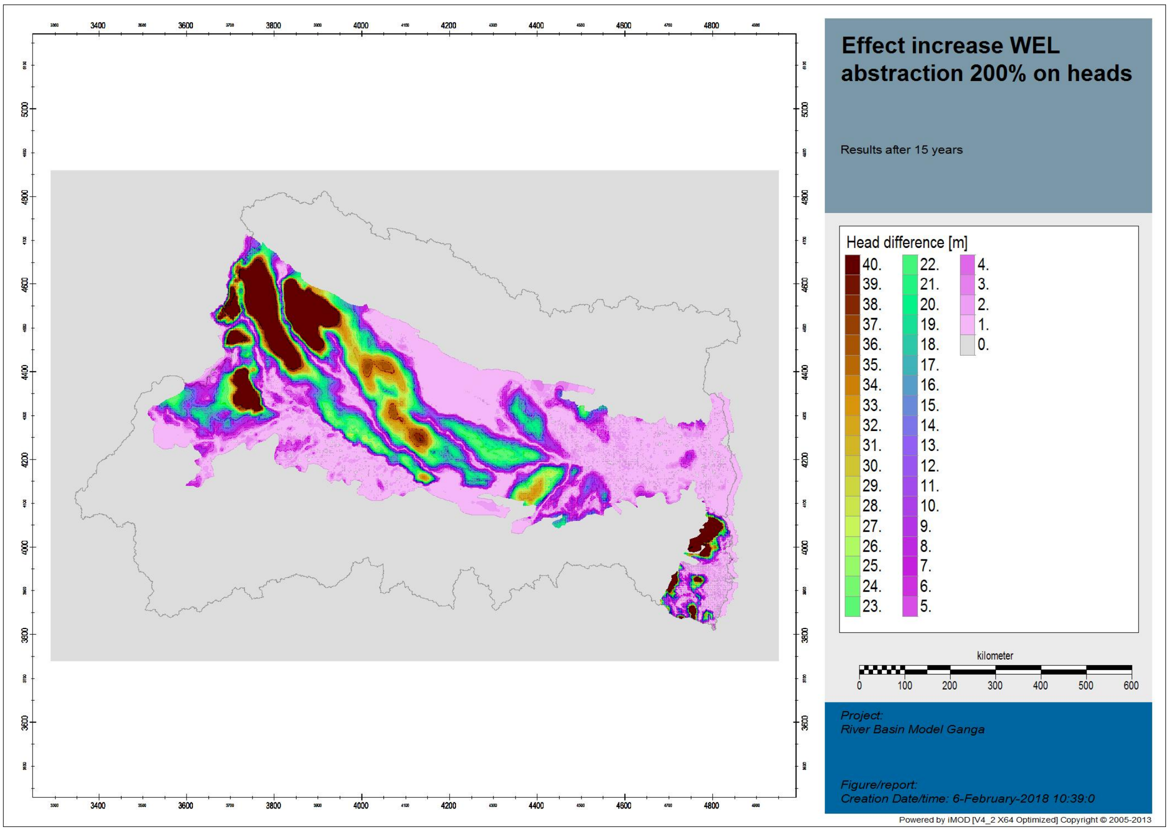


Figure 10.9 : Effect of an increase of the groundwater abstraction rate by 200% over a period of 15 years.

10.2.3 Water Quality Model

A linear response of the water quality model to a variation of the emissions to the model is expected if dilution and (first order) decay are the dominating processes.
An emission reduction of 25 percent will result in a 25 percent lower concentration, a 25 percent increase of the emissions in a 25 percent higher concentration.

The results of the sensitivity runs are presented for two locations in the Ganga, viz. Kanpur and Varanasi and one in the Yamuna (downstream Delhi). Figure 10.10 shows the monthly averaged BOD5 (top) and TColi (bottom) values simulated for the period 2000–2014 for the present run and the sensitivity runs. The relative change in the concentration is more or less constant over the year; the changes of the absolute concentration are obviously higher when concentrations are high (in the dry season).

