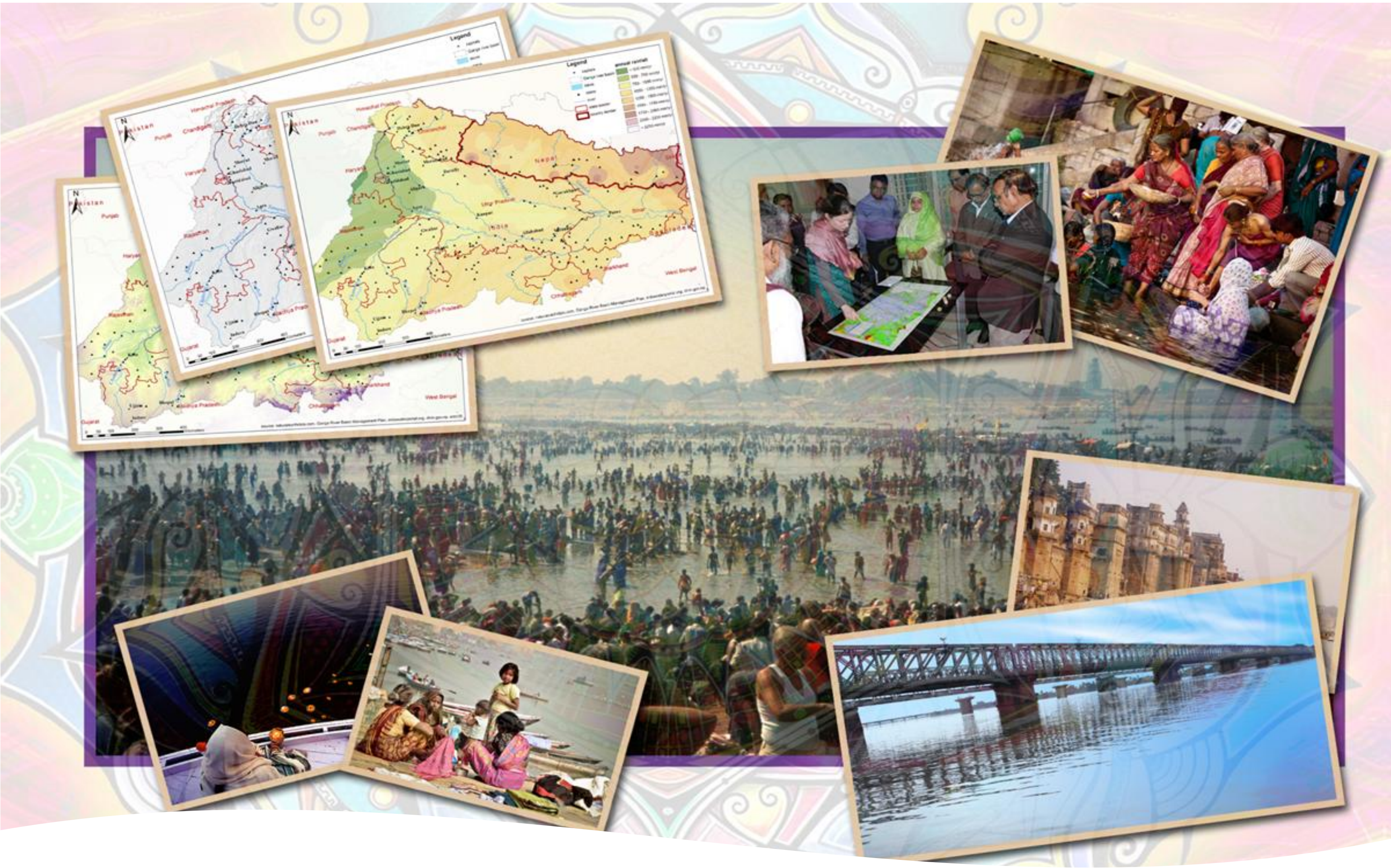
Strategic Basin Planning for Ganga River Basin in India



Ganga River Basin Planning Assessment Report

Final
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Title
Ganga River Basin Planning Assessment Report

Client	Project	Reference	Pages
World Bank and Government of India	1220123-002	1220123-002-ZWS-0003	170

Keywords
India, Ganga, Model, Information System, Hydrology, Geohydrology, Water quality, Ecology, Water allocation, Integrated Water Resources Management

Summary
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. This report contains:

- The scenario and strategy assessment;
- The environmental flow assessment;
- The groundwater-surface water interaction assessment.

This report contributes to project milestone 5 of the project.

Reference
Bons, C.A. (Ed.), 2018. Ganga River Basin Planning Assessment Report. Main volume and Appendices. Deltares with AECOM and FutureWater for the World Bank and the Government of India, Report 1220123-002-ZWS-0003.

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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 Assessment
IIASA	International Institute for Applied Systems Analysis
IIT	Indian Institute of Technology
IITM	Indian Institute of Tropical Meteorology
IMD	India Meteorological Department
iMOD	Graphical User Interface + an accelerated Deltares-version of MODFLOW
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
LOG	Logarithm
LOGNSE	NSE with logarithmic values
MERIS	Medium Resolution Imaging Spectrometer
MLD	Million Liters 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
ONGC	Oil and Natural Gas Commission
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	A powerful, open source object-relational database system developed by the PostgreSQL Global Development Group
PWS	Web Processing Service
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 Future Water
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
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	Distributed hydrological model platform developed by Deltares
WFS	Web Feature Service
WGS	World Geodetic System
WIS	Water Information System
WMS	Web Map Services
WPS	Web Processing Service
WQ	Water Quality
WRIS	Water Resources Information System
XML	Extensible Markup Language

Executive Summary

The Ganga river 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; 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 and strategies 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.

This report consists of three parts that report on:
- Part A: The scenario and strategy assessment;
- Part B: The environmental flow assessment.
- Part C: The groundwater-surface water interaction assessment;

Part A: Scenario and Strategy Assessment
A central project component was to develop, model and disseminate a series of plausible scenarios that explore alternative options for improving water management and river health. This task highlights the use of the river basin model for scenario and strategy assessment. The assessments were informed by the stakeholder consultation activities and workshops. As a result, stakeholders participated actively in the scenario and strategy development and assessment.

Generally the terms 'scenario' and 'strategy' are used without much distinction. For clarity herein, the terms are given clear definitions. A *scenario* describes developments that have impact on water resources, but that are outside the direct sphere of influence of the water managers in the basin. Examples are: climate change, population development, and economic developments. A *strategy* is defined as a combination of interventions that can be taken to overcome a problem or to address future issues, possibly influenced by scenarios. In this way a distinction is made between developments that may happen but cannot be influenced by water managers and developments water managers can actually plan and implement. It is also possible to evaluate the robustness of strategies in the light of more or less severe scenario development.

Except for the present scenario, all scenarios are based on assumptions or predictions and are therefore uncertain. In this assessment one scenario, the 'pristine' scenario, describes the situation before any human intervention. The remaining scenarios describe a possible future

for the year 2040, include increases in demands for domestic, industrial, and agricultural uses, with three different possible climate change developments: no climate change, climate change following the RCP4.5 scenario and climate change following the RCP8.5 scenario. The scenarios are used to develop model inputs that approximate the expected situation so that the model output provides a simulation of the river flow, water quality, and groundwater levels To examine possible outcomes, scenarios adjust or vary the model parameters: land use, infrastructure, population, industry, and agriculture settings as well as precipitation and temperature settings. Given the complexity of the system and the uncertainty about developments and their interaction, model scenarios can never represent the future conditions in detail but do give a reasonable idea about what could happen.

The project organized basin-wide and state workshops to obtain stakeholder input on promising and realistic strategies. The suggested strategy components are summarized in Table 0-1.

Table 0-1: Summary of interventions as part of strategies mentioned in the workshops in the states

	UP	UK	WB	Jharkhand	Rajasthan	HP	Delhi	Chhat.	MP	Bihar	Haryana
Catchment management	■	■	■	■	■	■	■	■	■	■	■
Waste Water treatment, recycling	■	■	■	■	■	■	■	■	■	■	■
Demand management, increase agric efficiency	■	■	■	■	■	■		■	■	■	■
Make new infrastructure	■		■		■	■	■	■	■	■	■
Increase Awareness	■	■		■		■	■	■	■		■
Cropping pattern change, Increase command area	■	■	■	■				■	■		■
Limit GW extraction	■		■	■	■	■	■				■
Financial incentives, Water pricing /metering	■		■		■			■	■		■
E-flow enforced	■		■				■			■	
Artificial recharge of GW	■			■			■	■			
Change in Water distribution rules			■							■	■
Increase flow for navigation			■								

Based on these inputs strategies were developed that can be implemented in the model in combination or separately. Most strategies are also scalable to increase their impacts:

- Do nothing: This represents the situation where due to lack of planning, lack of political decisiveness, lack of funds, or lack of implementation capacity or any other reason, no significant improvements in the water resources is implemented.
- Approved Infrastructure: In this strategy a number of infrastructure projects that are already approved (by early 2018) are implemented.
- Inter Basin Transfer Links: A strategy where the main Inter Basin Transfer Link projects in the Ganga Basin are implemented.
- NMCG planned treatment: This strategy includes the additional treatment as planned by NMCG so that its impact can be evaluated.
- Improved treatment: To evaluate the impact of additional investments in waste water treatment this strategy was designed in which all presently planned WWTP are considered operational, but where also the rural waste water impact is reduced by additional treatment.
- Increased irrigation efficiency with 20%: In line with this government policy to get more crop per drop, all irrigated agricultural areas are given a higher efficiency: surface water efficiency increases from 40% to 48% while groundwater efficiency goes from 70% to 74%.
- Conjunctive use: In this strategy the groundwater abstraction capacity is reduced by half for all over-extracted nodes. In the present scenario six nodes are over-extracted with an additional six nodes over extracted in 2040.

- E-flow: The strategy analyzed here aims to achieve at least a “Moderate” environmental flow status for the hydrological indicator in all zones. Moderate is defined as between 40 and 60 percent deviation from the reference pristine situation. The status is influenced by many factors related to high and low flows in value, duration and timing. This was modelled by setting a target of at least 41 percent of the reference discharges at twenty-eight locations in the Ganga for each month, not only for the lean period.

Planning models and planning assessment studies are most effective when the information on options or choices is not presented in the technical language of modellers, but as indicators on which decision makers actually use to base their decisions. The stakeholder engagement therefore included collaborative modelling where the project team together with the stakeholders identified the issues to be modelled, the data required and the relevant output indicators.

The indicator scores used in this assessment are derived from the model dashboard that presents a scorecard with a list of indicators with performance values for two selected run cases with a scale level of basin or state (Figure 0-1).

Indicator	Present	2040	Weights
State of Groundwater development (% critical areas)	41 (5)	89 (1)	100
Lowest discharge (m3/s)	2683 (9)	2170 (9)	100
Volume of water stored in reservoirs (Billion m3)	56 (5)	54 (5)	100
Agricultural crop production (% of area harvested)	96 (9)	88 (8)	100
Deficit irrigation water (%)	23 (7)	31 (6)	100
Deficit drinking water (%)	10 (8)	34 (6)	100
Surface water quality index (-)	4 (2)	4 (2)	100
Volume of groundwater extracted (Billion m3)	99 (3)	216 (0)	100
E-flow: Ecological status (-)	74 (7)	73 (7)	100
E-flow: Hydrological status (-)	62 (6)	60 (5)	100
E-flow: Socio-Economic status (-)	74 (7)	72 (7)	100
Total	68	56	100

Figure 0-1: Example of scorecard panel on model dashboard (number between brackets is contribution to total) showing the indicators used.

The scenarios described earlier all have impacts on the water resources situation in the basin, especially when no additional interventions are implemented. Figure 0-2 shows the basin-wide scores for the selected indicators of the considered scenarios. The impacts are most visible in the hydrological indicators; the percentage of areas with critical groundwater use increases significantly, and the lowest flow in the river in dry years diminishes significantly. The e-flow indicators differ significantly between pristine and the other scenarios, but differences are small between the other scenarios. The main reason is that the indicators focus on the worst situation and do not provide information on how widespread the bad conditions are. A second reason is that both water quality and environmental flow indicators are scaled relative to the ‘good or pristine’ situation.

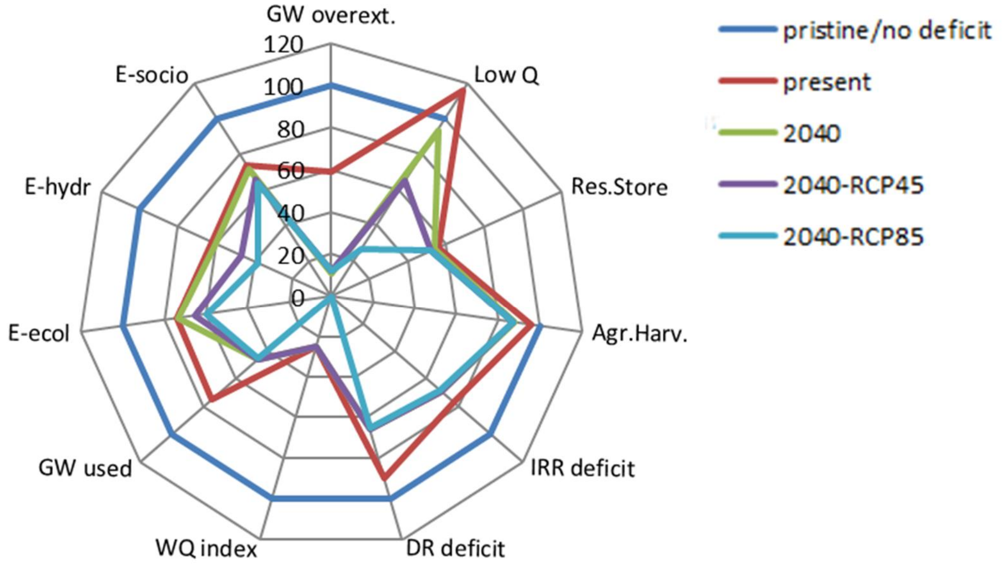

Figure 0-2: Pie chart of basin-wide indicators (longer names given in Figure 0.8) for the 5 scenarios (all values scaled between 0 and 100, with pristine or no deficit situation given as 100).

Considering the serious issues expected by 2040, it is interesting to evaluate whether the strategies discussed with stakeholder will address the issues to achieve the desired outcome. Table 0-2 and Figure 0-3 present the indicator scores for the individual strategies when applied in the 2040_RCP4.5 scenario. If several of the suggested strategies are combined, it is expected that a significant response can be achieved.

Table 0-2: Overview of basin wide indicator scores for the strategies applied in 2040_RCP4.5 scenario.

2040 RCP4.5 cases Indicator	Code	do nothing	Appr.Infra	GW use	IBTL+Apr.Infra	Efficiency	planned treatm.	improved treatm.	e-flow
State of Groundwater development (% critical areas)	GW overext.	88	88	79	83	88	88	88	95
Lowest discharge (m3/s)	Low Q	1502	1458	1622	1258	1483	1502	1502	1528
Volume of water stored in reservoirs (Billion m3)	Res.Store	52	55	53	41	53	52	52	20
Agricultural crop production (% of area harvested)	Agr.Harv.	87	89	74	92	89	87	87	84
Deficit irrigation water (%)	IRR deficit	31	31	47	30	29	31	31	39
Deficit drinking water (%)	DR deficit	34	34	35	35	34	34	34	39
Surface water quality index (-)	WQ index	4	4	4	4	5	4	4	5
Volume of groundwater extracted (Billion m3)	GW used	217	215	176	206	207	217	217	235
E-flow: Ecological status (-)	E-ecol	65	65	66	63	66	65	66	73
E-flow: Hydrological status (-)	E-hydr	47	46	49	44	47	47	47	56
E-flow: Socio-Economic status (-)	E-socio	66	66	67	68	66	67	69	75

Figure 0-3: Charts showing the percentage improvement (positive) or deterioration (negative) in basin-wide indicator scores for evaluated strategies. All scores are relative to the do-nothing strategy.

For this assessment the interventions on approved infrastructure, IBTL, 20 percent efficiency increase in irrigated agriculture, reduced groundwater use in over-extracted areas and improved waste water treatment are combined in one run. Table 0-3 and Figure 0-4 show the results in terms of basin wide indicator scores.

Table 0-3: Overview of impact of combined strategy.

Indicator	Code	present	2040-RCP45 do-nothing	2040-RCP45 combination
State of Groundwater development (% critical areas)	GW overext.	41	88	79
Lowest discharge (m3/s)	Low Q	2683	1502	1422
Volume of water stored in reservoirs (Billion m3)	Res.Store	56	52	43
Agricultural crop production (% of area harvested)	Agr.Harv.	96	87	85
Deficit irrigation water (%)	IRR deficit	23	31	42
Deficit drinking water (%)	DR deficit	10	34	35
Surface water quality index (-)	WQ index	4	4	4
Volume of groundwater extracted (Billion m3)	GW used	99	217	163
E-flow: Ecological status (-)	E-ecol	69	63	66
E-flow: Hydrological status (-)	E-hydr	52	43	46
E-flow: Socio-Economic status (-)	E-socio	69	64	73

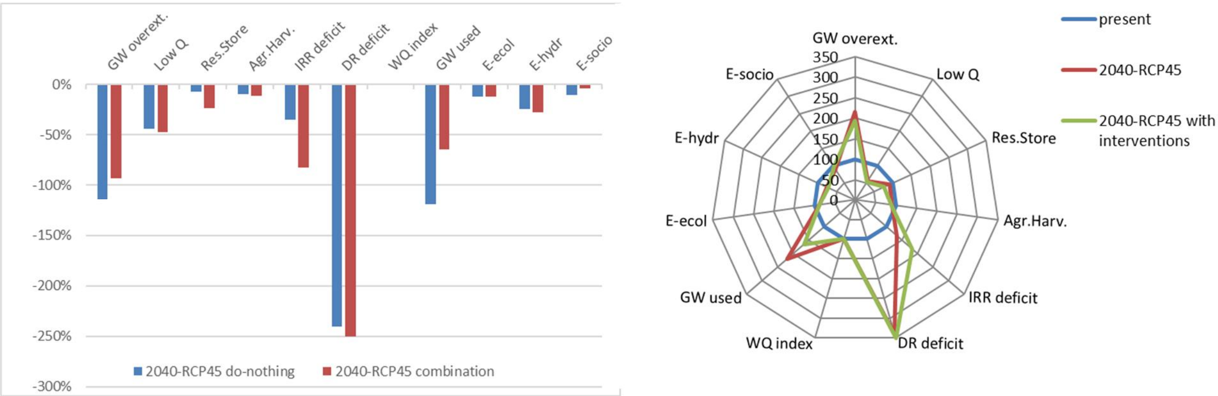

Figure 0-4: Charts comparing 2040_RCP4.5 and 2040_RCP with a combination of strategies relative to the present. Bars show the percentage deterioration (negative) in basin-wide indicator scores for evaluated scenario/strategy.

The first conclusion that can be drawn from the results is that the socio-economic developments that drive the progressively increasing demands are the main factor influencing the status of the basin. The scenario assessments indicate a significant decrease in future water availability, water quality and ecological status in the event no additional interventions are made. Future changes are mainly determined by socio-economic factors, much less by climate change.

The intervention that has the most beneficial impact is improvement of municipal waste water treatment. Whether centralized or decentralized, whether high or low technology, reduction in pollution loads gives a return on investment both in availability of clean water for downstream uses, including ecosystem services, as well as a drastic reduction in water related illnesses and deaths. Note that the river-oriented indicators selected for this study do not reflect the beneficial health impacts achieved in towns as a result of proper sewerage and waste water treatment.

The next ‘no-regret’ intervention is the increase in efficiency of all water uses: irrigation, domestic and industrial water use. However, it can be expected that farmers will increase their cropped areas in tune with the increased efficiency resulting in higher production, but not less abstractions from surface or groundwater. In case there is a reduced demand from surface water, care should be taken that the reduced drainage will not lead to over-extraction, even when groundwater abstractions themselves have not increased.

There is no ‘silver bullet’ intervention that solves all problems. Combinations of different interventions are required. However, the set of currently considered far reaching interventions, requiring huge investments and facing significant technical challenges and opposition from stakeholders, is insufficient to deal with future challenges regarding water availability, water quality and ecology, let alone to restoring the system to present conditions.

All stakeholders must realize that water availability will be insufficient to meet all the rising demands and there are no ‘easy’ technical solutions. Ambitious strategies need to be implemented aiming at reduction in demands in all sectors, but at the same time trade-offs need to be made between different sectors. The agricultural sector will have to adapt to lower water availability in terms of choice of crops, planting season and water efficiency. Farmers will need to develop a flexible approach: depending on the monsoon they may have to select irrigated or non-irrigated crops even when irrigated crops are already of high efficiency.

The consequences of these conclusions are far reaching and involve departments and ministries outside the traditional water resources realm. Non-technical interventions such as incentives to change cropping patterns and practices to reduce water demand are needed. Even more fundamental, a ‘more job per drop’ economy may be more beneficial than an economy with a focus on crop production. Service and industrial sectors consume much less water per employment with resulting economic benefits.

Part B: Environmental Flow Assessment
The aim of the environmental flow (e-flow) assessment was twofold: to develop possible management strategies to optimize use of the Ganga basin water resources for socio-economic benefits and to protect the Ganga ecosystem and its services for society. While the scenario and strategy analysis focused on the final outcome of all integrated indicators and combinations of different strategies and scenarios, the e-flow assessment is an in-depth analysis of in-stream hydrological, ecological and socio-economic indicators. This assessment provides a detailed analysis of hydrological changes in the Ganga river basin and describes how the present ecological and socio-economic values have been impacted and postulates how future change may be influenced by various scenarios and strategies. Three main indicator categories were considered:
- Hydrology;
- Ecology;
- Socio-economy.

For each indicator category a set of indicators were selected. The hydrological indicators were selected based on the impact on ecological processes. These indicators give information on changes in the magnitude, timing, duration and frequency of high- and low flows. The ecological indicators are expressed as habitat suitability for several fish species, the Ganga river dolphin, the Gharial and the Indian Flapshell turtle. Habitat suitability was calculated with response curves with environmental thresholds for water quality and water depth. The socio-economic indicators are fisheries, which extract habitat suitability information from the ecological indicators, ritual bathing and floodplain agriculture. The ecological and socio-economic indicators were developed in consensus with the stakeholders. Each indicator was calculated as a percentage of agreement with the pristine situation and expressed in classes of agreement.

Due to the large heterogeneity in the Ganga river basin, the rivers and tributaries were split into 70 ‘eco-zones’ (Figure 0-5). These zones represent river reaches with relatively homogeneous geomorphological, ecological and anthropogenic characteristics. All indicators were calculated per zone. This allows a spatially varying analysis which can help to identify degraded areas and pin-point areas where additional measures could be applied.

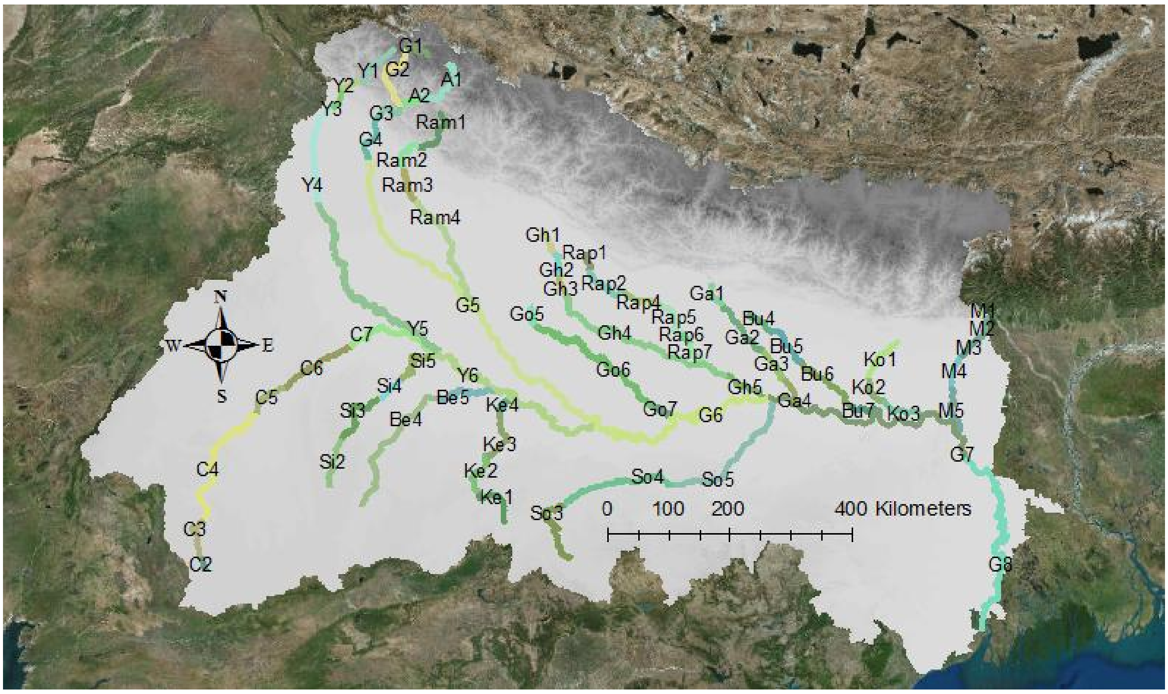

Figure 0-5: Zonation of the Ganga River and its tributaries into eco-zones with relatively homogeneous geomorphological, anthropogenic and ecological characteristics.

For the e-flow assessment a set of scenarios and strategies was analyzed. This included the scenario with socio-economic development until 2040 and two climate change scenarios RCP4.5 and RCP8.5, the individual strategies for the present and RCP4.5 scenario, and an e-flow strategy.

The assessments indicate that the Ganga river basin shows a severely altered state compared to the pristine situation due to alterations of the flow regime and poor water quality. Specifically, the middle reaches of the Ganga and Yamuna Rivers are strongly degraded. Future socio-economic development and climate change are expected to further deteriorate the ecological and socio-economic values of the Ganga river basin (Figure 0.13). The impacts of strategies to reduce water extraction and improve water quality are limited (Figure 0.14) and the effect of future developments and climate changes are much stronger, which suggests that the current strategies become even less effective in the future. The specific e-flow strategy in which river flows are prioritized over off-stream use does lead to an improvement in 30% of the modelled zones, but it does not improve all zones to a sufficient status due to mainly water quality problems. The river reaches that are mostly impacted by the scenarios, i.e. the middle reaches of the Ganga and Yamuna, the Gomti and the Betwa, are areas in which not all proposed strategies have an impact. This means that additional measures are necessary to preserve and protect the ecological and socio-economic values of the Ganga river basin and increase its robustness.

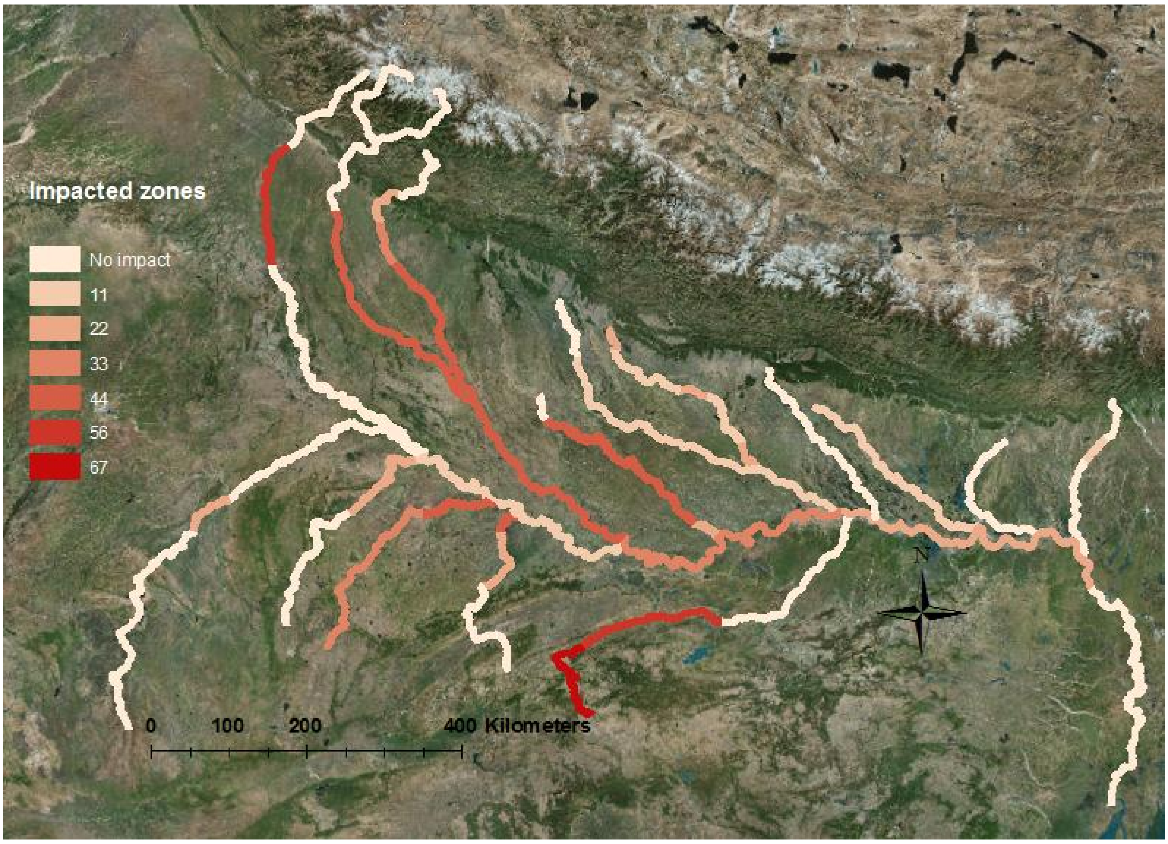

Figure 0-6: Zones that are negatively impacted by future scenarios, expressed as the percentage of scenario-indicator combinations per zone that become insufficient or decrease to the lowest class.

This study identifies the main information gaps and provides recommendations for improving future e-flow assessments. It is recommended to monitor both river parameters and availability of species and services in selected river zones to refine, expand and validate response curves. An adaptive management structure should be set up with clear roles and responsibilities to ensure the new insights from monitoring are used to update the model formulations and, together with stakeholders and experts, adjust river management practices.

Although an improved assessment of ecosystem responses can help to refine strategies per zone, it is not expected that the main conclusions regarding most impacted zones and limited effectiveness of the currently analyzed strategies will show large changes. Therefore, this assessment concludes that to further improve the Ganga ecosystem health and to create a climate robust system, it is required to reduce off-stream water use and groundwater pumping and locally restore species habitats to achieve at least ‘Class C’ or ‘no zones with insufficient conditions’. When that is not yet achievable, focus on specific zones rather than lower overall objectives. Clear choices need to be made reflecting how the Indian society values both their off-stream water use and their instream ecosystem and related services.

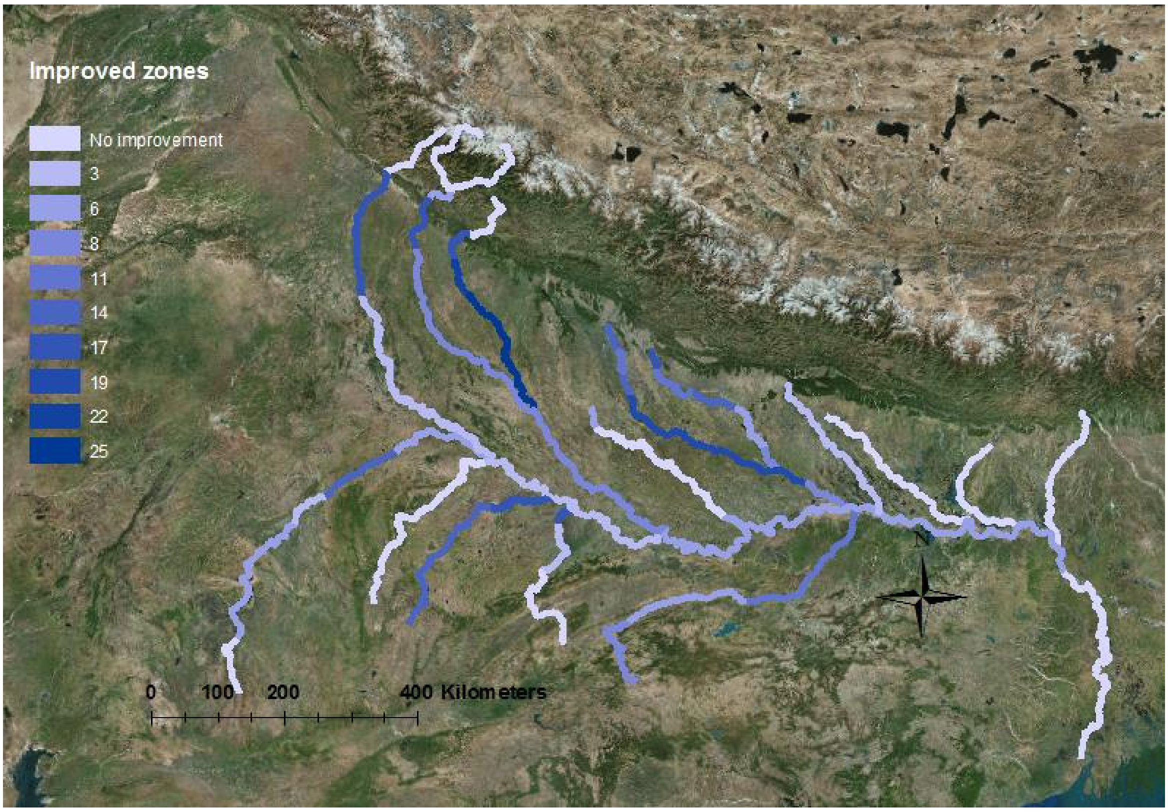

Figure 0-7: Zones that are positively impacted by strategies, expressed as the percentage of strategies-indicator combinations per zone that become sufficient or increase to the highest class.