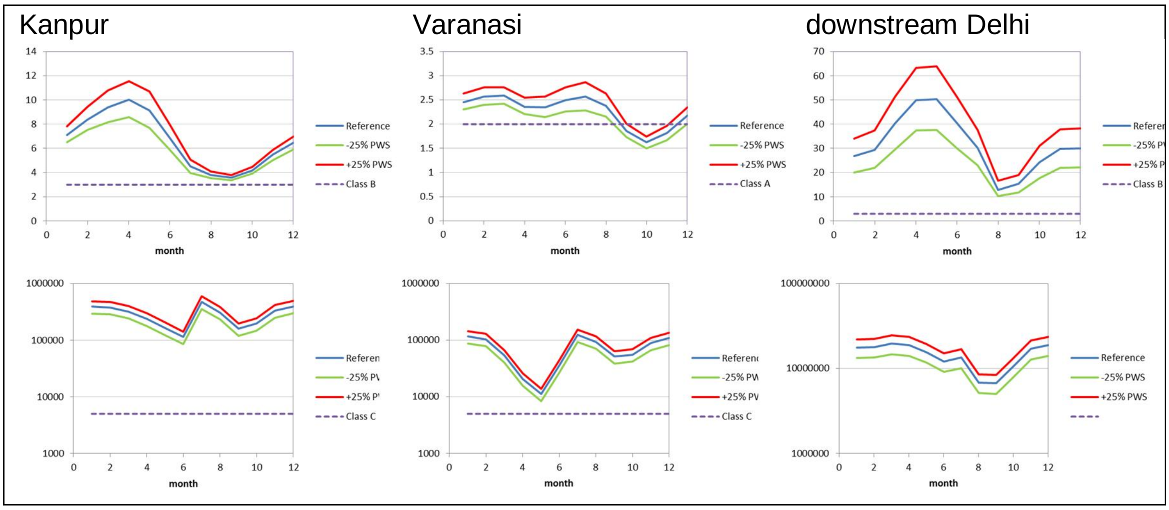


Figure 10.10: Comparison of average monthly simulated BOD5 (top) and TColi (bottom) for the period 2000–2014 for the with waste load variations for the Ganga near Kanpur (left) and Varanasi (middle) and the Yamuna below Delhi (right)

A summary of the model response is presented in Table 10.2. For TColi and BOD5 downstream of Delhi the model response is as expected when dilution and first order decay dominate the concentration: a 25 percent increase of the emissions results in a 25 percent increase of the concentration. For BOD5 concentrations at Kanpur and Varanasi a change of 25 percent of the emissions results in a more damped response: a reduction 8–11 percent only. This is because part of the BOD5 concentration at these locations originates from algae. The relative contribution of algae to BOD increases when concentrations of BOD are low due to dilution or decay, and when residence time in the river is long enough to support instream growth of algae.

Table 10.2: Response of the concentration to a 25 increase in emission.

	Kanpur	Varanasi	ds Delhi
BOD5	11%	8%	26%
Tcoli	25%	25%	25%

Water quality results are sensitive to the emissions from rural and urban public water supply systems. The waste load from rural inhabitants actually reaching the river system is hard to determine and therefore provides a large uncertainty in the model results.

10.2.4 Conclusions

Some conclusions can be drawn from the results of the sensitivity analysis and the calibration and validation of the river basin model that are very valuable for the application of the model to support strategic basin planning:

- The simulation results are very sensitive to the timing of the planting of. A variation of just one month in planting date may increase irrigation water demand substantially. This is caused by the fact that peak water demand and monsoon water availability are no longer aligned;
- The results are also very sensitive to the crop transpiration demand. A 20 percent decrease in transpiration demand decreases the simulated irrigation water demand by nearly 50 percent since a larger part of the transpiration demand can be met without irrigation;

- Irrigation water demand is sensitive to the values of irrigation efficiency. A 10 percent increase in surface water irrigation efficiency and a 5 percent increase in groundwater irrigation efficiency both lead to a 5 percent decrease in irrigation water demand. Irrigation efficiency values are now uniform in the model, but they will be spatially differentiated in reality. However, no data are available to derive efficiencies for individual irrigation areas;
- Water quality results are very sensitive to the emissions from rural and urban public water supply systems. The waste load from rural inhabitants actually reaching the river system is very hard to determine and therefore provides a large uncertainty in the model results;
- In strategic planning, the model results will be used for impact assessment by comparing results with and without certain future developments and/or measures. Therefore, the applicability of the model is determined by its ability to simulate the difference with and without certain changes and not by the absolute value of its results. The sensitivity analysis performed shows that the model varies in a plausible way to changes in its input. That provides confidence that the impact of developments and measures can be assessed with the model. It is recommended to test the model behavior further before applying it for other types of developments and measures.

11 Conclusions and Recommendations

This report presents the concepts, set-up, input data and calibration and validation results for the river basin model to support strategic planning in the Ganga river basin. Furthermore, the Ganga water information system (GangaWIS), which combines the model with a database and tools, presents the input data and the simulation results in graphical and map format.

The system is operational for the impact assessment of socio-economic and climates change scenarios and management strategies. The application of the system including the impact assessment is described in a separate report. As is true with the introduction of most new systems, the reliability and accuracy of the model for supporting strategic basin planning can be improved. It is recommended that this should be a continuous effort using new data and knowledge. However, improvement of the model should not delay its application for scenario analysis. On the contrary, the application will provide important insight into those areas where model improvement is most urgently required.

Improvement of the river basin model should aim to improve its relevancy as a tool to support strategic basin planning. Adding more detail input does not in itself improve the model. On the contrary, too much detail will make the model too complex for strategic planning and more difficult for interpretation of results. Furthermore, the improvement of the calibration and validation of the model does not in itself improve the relevancy for supporting strategic basin planning. Improvements should be sought in more reliable and accurate representation of the impact of scenarios and strategies and more insight into the value of impact assessment.

Based on the calibration and validation results, it is recommended that the following topics be considered for improvement:

- Add missing data on important input items, such as the storage capacity of some reservoirs;
- Improve the cropping calendar used to derive the water demand for irrigation;
- Add data on hydropower demand and generation;
- Add data on operation rules for dams and barrages;
- Calibrate the groundwater extraction from the inventory of installed pumping capacity and depth;
- Add an economic valuation of the societal benefit of different uses of water that would become input for a cost-benefit analysis of management strategies.

It is recommended that application and further development of the river basin model and the GangaWIS be executed by staff of the relevant Indian organizations, such as CWC, CGWB, CPCB, NIH and IIT in order to ensure that the system is maintained and utilized following project completion.

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