Part C: Groundwater-Surface Water Interaction Assessment

Surface water and groundwater are the two principal water sources within the Ganga River basin. To effectively manage this valuable resource, it is imperative to understand the dynamic interactions of surface water and groundwater. To assess the implications of changed water management practices on both surface water and groundwater upstream of Farakka, the project undertook an extensive groundwater modelling analysis as well as a comprehensive model of the basin rivers and tributaries. Background information included available Ganga basin groundwater literature, recent and historical maps, and the iMOD groundwater study complemented by other existing model studies. The assessment yielded suggested improvements in water management practices.

Physical geography: Historical maps present an impression of the water situation from the late 1700s. Renel's map of 1794 (Figure 0-8) depicts a natural meandering network of numerous streams with most of the land already devoted to agriculture. The map suggests bulging groundwater levels between the main rivers. Groundwater levels at the groundwater divides were considerably higher than river levels, indicating significant groundwater recharge by rain. Renel's map also shows a long, wet forest zone at the foothills of the Himalaya Mountains with numerous small streams and rivers originating from this area.

It appears that this area possessed a sponge function, creating longer time base flow conditions. The Ganga basin groundwater system completely changed after the construction of the irrigation canal system around 1854. Constructed after some calamitous drought events, like the Agra Famine. Before this construction, groundwater was only recharged by rain and outflow from streams and rivers. After the introduction of the irrigation infrastructure, canal outflows and extra irrigation loss became important for groundwater recharge. In the second half of the twentieth century numerous deep wells were installed thus significantly increasing groundwater pumping and again dramatically changing the groundwater system.

Figure 0-8: The historical map of James Renel (1794). Green indicates forested areas.

Hydrogeology: An analysis of hydrogeological information is summarized in Figure 0-10. A deep alluvial valley, including faults, lies between the Himalaya area in the north and the solid craton rocks in the south. The northern Piedmont Fan area and the covering Mega Fans form an important hydrogeological area. The coarse sediments of the Piedmont Fan, interfingering into the Alluvial plain deposits (e.g. see CGWB-Utter Pradesh Ganga Basin atlas) in a relative humid area with very high hydraulic conductivities, provide excellent groundwater recharge conditions with the possibility of recharging the deeper parts of the alluvial deposits at a regional scale (Figure 0-9). Similar but smaller circumstances exist at the transition zone of the craton and the Ganga plain. Groundwater management is critical to protecting these recharge functions for deeper groundwater and the ecological flow downstream. In the Po Basin exists a similar situation and this area is protected by the European Water Framework Directive. Little knowledge is available on the hydro-geological characteristics of the very deep and very thick layer of Proterozoic sediments, between the alluvial deposits and the hard rock basis of the alluvial deposits.

The groundwater flow information is conceptualized in Figure 0-10. It seems clear that the Ganga basin groundwater system includes a relative shallow completely man-made flow system of approximately 0-150 meters deep. Infiltrated rainwater, canal and river waters, and irrigation loss water is continuously recirculated: pumped-up, used for irrigation and partly returning again. What does this continuous re-use system mean for water quality?
Most likely total dissolved solids, including pollutants, of this shallow groundwater body will increase over time due to the continuous pumping-evaporation-infiltration cycle.

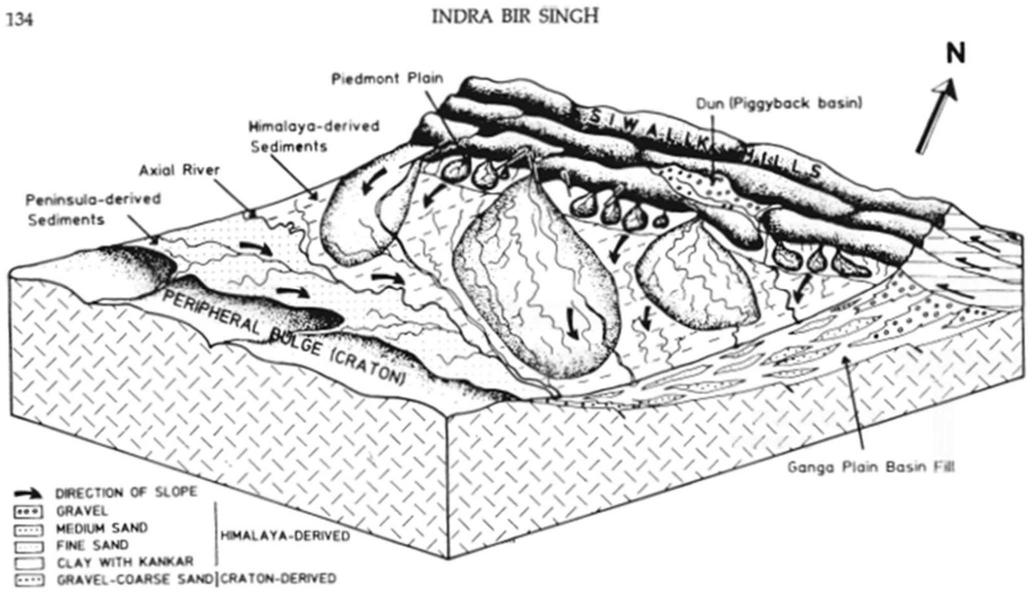

Figure 0-9: Distribution of main hydro-geological (geomorphological) units in the Ganga Basin: Piedmont Plain, Mega Fans, shallow and deep alluvial plain, southern marginal alluvial plain, southern craton (Singh, 2003).

The northern Mega Fans and Piedmont Fan area, and the southern craton transition zone, are important for recharge of deeper groundwater; however, it seems that this natural system interaction is strongly disturbed by pumping. It is possible that groundwater flow from this area into the Alluvial plain is captured by pumps at the Piedmont plain-Alluvial plain transition zone. Based on information of the deep oil and gas boreholes, groundwater can be fresh, even at 700 meters depth. There is little understanding of the very deep groundwater (> 150 m) and no evidence that this groundwater is still actively recharged. Under the present recharge and flow conditions, this groundwater can be considered “paleo- groundwater”.

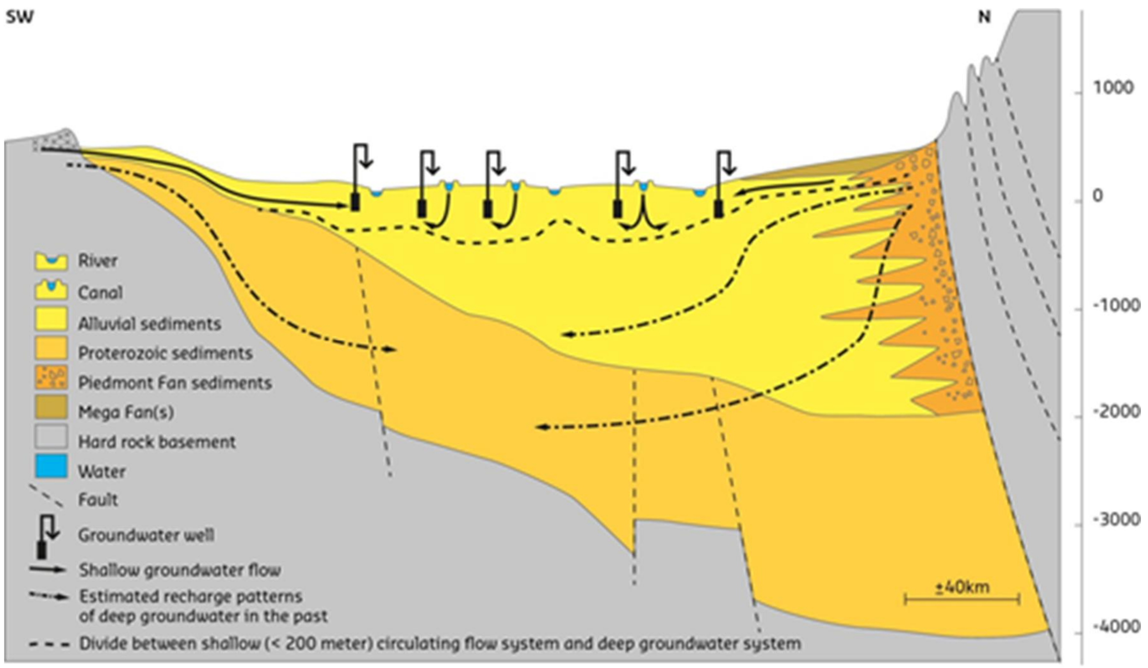

Figure 0-10: Generalized regional hydrogeological conceptual model and schematization of the current groundwater flow system in the Ganga river basin.

Groundwater quality: Information about the distribution of brackish-saline groundwater is largely fragmented. Only in Uttar Pradesh is the distribution of brackish-saline water well documented. A few deep borings determined brackish-saline water exists at depths of several hundred meters. The genesis of this deep saline groundwater is not well understood because the basin deposits are not of marine origin, and the alluvial basin was never flooded with sea water in the past. Salinization of the groundwater in the Ganga river basin is a serious issue. In the western and southern part of the basin a huge volume of “shallow” brackish or saline groundwater can be found, at depths of 50-300 meters. Fresh groundwater can be found both above and below this saline water body. To achieve sustainable groundwater use, it is very important to understand the dynamics of fresh-saline groundwater interaction during pumping and use in irrigation.

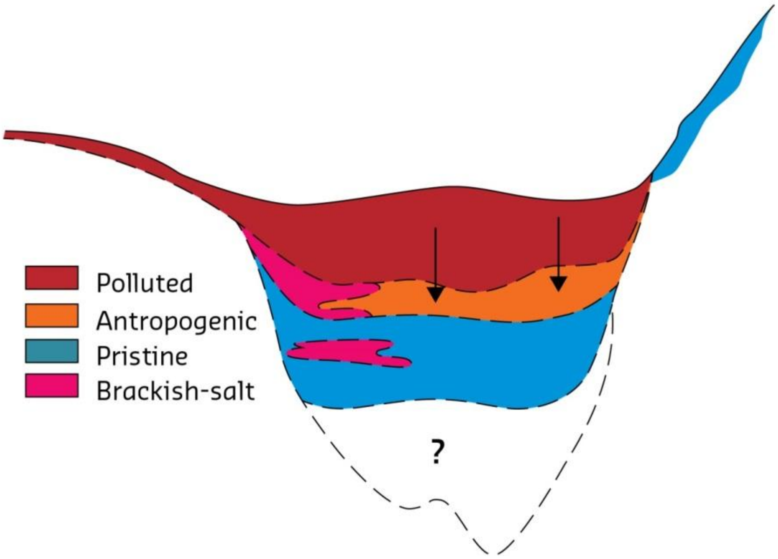

Figure 0-11: Schematic presentation of vertical zoning of general water quality types. Below the pristine water zone. Saline water is observed in some deep oil borings.

Groundwater quality is threatened at a regional scale by man-made pollution from agricultural chemicals and by the naturally occurring geological conditions of arsenic, fluoride, and uranium. Because water quality observation wells are not optimally distributed in space and depth, the spatial distribution of pollutants is unclear. Nearly all samples show anthropogenic influence. Nitrates are also found in deeper groundwater. The data support the conceptual groundwater flow idea of an active, circulating, pump-infiltration of irrigation water flow system in the upper 100-150 meter range. This theory can be improved with data from deeper wells, i.e. water quality and isotopes data with a depth dimension. It is very plausible that groundwater quality will decrease over time because of this irrigation circulation system. Another risk is deepening of the boundary between anthropogenic and pristine groundwater by vertical leakage caused by an increasing number of deep wells polluting groundwater, often still free of excessive arsenic (Tayler et al, 2014, MacDonald et al, 2010). Figure 0-11 presents the distribution of general water types in the Ganga basin:

- Polluted groundwater, at least one pollutant exceeds a chosen threshold;
- Anthropogenic influenced groundwater, water type clearly shows anthropogenic influences but not exceeding acceptable standards;
- Pristine groundwater, water type without any human influence most often found in groundwater discharge areas but also at greater depths;
- Brackish-saline groundwater, water type normally found below the pristine zone. In the Ganga basin this water type may be found as “isolated” water bodies surrounded by

fresh water due to dissolution of local/regional saline sediments, i.e. evaporates, paleo soils.

Water balance: In agreement with other model studies and the BGS monitoring based study, the estimated "recharge minus pumping" results are rather positive for the present time, except for the over-pumped north-west area (Figure 0-12). However, over the longer term this view may be overly optimistic considering the groundwater–surface water interaction in the river system during the non-monsoon period, i.e. low river water levels with river infiltration (Figure 0-13). Base flow is an integral component of the groundwater system; according to the groundwater model, base flow is very low or non-existent in large parts of the basin. The modelling results indicate a very negative future groundwater scenario without a far-reaching groundwater management program. During the non-monsoon period with very low river water levels, large parts of the river are losing water to the groundwater system. This observation is confirmed by Maheswaran et al. (2016).

Scant solid information exists about the groundwater–surface water interaction. In general, knowledge is based on modelling. Water balance studies based on modeling suggest that canal water loss may be an important factor in groundwater recharge. To better understand this groundwater-surface water interaction, dedicated monitoring networks could be designed and installed. For example, a cross-section of groundwater observation wells perpendicular to irrigation canals and rivers with a depth exceeding 100 meters and having multiple filters could capture water samples to help determine origin using isotopes or other traces. Simple groundwater temperature measurements can provide clues on groundwater-surface water interactions. The locations of these transects can be based on existing modelling results.

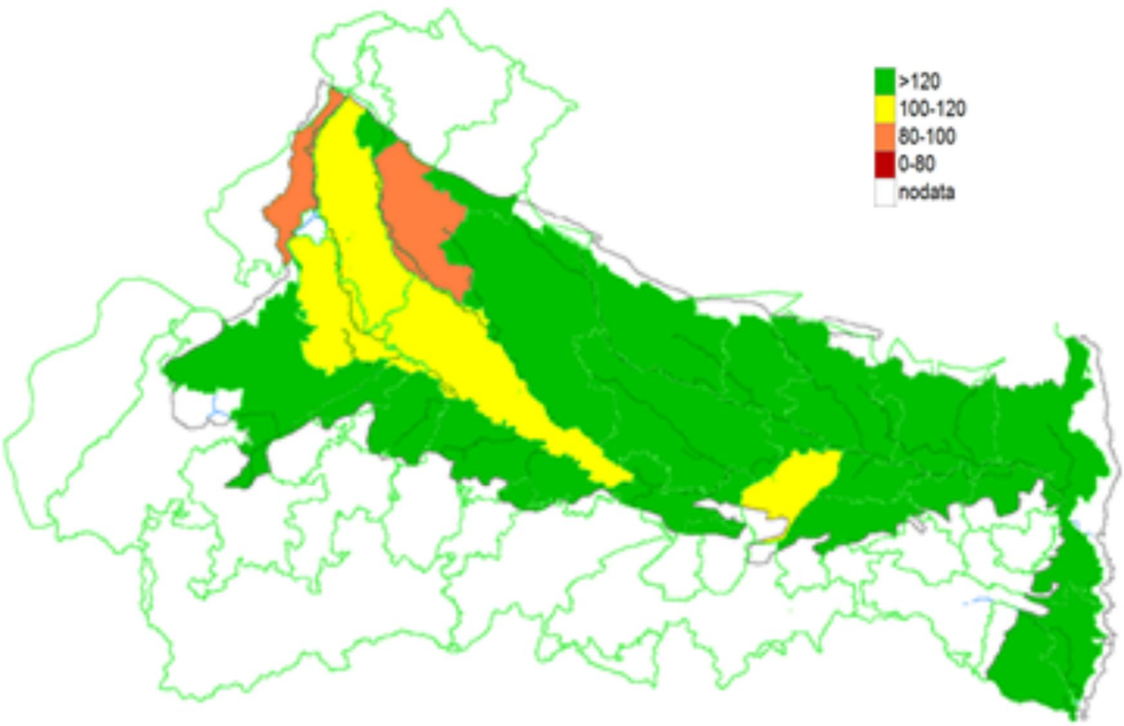

Figure 0-12: The present difference between total recharge and groundwater pumping (mm/year). Recharge is in general higher than pumping rates.

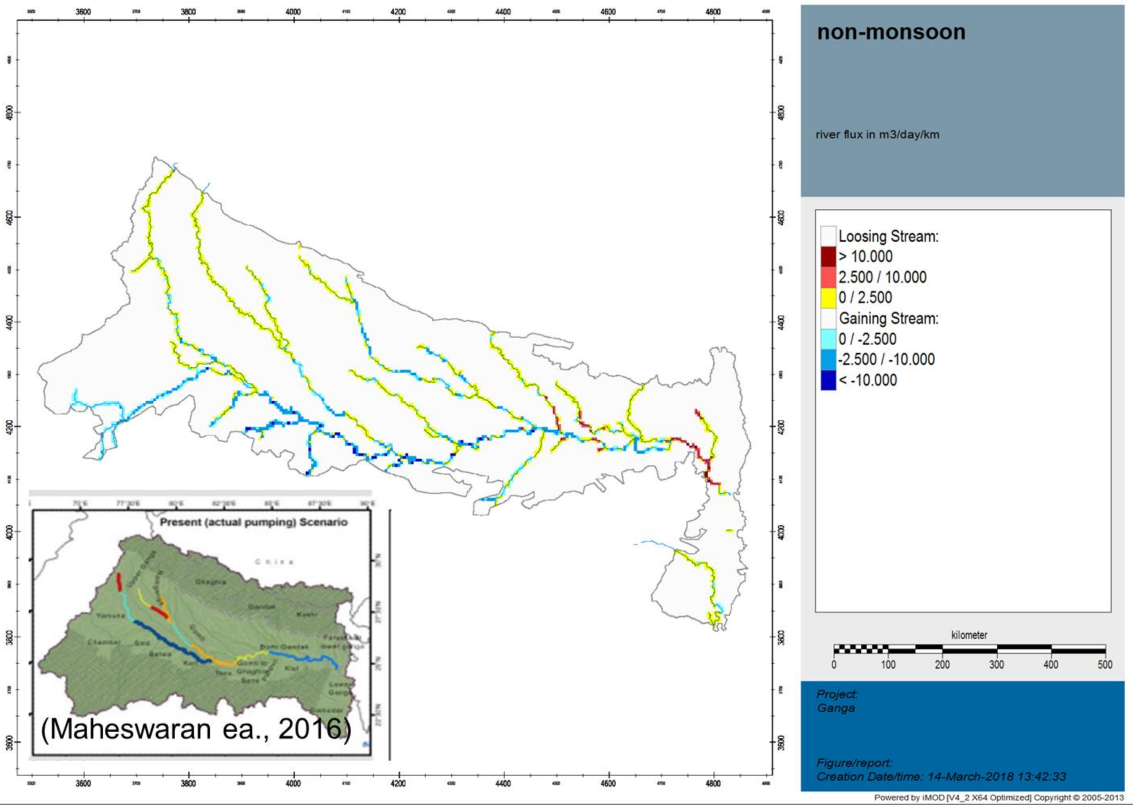

Figure 0-13: River-groundwater interaction during non-monsoon period, compared with the modelling results of Maheswaran et al., 2016. During very low river water levels large parts of the river are losing water to the groundwater system.

Subsidence: Geological subsidence is a naturally occurring condition studied by geologists and geomorphologists; as such there is a substantial knowledge base. Subsidence accelerated by groundwater pumping has been studied in Delhi and Lucknow with results showing serious subsidence velocities. Information about subsidence caused by pumping in other cities and the agriculture area is lacking. Often, groundwater pumping in cities is related to an inadequate drinking water distribution system or to cost considerations. There exists little or no information on subsidence caused by drainage of shallow groundwater. Some incidents of cracking and swelling soils have been reported. Subsidence can increase the effects of groundwater and surface water flooding during the Monsoon, which creates risks for the levee system.

Recommendations: The Ganga river basin can be divided into Groundwater Management Units based on (1) hydrogeology, including water flow processes, (2) geomorphology, and (3) groundwater stress issues. The points of departure are the six main hydrogeological units (Figure 0-14).

The Himalayan foothill and Piedmont Margin zones are extremely important for groundwater recharge and require protection. Recharge stimulation should always be considered as a possible option. Italy's Po Basin has similar hydrogeological conditions as those found in the Ganga river basin (Fontana, 2014). The foothill area there became a groundwater protection zone in accordance with the EU Water Frame Work Directive (E-R Ambiente, 2013). A similar approach for groundwater protection zones could be undertaken in the Ganga Basin;

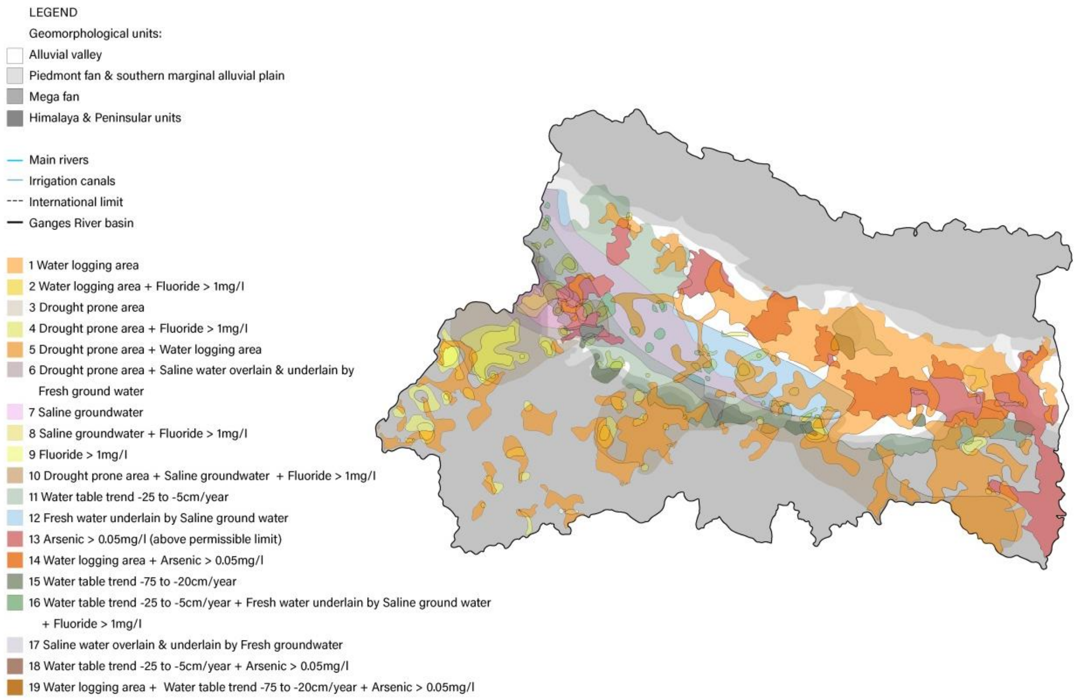

Figure 0-14: Combination map of detailed water management units.

Monsoon period peak flows provide opportunities for groundwater recharge. River water discharge could be delayed; storm water could be stored, preferably below ground to support groundwater demand during dry periods. Water logging may be reduced by management of the river and canal system to realize lower surface water levels during monsoon periods, e.g., by dredging (deepening profile) or by widening, creating additional (surface water) storage (“room for rivers or canals”). A basin wide “storage opportunity” map would be an important first step;

Main alluvial areas can be used for groundwater extraction as long as abstraction does not exceed recharge, taking the recharge from inefficient agriculture into account. However, in saline zones upconing or downconing of saline water should be avoided. Special care should be taken in Arsenic zones. Shallow groundwater should not be used for drinking or rice cultivation.

The hard-rock area and southern shallow alluvial cannot sustainably supply groundwater for use in irrigation.

The deep Alluvial Plain unit (> 150 m) possesses unknown opportunities. North of the Ganga River there are indications that fresh groundwater is available at depths of several hundred meters (ONGC/CGWB). An assessment of this deep water body could determine opportunities and potential water quality risks, whether natural or man-made.

All existing groundwater models are based on over-simplified hydrogeological schematizations. The simple schematization could be improved by creating a 3D hydrogeological model based on lithology and sedimentation characteristics. A 3D model would employ voxels, 3D building stones at a resolution of 1 km^3.

The existing groundwater monitoring network has evolved over time but was not designed to answer present groundwater questions. Most observation wells are shallow or phreatic and are not well documented for land-use and depth. The number of deeper observation wells is limited with heterogonous distribution. Very deep observation wells over 200 meters in depth are very rare. With present monitoring objectives, an improved basin monitoring network could be designed utilizing existing monitoring sites and constructing new observation wells.

Groundwater quality and origin are important issues to assess for the Ganga river basin. By giving special attention to vertical zoning of water types and using tracers and isotopes, the origins of brackish-saline groundwater and saline water in general could be determined at a basin scale.

Over the past decades many Ganga river basin subsurface and groundwater studies were produced, improving basic understanding of the river system; however, results were sometimes disparate generating new questions. There is no shortage of Ganga basin groundwater experts: CGWB, BGS, universities, GRACE experts, groundwater model experts, subsidence experts, geology experts. A workshop to identify knowledge gaps and determine priorities would take advantage of this important basin resource.

Preamble

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 for a variety of reasons: 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, 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 undertake the present project "*Analytical Work and Technical Assistance to support Strategic Basin Planning for Ganga River Basin in India*".

The key project objectives 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 and strategies that balance significantly improving the health of the river while maintaining an acceptable level of economic productivity;
- Build a stronger 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 strategic basin planning process; and

- Ensuring wide access to the models and analyses, with quality documentation.

The main deliverables of the project consist of:
- Report on river basin modelling and documentation of information systems;
- 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 contributes to project milestone 5 and combines three of the above deliverables in one report:
- The scenario and strategy assessment;
- The environmental flow assessment;
- The surface water – groundwater interaction assessment.

Part A: Scenario and Strategy Assessment

1 Introduction

Ganga rejuvenation 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 state and central governments have committed themselves to targets and objectives that may prove to be difficult to achieve if not integrated into a comprehensive coordinated program. The increasing water requirements for domestic water supply and food production compete with the environmental flow requirements and the wish to recover depleted groundwater reserves.

A central project component was to develop, model and disseminate a series of plausible scenarios that explore alternative options for improving water management and river health. This Part B of the report highlights the use of the river basin model for scenario and strategy assessments. The assessments were informed by the stakeholder consultation activities and workshops. Whether any of the scenarios or strategies explored lead to agreement on a Ganga basin plan will be determined by the collective governments, central and state, managing the water and related resources of the basin. At a minimum the scenarios will enable deeper exploration of options for river development and rejuvenation, increase the collective understanding of the river basin and reduce the likelihood of uneconomic investments in river clean-up.

Stakeholders participated actively in the scenario and strategy development and assessment. During the first round of basin-wide and state workshops the participants shared their main water management issues and priorities. In the second round of workshops the stakeholders formulated indicators that were considered important to assess whether proposed solutions achieve the desired results; and the indicators and the strategy components formulated corresponded to the respective priorities. In the third round of workshops the interaction between interventions were determined using model runs and strategies.

Generally the terms ‘scenario’ and ‘strategy’ are used without much distinction. For clarity herein, these terms are given specific definitions. A *scenario* describes developments that have impact on water resources, but that are outside the direct sphere of influence of the water managers in the basin. Examples are: climate change, population development, and economic developments. A *strategy* is defined as a combination of interventions that can be taken to overcome a problem or to address future issues, possibly influenced by scenarios. In this way a distinction is made between developments that may happen but cannot be influenced by water managers and developments water managers can actually plan and implement. It is also possible to evaluate the robustness of strategies in the light of more or less severe scenario development.

This report does not elaborate on the modelling process itself. The reader is referred to the report Ganga River Basin Model and WIS Report and Documentation (Deltares, 2018) for details on the model and its operation.

2 Scenarios

Scenarios describe the circumstances that could have existed, if the scenario describes the past, or that may materialize, if the scenario describes the future. Except for the present scenario, all scenarios are based on assumptions or predictions and are therefore uncertain.

In this assessment one scenario, the ‘pristine’ scenario, describes the situation before any human intervention. The remaining scenarios describe a possible future for the year 2040, that include the increase in demands for domestic, industrial, and agricultural water uses, with three different possible climate change developments.

The scenarios are used to develop model input that approximates the expected situation so that the model output provides a simulation of the river flow, water quality, and groundwater levels. The model parameters that scenarios affect are land use, infrastructure, population, industry, and agriculture settings as well as the precipitation and temperature settings. Given the complexity of the system and the uncertainty about developments and their interaction, model scenarios can never replicate the intended situation in detail but give a reasonable idea about possible outcomes.

The selected settings for each scenario are described in this chapter. The resulting model outcomes are discussed in chapter 16.

2.1 Present

The present scenario intends to describe the present situation. Because data is not available for a definitive ‘moment’, the present scenario is best interpreted as describing the situation between 2010 and 2015. Table 13.1 presents the settings for this scenario.

Table 2-1: Settings of the 'present' scenario.

Parameter	Settings in this scenario
Land use	Land use based on the land-use map as developed by IIT
Infrastructure	The main Barrages, dams, canals, treatment plants and drains are included.
Population	Based on 2011 census data
Industry	Based on CPCB data
Irrigated agriculture	Based on Ministry of Agriculture and Farmers Welfare data
Temperature	Based on EUWATCH and FWDEI data
Precipitation	Based on IMD observations for India

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 300 m x 300 m to 1 km x 1 km to fit the model requirements. Figure 2-1 shows the model’s combined land-use map.

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 groundwater.

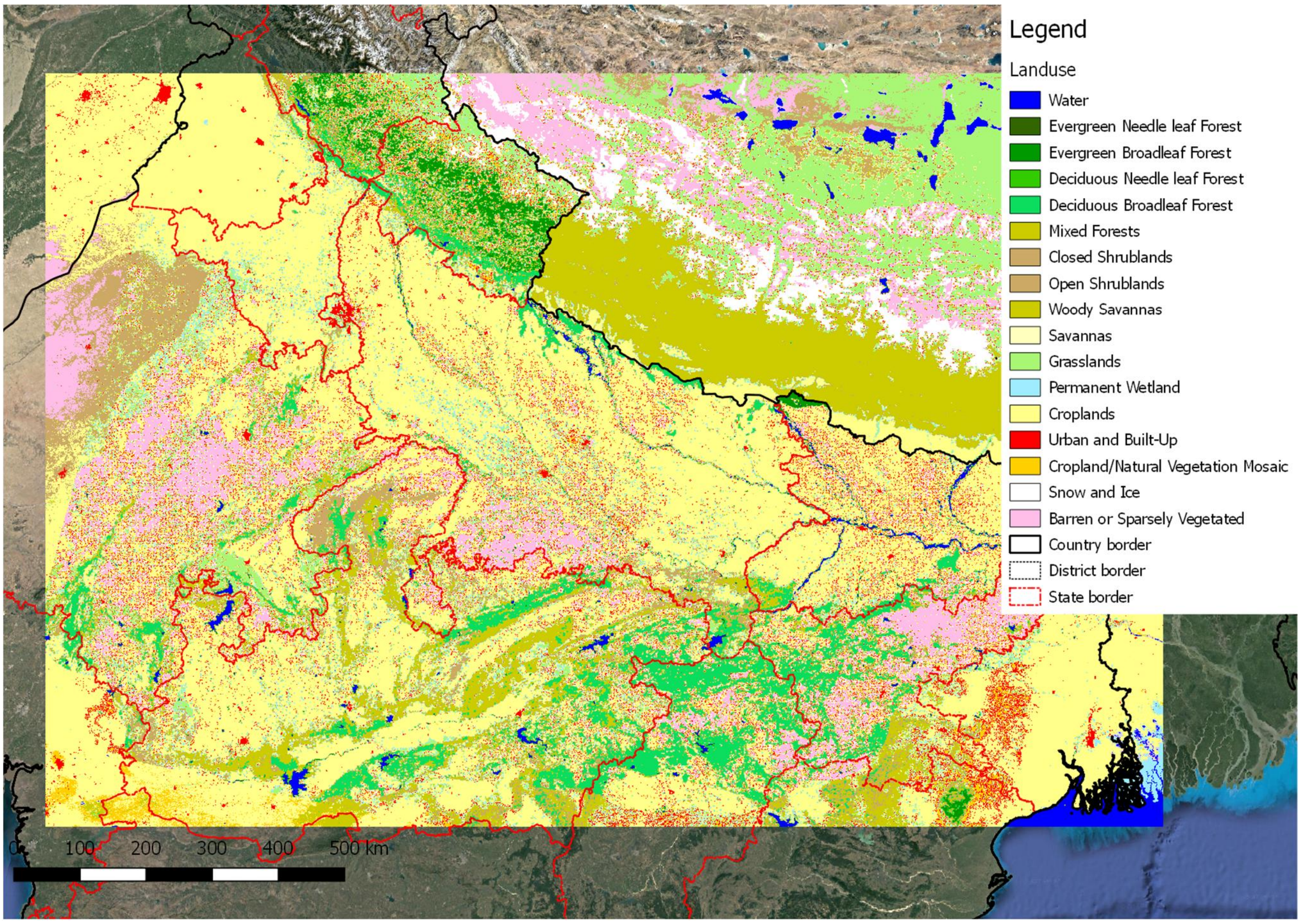

Figure 2-1: IIT land-use map, based on NRCS data.

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 2-2 shows the RIBASIM schematization of the Ganga basin.

Population data for the districts within the Ganga basin from the 2011 census have been distributed over the polygons representing the RIBASIM population nodes based on geographic location. Rural and urban population is represented in different nodes. Information on waste water treatment, whether by centralized facilities or other means, is based on the best available knowledge collected from CPCB, NMCG and state workshops.

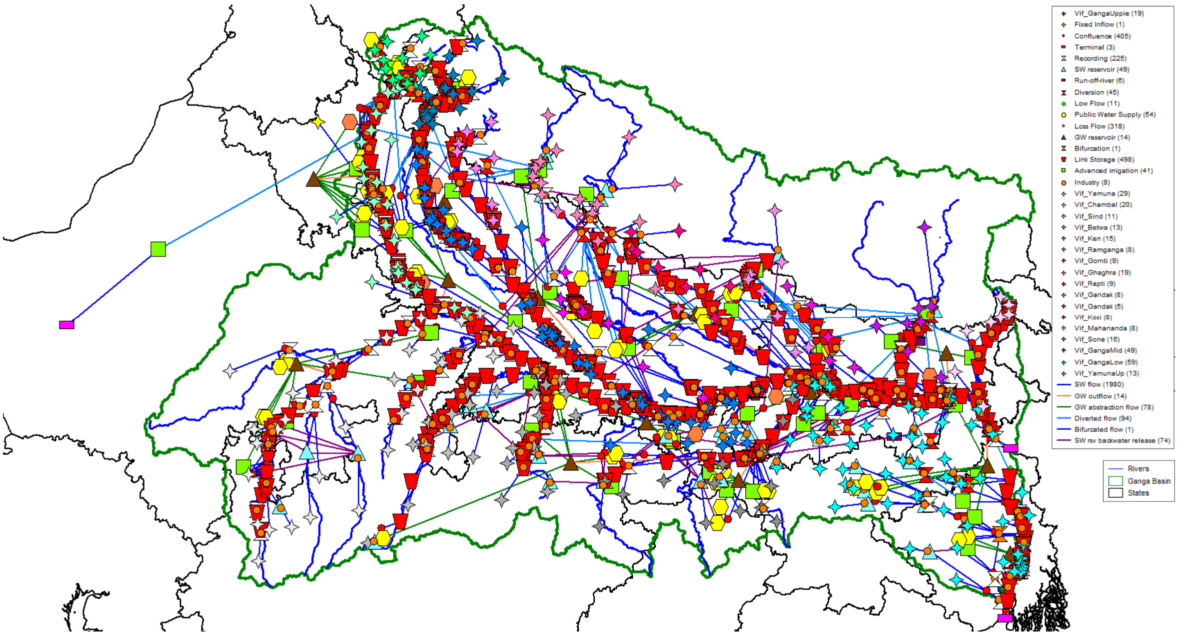

Figure 2-2: Schematization of the Ganga river basin in RIBASIM

Industry parameters are based on data from the Central Pollution Control Board (CPCB, 2013) which lists 764 individual industries with information on 'water consumption' in m3/d and 'waste generation' also in m^3/d. RIBASIM defines water consumption as explicit use. For the pollution assessment, the waste generation in m3/d is combined with typical effluent concentrations per type of industry, which were derived from the literature. Waste generation differs by type of industry. The following types are distinguished: chemical, distillery, dying textile and bleaching, food, dairy and 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 eight industrial nodes.

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[1]. 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[2]. Estimates for irrigation efficiencies and fractions return flow from irrigated areas have been taken from Gupta and Deshpande (2004).

The meteorological forcing in the 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 Indian Meteorology Department (IMD) data, WATCH Forcing ERA-Interim, WFDEI (Weedon et al., 2014) data, and EU-WATCH (Weedon et al., 2011) data, the model uses forcing data from the different sources as presented in Table 13.2.

Table 2-2: Sources of meteorological data.

Type of data	IMD	EUWATCH	WFDEI
Precipitation India	1959-2012		2012-2014
Precipitation Nepal		1959–1978	1979–2014
Evaporation and temperature		1959–1978	1979–2014

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

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

2.2 Pristine

The pristine scenario attempts to describe the water resources situation before human interventions changed the Ganga basin. It functions as a reference for comparison of the present and future simulated scenarios and strategies. Table 2-3 presents the settings for this scenario. The absence of any human presence is simulated by eliminating any population, industry or agriculture input data in the model. Also, all infrastructure is disabled in the model.

The natural vegetation map of India was the basis for a land use map of the pristine situation (Figure 2-3). For Nepal there is a national land cover database developed by ICIMOD[3] that provides insight into the country's different forest types. The forest types were extrapolated based on the physiographic map of the Soil Science Division, NARC, Nepal (Kabir Uddin et.al., 2015) for agricultural areas and fitted with the natural vegetation map of India. The resulting map was gridded and prepared in the correct projection to be used in the models.

Table 2-3: Settings of the 'pristine' scenario.

Parameter	Settings in this scenario
Land use	Natural vegetation of climatic zones
Infrastructure	None
Population	None
Industry	None
Irrigated agriculture	None
Temperature	The same as present
Precipitation	The same as present

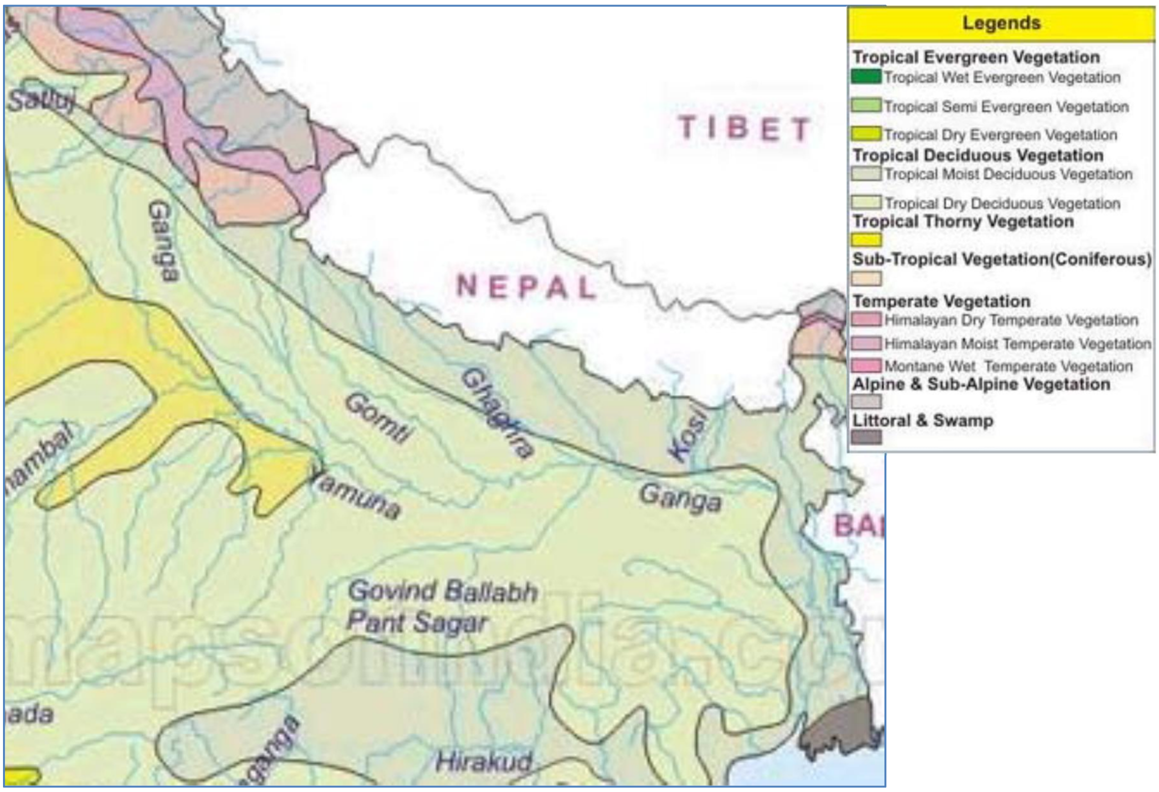

Figure 2-3: Cut-out of natural vegetation map of India (mapsofindia.com)

[3] http://www.sciencedirect.com/science/article/pii/S0301479714004009?via%3Dihub

The same meteorological data as in the present case is used although it is probable that the micro climatic conditions were different due to the different forest cover. However there is no better estimate available.

2.3 2040

Based on the workshop discussions the year 2040 was selected as a suitable year to develop predictions of future circumstances that would make sense in planning. Several climate scenarios can be developed for 2040. This is the case without climate change. Table 2-3 presents the settings for this scenario.

Table 2-4: Settings of the '2040' scenario.

Parameter	Settings in this scenario
Land use	The same as present
Infrastructure	The same as present (can be included in strategy)
Population	Projected autonomous growth to 2040
Industry	Projected autonomous growth to 2040
Irrigated agriculture	Projected autonomous growth to 2040
Temperature	The same as present
Precipitation	The same as present

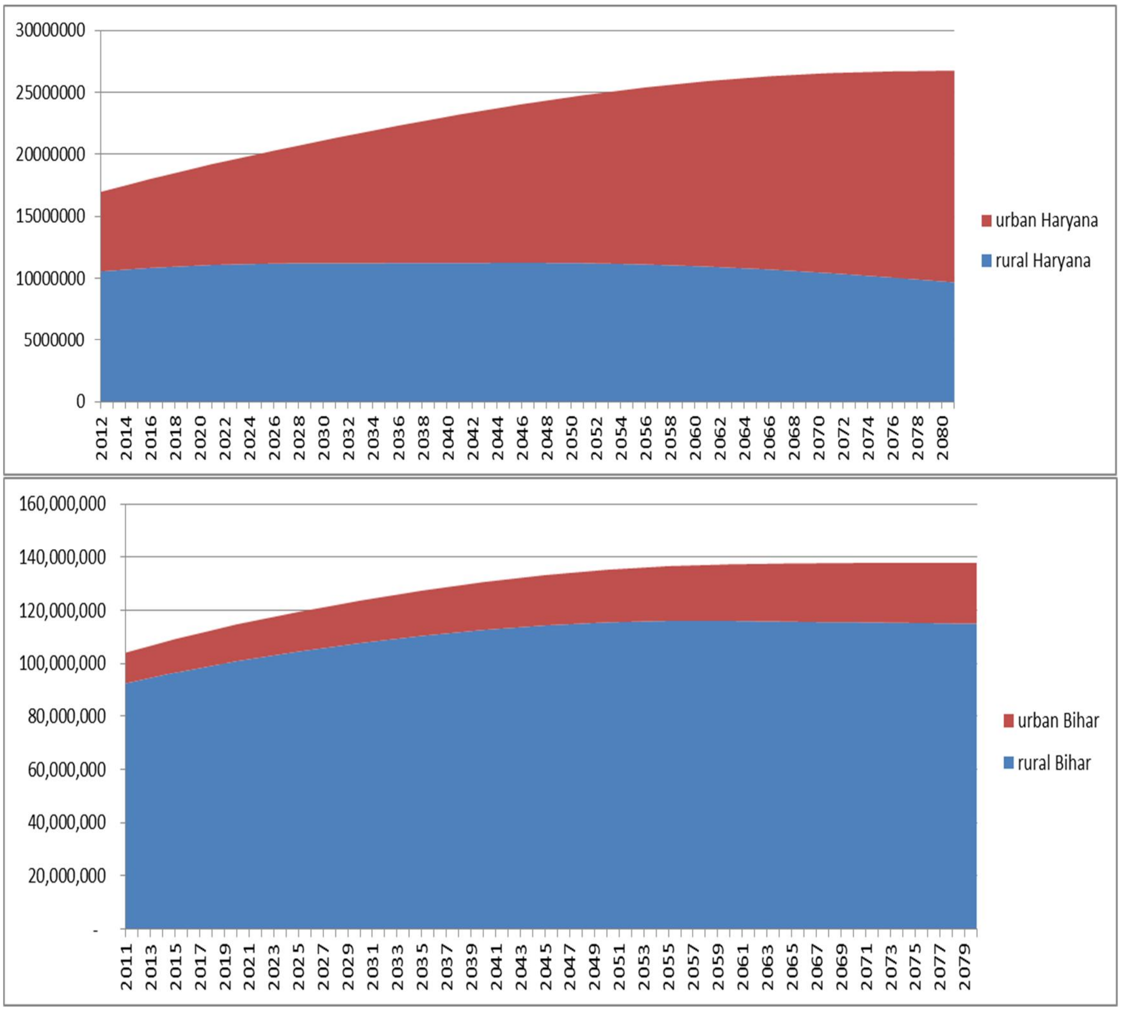

Figure 2-4: Examples of population projections for Haryana (top) and Bihar (bottom) to 2080.

Although it is highly unlikely that the infrastructure in 2040 remains the same as present, the 2040 case as a basic scenario does not include any additional infrastructure. Any additional infrastructure to be considered is included in a strategy as it will require proper planning and implementation.

In respect to water resources the most interesting autonomous developments to predict are domestic, industrial and agricultural demands. At the time the scenario was developed no formal projection was available so other sources and methods were used. Recently the National Institute for Transforming India (NITI) Aayog has developed the Composite Water Management Index (CWMI) to enable effective water management in Indian states (NITI Aayog, 2018). The warning is clear: by 2030, the country's water demand is projected to be twice the available supply.

In this scenario the total population growth for each state is based on The Indian National Commission on Population 2001-2026 projection (2006) which is corrected for the 2011 census results and extended until 2080 using a slowly declining yearly growth rate at the same rate as assumed in 2001-2026 report. The urban population growth is based on the growth in urban population as a percentage of the total population between the 2001 census and the 2011 census. This percentage of growth in urban population is assumed constant until it reaches 100 percent in a district. The rural population in each district is then calculated as the difference between total projected population minus the urban population.

Although it is relatively simple, this approach gives a realistic projection of both the total population growth and the division between urban and rural populations. Figure 2-4 presents examples for Haryana and Bihar showing that State characteristics are well maintained. To create the model input, the projected data at the district level is used and allocated to nodes. The total population of the Ganga basin is estimated to increase by 45 percent from 485 million in 2011 to 706 million in 2040. The rural population increases by 35 percent from 341 million to 463 million, while the urban population increases by 68 percent from 144 million to 243 million (Figure 2-5).

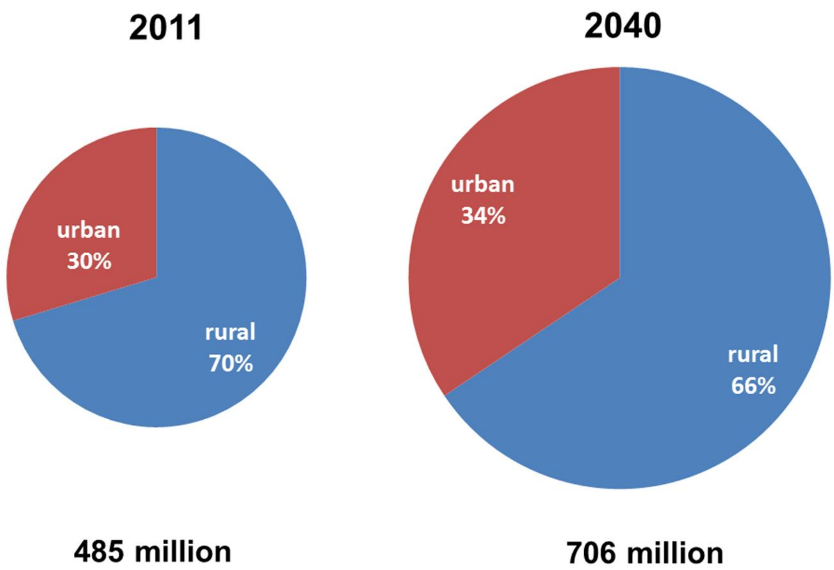

Figure 2-5: Predicted population Indian increase in the Ganga basin between 2011 and 2040.

The projection of irrigation water demand is more complex. It depends on population increase but also on changes in consumer demands and on developments on the world market. NCIWRD (1999), Amarasinghe et.al. (2006 and 2014), Jain (2011), and the 2030 Water Resources Group (2009) are a few of the many researchers that have published an elaborate analysis of the future water demands of India. A complicating factor is that almost all of the predictions also include a prediction of interventions while in this study interventions are separated from the scenarios to better analyze the impact of the implementation of plans. As a consequence in this report the prediction of the 2030 Water Resources Group (2009) is followed. It estimates the annual growth in agricultural water demand at 2.4 percent per year (Figure 2-6). This implies an increase in agricultural water demand of about 80 percent in the year 2040. The same source estimates the industrial water demand will quadruple.

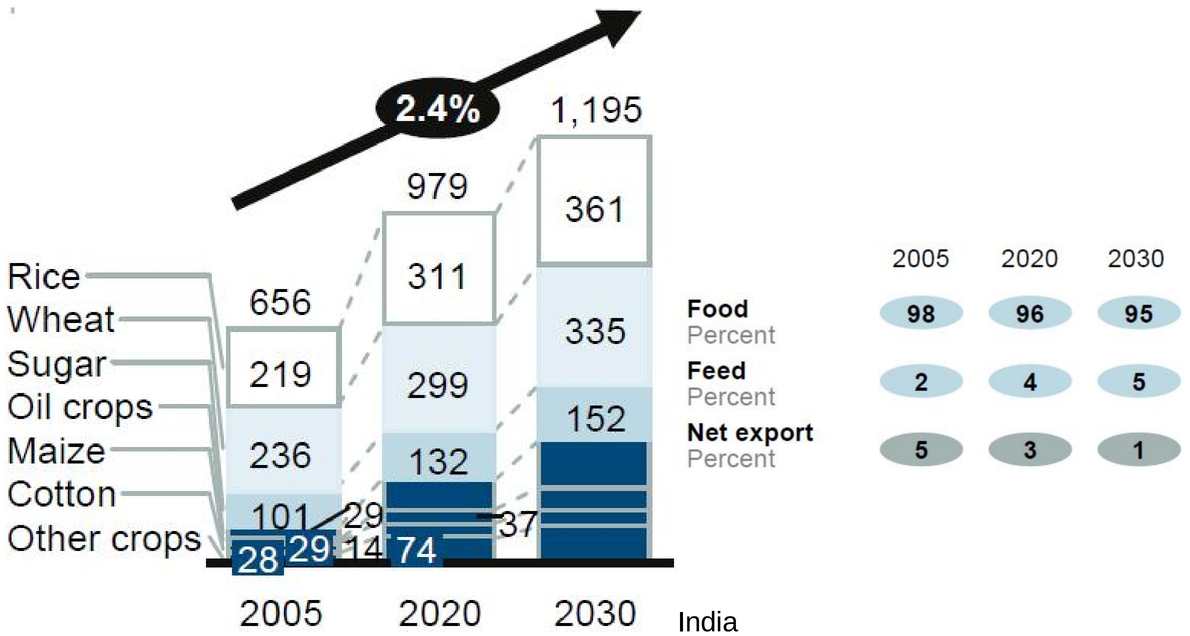

Figure 2-6: Agricultural water demand for India in billion m³ (2030 WRG, 2009).

2.4 2040 RCP4.5 and 2040 RCP8.5

The 2040 RCP4.5 scenario is equal to 2040 but the climate is used from the RCP4.5 assumptions. Table 2-5 presents the settings for this scenario.

Table 2-5: Settings of the '2040 RCP4.5' scenario.

Parameter	Settings in this scenario
Land use	The same as present
Infrastructure	The same as present (can be included in strategy)
Population	Projected growth to 2040
Industry	Projected growth to 2040
Irrigated agriculture	Projected growth to 2040
Temperature	Based on RCP4.5 scenario of greenhouse gas concentration
Precipitation	Based on RCP4.5 scenario of greenhouse gas concentration

Representative Concentration Pathways (RCPs) are four greenhouse gas concentration, not emissions, trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014.

The pathways describe four possible climate futures, all of which are considered possible depending on the amount of greenhouse gases emitted in the future.

The downscaled P, T and ET values were obtained from the Centre for Climate Change Research, IITM Pune. IITM modelled climate data were provided for a historical period and two RCP scenarios: 4.5 and 8.5. This modelled data required bias correction. The shift, also called *delta*, in monthly average data between the modelled historical record and the modelled RCP scenarios was determined for each model pixel (Figure 2-7). Subsequently this *delta* was applied to the measured historical data from IMD to obtain the bias corrected RCP data series. Results show that climate change impacts tend to be higher in the mountains. Figure 2-8 shows the predicted change in annual rainfall, and Figure 2-9 shows some results for the temperatures in Delhi. For the period 1980-2014 the number of days above 35 degrees in Delhi would increase from 5 to 11 in the RCP4.5 scenario or 15 in the RCP8.5 scenario. Similarly, the number of days below 15 degrees would decrease from 38 to 20 or 13 respectively.

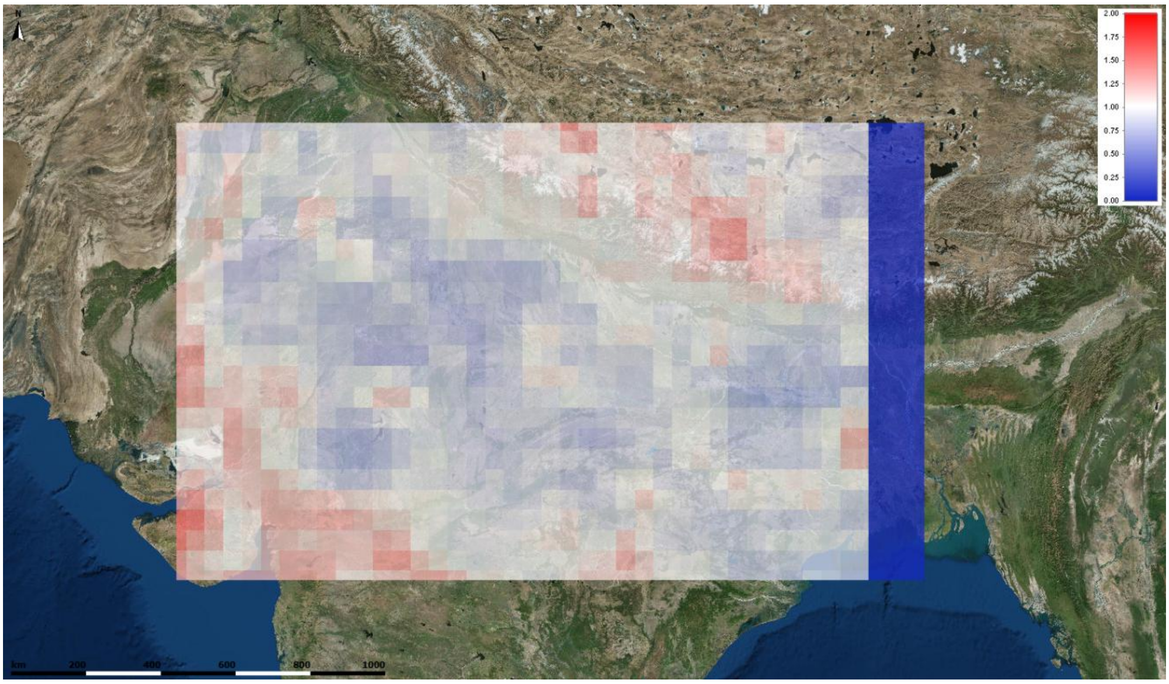

Figure 2-7: Difference, or delta, between historical modelled and RCP4.5 modelled rainfall data for July.

The 2040 RCP8.5 scenario is equal to the case for 2040 with climate change based on the RCP8.5 scenario of carbon concentrations. Table 2-6 presents the settings for this scenario.

Table 2-6: Settings of the '2040 RCP8.5' scenario.

Parameter	Settings in this scenario
Land use	The same as present
Infrastructure	The same as present (can be included in strategy)
Population	Projected growth to 2040
Industry	Projected growth to 2040
Irrigated agriculture	Projected growth to 2040
Temperature	Based on RCP8.5 scenario of greenhouse gas concentration
Precipitation	Based on RCP8.5 scenario of greenhouse gas concentration

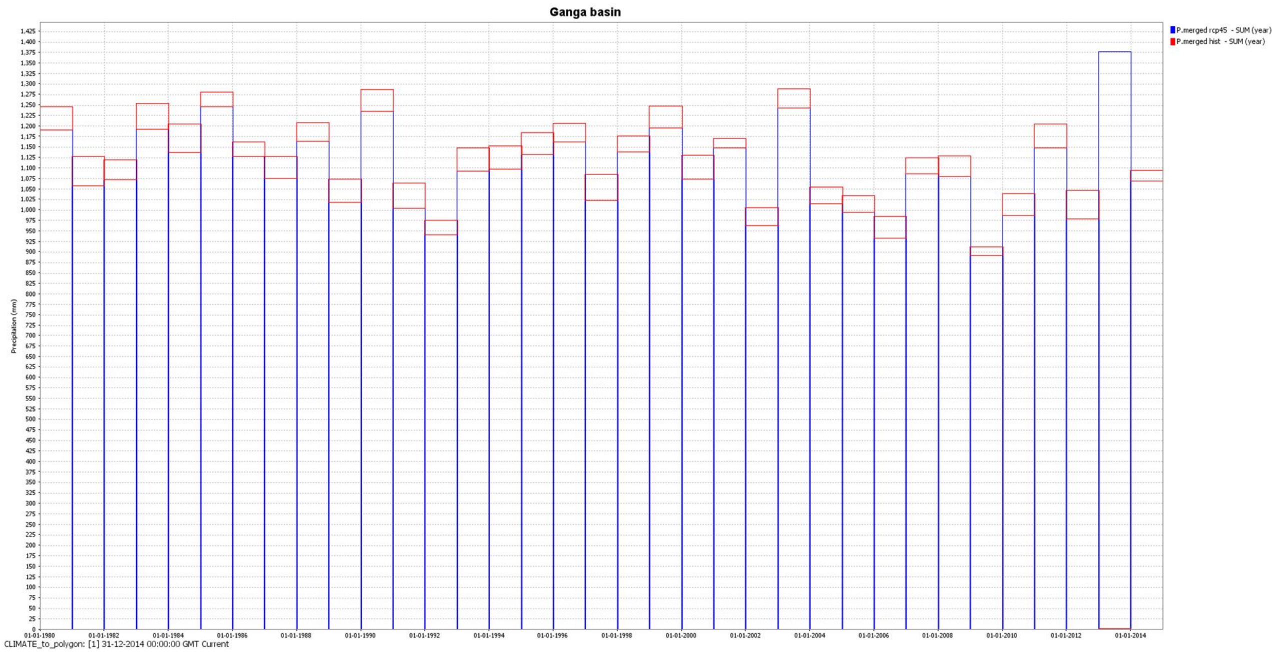

Figure 2-8: Example of impact of climate change. Historical (red) and RCP4.5 scenario (blue) annual rainfall.

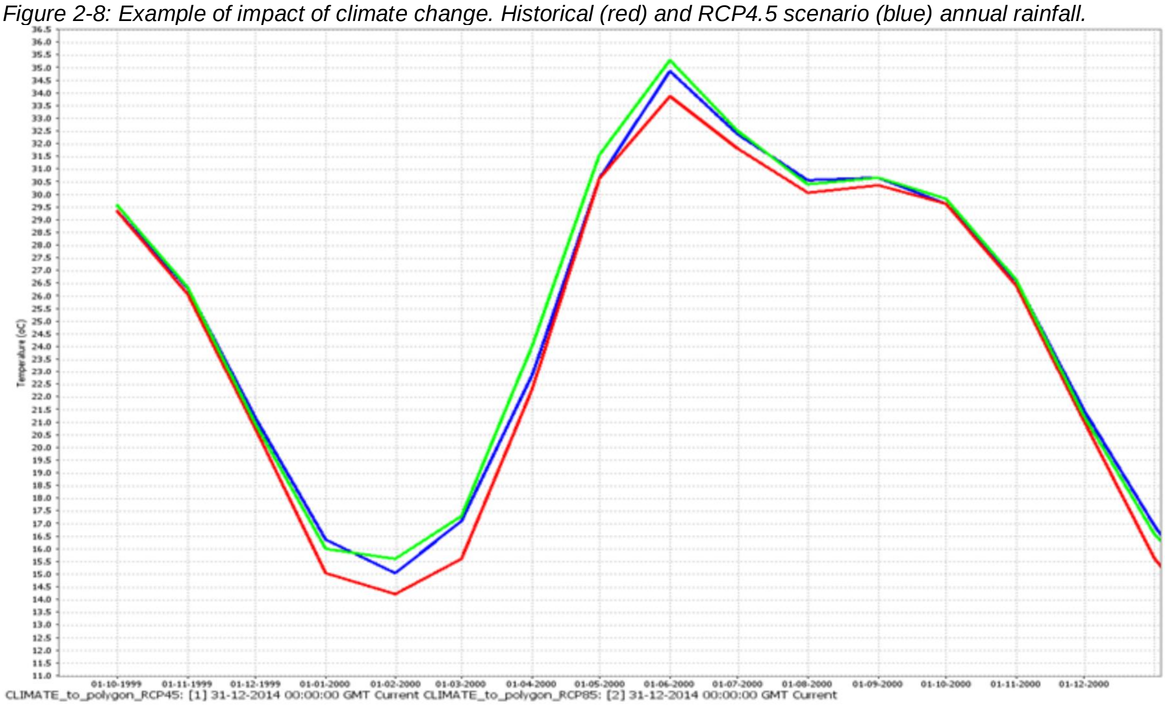

Figure 2-9: Example of temperature difference for Delhi between present scenario (red), RCP4.5 (blue) and RCP8.5 (green).

3 Strategies

Stakeholders, whether in central or state government, private sector, NGO or individuals, all have the option to plan and act in order to achieve their objectives of further development. In principle the number of possible interventions is limitless. The objective of strategy selection in this project is not to recommend the optimal strategy, because what is optimal changes with each stakeholder's perspective. The objective is to show the impact of realistic options and the interactions.

The project organized basin-wide and state workshops to obtain stakeholder input. One workshop in each state focused on identifying the perceptions regarding promising and realistic strategies. The participants were divided into two break-out groups that were each directed by a team of two facilitators, at least one of whom spoke Hindi. The suggested strategy components are summarized in Table 3-1.

Table 3-1: Summary of interventions as part of strategies mentioned in the workshops in the States

	UP	UK	WB	Jharkhand	Rajasthan	HP	Delhi	Chhat.	MP	Bihar	Haryana
Catchment management	■	■	■	■	■	■	■	■	■	■	■
Waste Water treatment, recycling	■	■	■	■	■	■	■	■	■	■	■
Demand management, increase agric efficiency	■	■	■	■	■	■		■	■	■	■
Make new infrastructure	■		■		■	■	■	■	■	■	■
Increase Awareness	■	■		■		■	■	■	■		■
Cropping pattern change, Increase command area	■	■	■	■				■	■		■
Limit GW extraction	■		■	■	■	■	■				■
Financial incentives, Water pricing /metering	■		■		■			■	■		■
E-flow enforced	■		■				■			■	
Artificial recharge of GW	■			■			■	■			
Change in Water distribution rules			■							■	■
Increase flow for navigation			■								

Based on these inputs strategies were developed that can be implemented in the model in combination or alone. Most strategies are also scalable to increase their impacts. They are discussed in the following paragraphs.

3.1 Do Nothing

In any planning assessment one realistic option that has to be considered is the option not to act. This represents the situation where due to lack of planning, lack of political decisiveness, lack of funds, or lack of implementation capacity or any other reason no significant improvements in the water resources is implemented. When the models are run for the future scenarios, with or without climate change, the use of this strategy will illustrate how the water resources availability will be affected in light of the changed demands. All existing infrastructure, diversions, irrigated areas and waste water treatment systems as included in the present calibrated case are assumed to continue to operate as they do at present.

3.2 Approved Infrastructure

Considering the long process required to develop plans, obtain approval and then complete implementation, one of the most realistic strategies for infrastructure development is to implement those infrastructure projects approved prior to early 2018. The list has been prepared by CWC. Apart from one Inter Basin Transfer Link (Ken-Betwa) it concerns some smaller dams and irrigation projects as listed in Table 3-2.

Where the irrigation project includes expansion of irrigation area, the additional demand is considered to be already included in the increased irrigation demand of the scenario to prevent double counting, but the new storage, diversion, or conveyance capacity of the infrastructure is included in the model run.

Table 3-2: List of approved infrastructure projects in the Ganga basin (source: CWC).

S.no	Project Name
1	Kachal reservoir
2	Arjun_shayak reservoir
3	Bhanurat dam
4	Burhai reservoir
5	Pawai_Irrigation reservoir
6	Babina Block project
7	Bateswarsthan Ganga canal
8	North Koel irrigation project
9	Kanhar irrigation project
10	Renukaji dam
11	Koshi-Mechi intrastate link
12	Ken Betwa IBTL

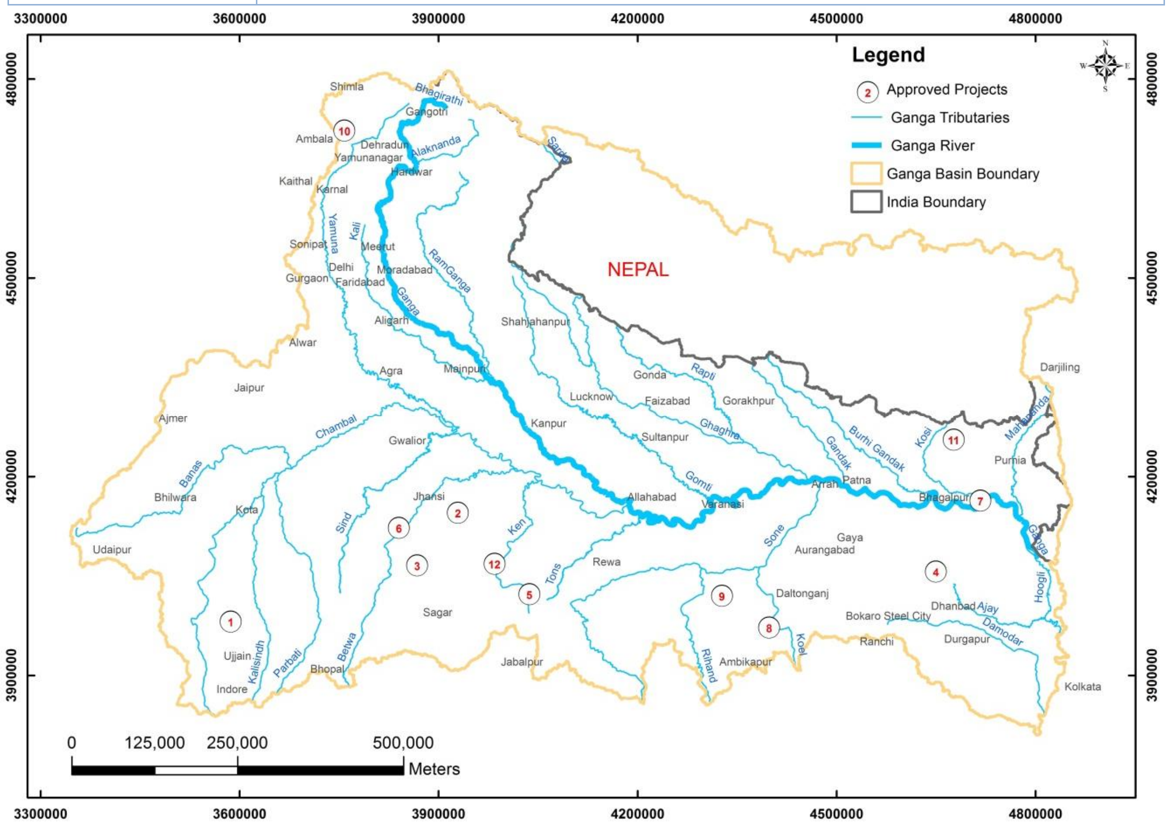

Figure 3-1: Locations of approved new infrastructure. Numbers correspond to number in Table 3-2.

3.3 Inter Basin Transfer Links

Many stakeholders have suggested the Inter Basin Transfer Links (IBTL) that have been discussed for many years are good options to address the water resource issues in the basin. However, a number of other stakeholders oppose these links as they fear implementation will do more harm than good. A strategy where the main Inter Basin Transfer Link projects in the Ganga Basin are implemented is therefore an interesting one to assess using the integrated modelling tool. IBTL generally consist of one or more dams with storage, a diversion, irrigation supply to a number of new and existing irrigation areas and a final connection to another river. Most IBTL under consideration for the Ganga basin upstream of Farakka are sub-basin transfers. Only the Yamuna–Rajasthan links exports water out of the Ganga basin. It is observed that the term IBTL is misleading because only a small part of the diverted water actually enters the other river.

Many IBTL are debated in India, and quite a few affect the Ganga basin (Figure 3-2). For this strategy a selection was made that was considered most appropriate, and for which enough data could be collected or assumed to make a realistic simulation. Note that very little data on reservoir volume or canal capacities is known. The selected IBTL and the affected irrigation nodes are presented in Table 3-3. Unless the water quantity to be transferred to the interlinked river was specified, it was assumed that the priority of water allocation would be to the newly developed irrigation areas along the IBTL. As in the previous strategy the increase in agricultural demand is not added to the increase already included in the scenario but considered a part thereof.

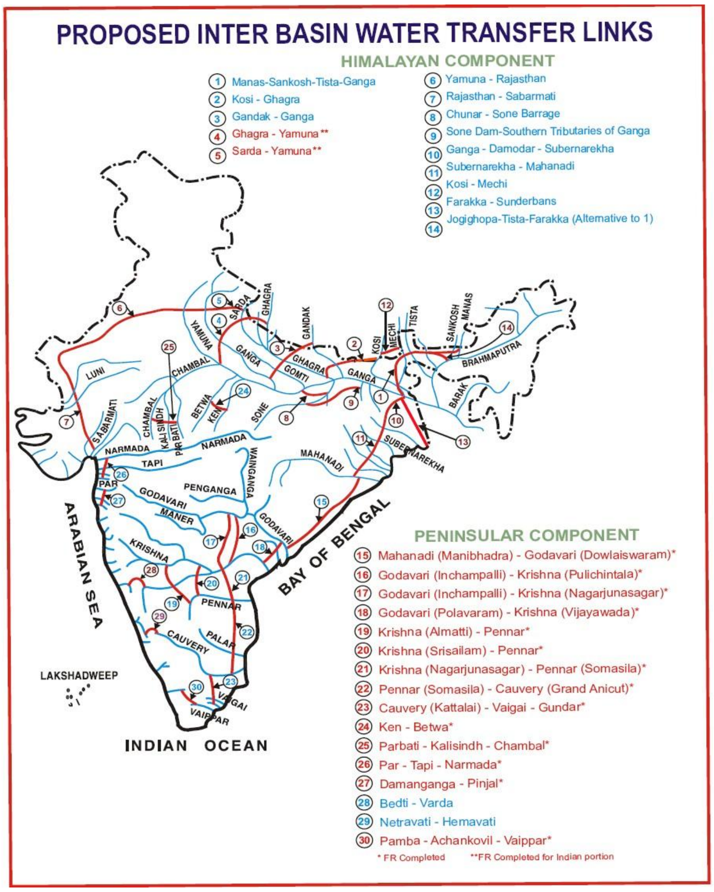

Figure 3-2: Inter Basin Transfer Links under discussion in India (source NIH).

Table 3-3: List of IBTL included in the IBTL strategy.

S.no	IBTL project Name.	Irrigation Polygon No.	Irrigation Polygon Name	% increase in land use
1	IBTL_Kosi_Ghagra	37	Irr_CE_Gandak	12.26
		280	Irr_Budhi_Gandak	24.17
		34	Irr_Kosi	47.07
		127	Irr_Badua_&_Chandan	12.15
		591	Irr_Nepal_three	10.03
		75	Irr_Punpun	4.61
		137	Irrg_Bihar	21.26
2	IBTL_Chunar_Sone	41	Irr_CE_Son	0.50
		21	Irr_CE_Sarda_Sahay	0.48
		73	Irr_Son	1.64
3	IBTL_Gandak_Ganga	577	Irr_Nepal_one	100.05
		37	Irr_CE_Gandak	1.46
		21	Irr_CE_Sarda_Sahay	0.16
		6	Irr_CE_Saryu_Parojn	1.34
		17	Irr_for_CE_Sarda	0.92
4	IBTL_Ghaghra_Yamuna	584	Irr_Nepal_two	228.88
		17	Irr_for_CE_Sarda	4.82
		12	Irr_CE_East_Ganga	13.14
		4	Irr_CE_Ramganga	1.99
5	IBTL_Ken_Betwa	152	Irr_ken	6.39
		46	Irr_CE_Betwa	1.13
6	IBTL_Parv_Kali_Sindh	401	Irr_Chambal_MP	3.46
		184	Irr_Chambal_Rajastan	1.08
7	IBTL_Sarda_Yamuna	592	Irr_Nepal_four	100.00
		97	Irrg_Sarda	5.21
		12	Irr_CE_East_Ganga	20.62
		50	Irr_CE_Ganga	1.38
		17	Irr_for_CE_Sarda	4.46
8	IBTL_Sone_and_southern	75	Irr_Punpun	3.70
		137	Irrg_Bihar	18.68
		210	Irr_Batane	15.30
9	IBLT_Yamuna_Raj	109	Irr_IBLT_Yamuna_Raj	24.34
		53	Irr_Haryana	0.00

3.4 NMCG Planned Treatment

The National Mission Clean Ganga (NMCG) stimulates and funds programs to reduce pollution in the Ganga. The project has requested NMCG to provide a list of waste water treatment facilities expected to be finalized through its program by 2040. This strategy includes the additional treatment as planned by NMCG so that its impact can be evaluated. It is estimated that basin wide this intervention will lead to a 10 percent reduction in generated waste loads. More detail on the treatment facilities is provided in Appendix J.

3.5 Improved Treatment

To evaluate the impact of additional investments in waste water treatment this strategy was designed in which all presently planned WWTP are considered operational, but where also the rural waste water is reduced by additional treatment, using for example septic tanks, and local small scale systems. More details on the additional treatment facilities is provided in Appendix J.

3.6 Increased Irrigation Efficiency with 20 Percent

"The Government of India is committed to accord high priority to water conservation and its management. To this effect Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) has been formulated with the vision of extending the coverage of irrigation 'Har Khet ko pani' and improving water use efficiency 'More crop per drop' in a focused manner with end to end solution on source creation, distribution, management, field application and extension activities." (https://pmksy.gov.in/). In line with this government policy to get more crop per drop, in this strategy all irrigated agricultural nodes in Ribasim are given a higher efficiency: Field application efficiency (%) = 82 and SW conveyance efficiency (%) = 65. As a result the surface water efficiency increases from 40 percent to 48 percent while ground water efficiency increases from 70 percent to 74 percent.

3.7 Conjunctive Use

Groundwater is the main source of water for agriculture in the basin. This has led to over extraction of groundwater in some districts. However, in some other districts there is enough groundwater available. In this strategy the groundwater abstraction capacity is reduced by half for all over-extracted nodes. In the present scenario six nodes are over-extracted and in 2040 six additional nodes (Figure 3-3 and grey in Table 3-4):

Table 3-4: List of irrigation areas where groundwater is over extracted (white cells in present scenario, grey cells additional in 2040 scenario).

Node	Name	Link	New capacity
79	Irr_Haryana	53	150
10	Irr_CE_East_Ganga	12	300
417	Irr_Agra_and_Gu	51	150
4	Irr_CE_Ramganga	13	500
50	Irr_CE_Ganga	67	125
21	Irr_CE_Sarda_Sahay	47	750
184	Chamb.Raj	475	1250
37	Irr_CE_Gandak	46	600
73	Irr_Son	420	100
17	Irr_CE_Sarda	22	450
97	Irr_Sarda	733	25
75	Irr_Punpun	421	100

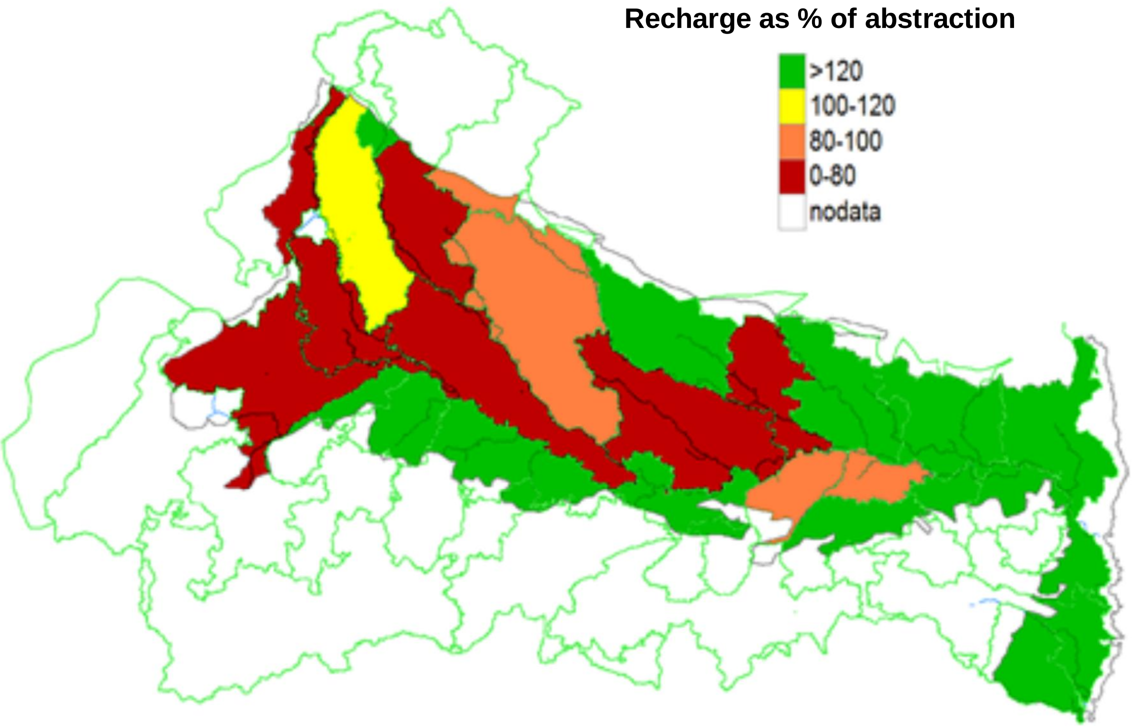

Figure 3-3: Groundwater over extracted area in 2040 scenario. Colors indicate recharge as a % of abstraction.

3.8 E-flow

E-flow: The strategy analyzed here aims to achieve at least a “Moderate” environmental flow status for the hydrological indicator in all zones. Moderate is defined as between 40 and 60 percent deviation from the reference pristine situation. The status is influenced by many factors related to high and low flows in value, duration and timing. This was modelled by setting a target of at least 41 percent of the reference discharges at twenty-eight locations in the Ganga for each month, not only for the lean period. This strategy shows that an average reduction of about 50 percent of the diversions from the river will be needed to achieve flow restoration that will score least moderate in terms of environmental hydrological conditions in all zones.

4 Indicators

Planning models and planning assessment studies are most effective when the information on options or choices is not presented in the technical language of modellers, but as indicators on which decision makers actually use to base their decisions. The stakeholder engagement therefore included collaborative modelling where the project team together with the stakeholders identified the issues to be modelled, the data required and the relevant output indicators. The process, participation and results have been reported in “Initial stakeholder engagement identification and roadmap” (Deltares, 2017). Figure 4-1 illustrates the workshop results where indicators were identified based on a causal loop diagram made by the participants jointly.

Figure 4-1 Causal loop diagram: Yellow boxes are factors (issues, causes and impacts), Orange boxes are suggested indicators, and Pink boxes are possible measures/interventions.

The suggested indicators from each State were collected: a list of eleven indicators was prepared to assess the model results for the scenarios and strategies. These indicators are explained in the following paragraphs.

The term 1/10 dry year in the descriptions of the 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 to a hydrological year, which is defined for India as starting in June and ending in May the following year.

This term is used because generally the problems facing water managers do not occur in average years. Managers must understand how the system performs under stress.

4.1 State of Groundwater Development

Groundwater is the major water source of water for water supply, industry and agriculture, especially in the long period between monsoons. Therefore, the status of groundwater is an important indicator. In the present assessment it is defined as the percentage of the area where the simulated groundwater abstraction amounts to 90 percent or more of the simulated recharge. The basis for this information is obtained from the model irrigation nodes, which cover large areas. As a consequence, this indicator does not give detailed information on smaller units. In the present scenario about 27 percent of the area is classified as critical, while in the 2040 scenario 37 percent is predicted to be critical.

4.2 Lowest Discharge

River discharge is another indicator that was widely suggested. In the assessment the lowest monthly simulated discharge, expressed in cubic meters per second, of the Ganga river and its main tributaries is shown for a 1/10 dry year. When the Ganga basin as a whole is considered the simulated flow above Farakka Barrage is used. For the States the outflow from the selected state is used.

4.3 Volume of Water Stored in Reservoirs

The available storage in reservoirs is also an important indicator to decision makers, because it determines how much water can be released in the dry season. Strategies that develop new infrastructure, but also those that reduce demand are expected to impact the indicator score. In this assessment the total sum of simulated water stored in the main basin reservoirs or the selected state at the end of the monsoon period, October, for a 1/10 dry year is expressed in billion cubic meters. The indicator only considers the reservoirs that are included in the model, which are only the larger basin reservoirs.

4.4 Deficit in Irrigation Water

The deficit in irrigation water is a generally used term by water resource managers. It is defined in this assessment as the difference between simulated irrigation water supply and simulated demand as a percentage of the simulated demand for a 1/10 dry year.

4.5 Agricultural Production

Crop production is not linearly related to the deficit of irrigation water. Apart from the deficit in irrigation water as described in the previous indicator, decision makers need information on crop failure. In the present modelling, if field moisture falls below the root zone soil moisture threshold for drought stress the crop on that field, the harvest is assumed lost. The indicator provides agricultural production expressed in ratio between the actual and potential harvested area at basin/state level. The ratio for 1/10 lowest production is presented.

4.6 Deficit in Drinking Water

Similarly to the deficit in irrigation water, the drinking water deficit is defined as the difference between simulated drinking water supply and simulated demand as a percentage of the simulated demand for a 1/10 dry year.

4.7 Volume of Groundwater Extracted

To obtain the contribution of groundwater to the basin water usage, the water resources managers need information on the total volume of groundwater abstracted. Consequently the assessment indicator is defined as the total simulated volume of groundwater, in billion cubic meters, abstracted for public water supply and irrigation during the 1/10 driest hydrological year, the year with the 1/10 highest abstraction.

4.8 Surface Water Quality Index

The "surface water quality index" is the only 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 4-1). 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.

Table 4-1: 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

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 or Boron are modelled. Therefore, the surface water quality classification in the present assessment is based on simulation results of Total Coliform Bacteria, Dissolved Oxygen and Biochemical Oxygen Demand only. Interpretation of the indicator shown in Table 4-2 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 also be evaluated. This is considered a limitation which cannot easily be solved as ammonia is not modelled, because it is 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.

Table 4-2: 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					

When one indicator is used for State or basin-wide assessment the lowest observed value is used. Additionally, 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.

4.9 Environmental Flow

To assess the impact of alterations in discharge and water quality on the Ganga ecosystem and services, three main environmental flow indicators are calculated within the Ganga river basin model: hydrological alteration, species habitat suitability and ecosystem service availability. 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. More details can be found in the Ganga River Basin Model report (van de Vat, 2108). 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’.

Figure 4-2 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.

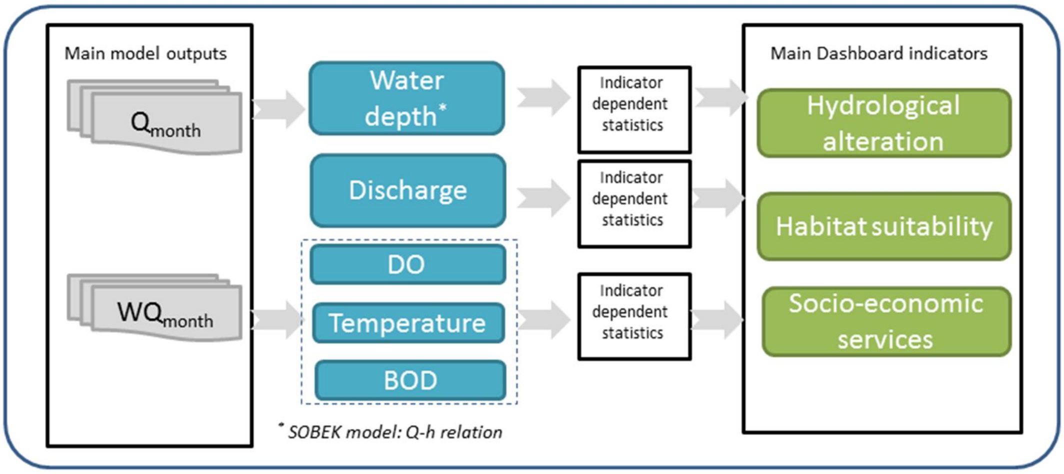

Figure 4-2: Flow diagram for the calculation of indicators for the environmental flow analysis.

All indicators are computed as deviations from a reference situation, which is the situation without human influence or 'pristine' situation. 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 4-3).

Table 4-3: 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

Three types of indicators are considered:

- Indicators describing alteration in ecologically-relevant flow characteristics;
- Indicators showing the habitat suitability for key species;
- Indicators showing the extent of the ecosystem services offered to society.

In this assessment the resulting scores are used. On the model dashboard results are also presented in a river chart and a map.

4.10 Scorecard

The indicator scores used in this assessment are derived from the model dashboard that presents a scorecard with a list of indicators with performance values for two selected run cases and scale level, basin or state (Figure 4-3).

Indicator	Present	2040	Weights
State of Groundwater development (% critical areas)	41 (5)	89 (1)	100
Lowest discharge (m3/s)	2683 (9)	2170 (9)	100
Volume of water stored in reservoirs (Billion m3)	56 (5)	54 (5)	100
Agricultural crop production (% of area harvested)	96 (9)	88 (8)	100
Deficit irrigation water (%)	23 (7)	31 (6)	100
Deficit drinking water (%)	10 (8)	34 (6)	100
Surface water quality index (-)	4 (2)	4 (2)	100
Volume of groundwater extracted (Billion m3)	99 (3)	216 (0)	100
E-flow: Ecological status (-)	74 (7)	73 (7)	100
E-flow: Hydrological status (-)	62 (6)	60 (5)	100
E-flow: Socio-Economic status (-)	74 (7)	72 (7)	100
Total	68	56	100

Figure 4-3: Example of scorecard panel on model dashboard comparing runs for present and 2040 scenarios. Number between brackets is contribution to total score.

When analyzing the indicator results it is good to realize that model settings will influence how the indicators respond. For example, in the present settings the model will over-extract groundwater rather than generate a deficit in water supply in case demand is higher than available sustainable supply. In practice this is the way the current system functions. Responding by limiting groundwater extraction, as often suggested in workshops, will only lead to a corresponding increase in the deficit indicator and the problem is shifted from groundwater to the demanding sector.

5 Assessment

In this assessment the different scenarios are compared to analyze the impact of autonomous developments and climate change. This will give an impression of the challenge that needs to be addressed with the strategies. The effects of individual strategies are assessed to determine what certain interventions can achieve. Strategies are combined to illustrate the impact of an integrated combination of interventions in different domains. The final step in the assessment is an analysis of the results.

5.1 Results for Scenarios

Table 5-1: Overview of basin wide indicator scores for 5 scenarios

Indicator	Code	Pristine	Present	2040	2040-RCP45	2040-RCP85
State of Groundwater development (% critical areas)	GW overext.	0	41	89	88	88
Lowest discharge (m3/s)	Low Q	2312	2683	2170	1502	617
Volume of water stored in reservoirs (Billion m3)	Res.Store	0	56	54	52	52
Agricultural crop production (% of area harvested)	Agr.Harv.	0	96	88	87	87
Deficit irrigation water (%)	IRR deficit	0	23	31	31	32
Deficit drinking water (%)	DR deficit	0	10	34	34	35
Surface water quality index (-)	WQ index	1	4	4	4	5
Volume of groundwater extracted (Billion m3)	GW used	0	99	216	217	218
E-flow: Ecological status (-)	E-ecol	100	74	73	65	60
E-flow: Hydrological status (-)	E-hydr	100	62	60	47	38
E-flow: Socio-Economic status (-)	E-socio	100	74	72	66	64

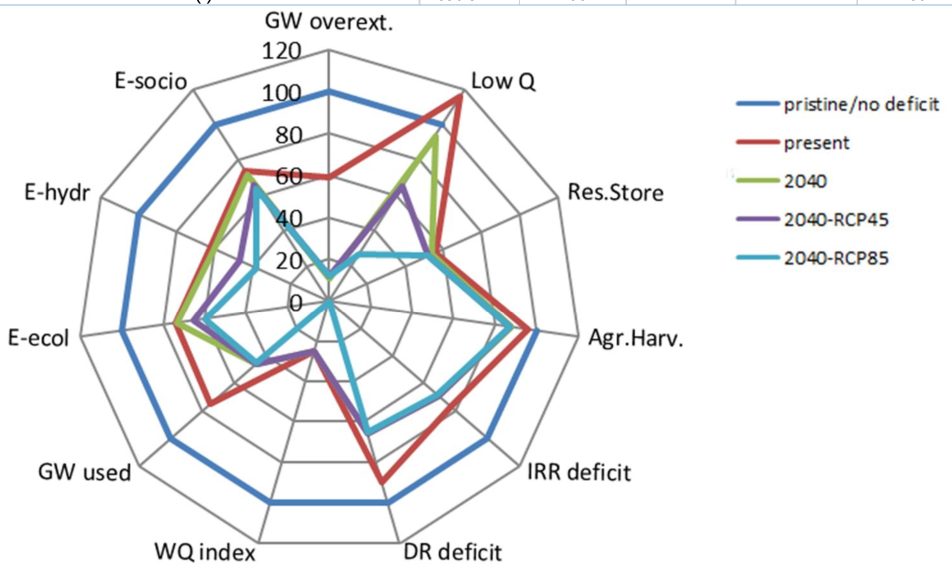

Figure 5-1: Pie chart of basin-wide indicators for the 5 scenarios. All values scaled relative to pristine or no deficit situation given as 100.

The scenarios described earlier impact the water resources situation in the basin, especially when no additional interventions are implemented. Table 5-1 and Figure 5-1 show the basin-wide scores for the selected indicators for the considered scenarios.

The impacts are most visible in the hydrological indicators: the percentage of areas with critical groundwater use increases significantly, and the lowest flow in the river at Farakka, which is higher than pristine at present due to irrigation return flows will diminish significantly in dry years. The quality and e-flow indicators differ significantly between pristine and the other scenarios, but differences are smaller between the other scenarios. The main reason is that the indicators focus on the worst situation and do not provide information on how widespread the bad conditions are. A second reason is that both water quality and environmental flow indicators are scaled relative to the 'good or pristine' situation.

The first conclusion that can be drawn from the results is that the socio-economic developments that drive the progressively increasing demands are the main factor influencing the status of the basin. It is difficult to differentiate between population growth and economic developments as the population growth figures for urban and rural areas reflect both economic aspects driving urbanization as well as birth rates. Climate change is expected to have an impact, but its impact is smaller compared to the impact of increasing agricultural, industrial and domestic demands. Because climate change only influences the availability of water to some extent, the slightly reduced rainfall is somewhat compensated by increased snow and glacier melt. An important consequence of this is that the discussion on whether climate change is occurring in the Ganga basin should not hamper decision making for water resources planning. The socio-economic developments are enough reason to act.

In case no interventions are made by 2040, with or without climate change, the amount of crop failures in dry years is expected to increase threefold and drinking water deficits will occur in one third of the domestic centers. The volume of extracted groundwater is expected to more than double leading to an increase in the critical blocks. Low flow values in the rivers are predicted to decline compared to present levels. Water quality and environmental flow conditions already critical will deteriorate further.

Table 5-2: Increase in percentage irrigation and drinking water deficit per State between present and 2040_RCP4.5 scenarios.

Increase between Present and 2040_RCP4.5	HP	UK	UP	Har	Del	Raj	MP	Chh	Bih	Jha	WB
Deficit irrigation water (%)	10	28	10	5	NA	0	7	0	15	0	4
Deficit drinking water (%)	2	10	25	0	22	20	39	8	22	13	11

The impacts are not equally distributed in the basin as illustrated by Table 5-2 which shows the increase in percentage irrigation and drinking water deficit per State between present and 2040_RCP4.5 scenarios. Factors that determine the differences are: rate of urbanization, as urban areas demand more water per capita compared to rural areas; upstream demands; division between groundwater and surface water as source, volume of state demands, and whether the State already experiences stress in the present scenario.

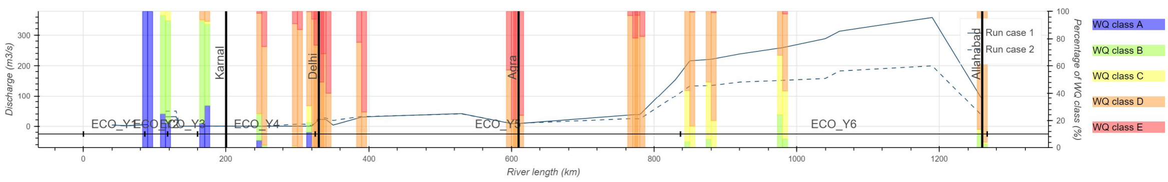

Figure 5-2: Water quality index distribution along Yamuna for present (left bar) and 2040_RCP4.5 (right bar) scenarios.

The water quality index results are quite diverse from location to location. Figure 5-2 shows the longitudal profile along the Yamuna where each bar indicates what percentage of the time the location had water quality index value A, thru E. At the highest locations, where not much pollution has reached the river the status is A most of the time. However, as pollution loads increase the status deteriorates to mainly D or even E.

Further downstream contributions from tributaries and decay of pollutants lead to improved status. The 2040 situation, depicted by the right side of each bar in the figure, mostly shows a worse situation due to both higher loads and higher abstractions that reduce dilution.

Also, the ecology indicator shows a diverse response geographically as visualized in Figure 5-3. The zones below the main barrages experience little change as they are already very much affected. The main differences are visible in the southern and eastern zones.

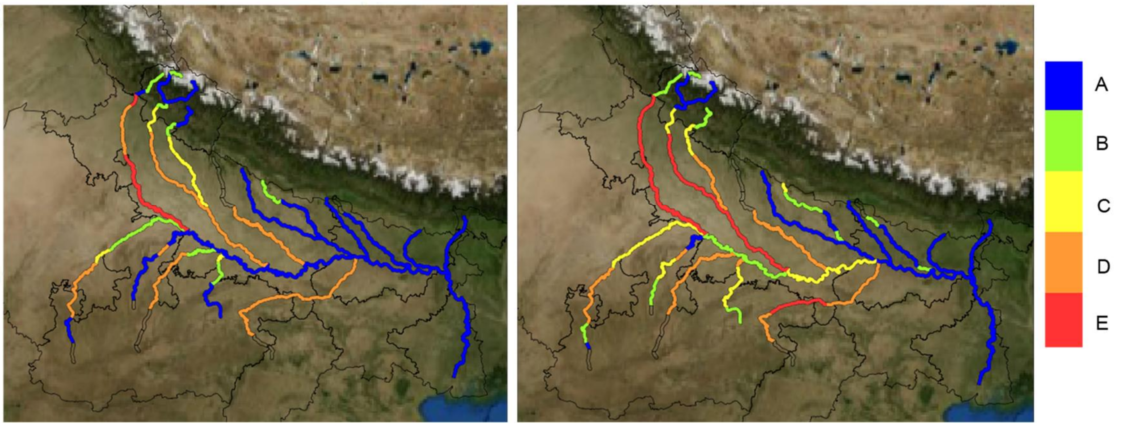

Figure 5-3: Geographical distribution of change in ecological indicator from present (left) scenario to 2040_RPP4.5 (right) scenario (scores are defined in Table 8-1).

5.2 Impact of Strategies

Considering the serious issues expected by 2040, it interesting to evaluate whether the strategies discussed with the stakeholders will achieve the desired improvement. Table 5-3 and Figure 5-4 present the indicator scores for the individual strategies when applied in the 2040_RCP4.5 scenario.

The strategy that includes the approved projects will have a beneficial effect on agricultural crop failures, achieving a two percent reduction. Groundwater usage will decrease slightly accompanied by an increase in reservoir volumes at the end of the monsoon season. The result is a slight decrease in low flow volumes and a slight worsening of the hydrological e-flow score.

When the approved infrastructure and the identified IBTL are assumed to be operational, agricultural crop production is increased significantly. However, most resources that are made available in the IBTL are consumed in the additional irrigated areas along the canals, and little water is actually transferred to the destination river. As such IBTL projects do not provide much relief to shortages in the destination (sub)basins. Because reservoir water is used actively in IBTL projects, the remaining storage does not increase and low flow in rivers and e-flow parameters are reduced in the source (sub)basin, reducing the resources downstream.

The strategy that limits groundwater use in over-extracted areas, will have dramatic impact on crop failures as irrigation deficits increase significantly. Drinking water will suffer less. The volume of extracted groundwater is reduced significantly, the over-extracted area is reduced by 9 percent.

The strategy that increases the irrigation efficiency does not affect the over-extracted groundwater areas but reduces the crop failures without negative effects on environmental flows. Of all evaluated individual strategies it has the least impact on low flows. However, it must be noted that it can be expected that farmers will increase their cropped areas in tune with the increased efficiency resulting in higher production, but not less abstractions from surface or groundwater. In case of reduced demand from surface water care should be taken that the reduced drainage will not lead to over-extraction, even when groundwater abstractions themselves have not increased.

Table 5-3: Overview of basin wide indicator scores for the strategies applied in 2040_RCP4.5 scenario.

2040 RCP4.5 cases Indicator	Code	do nothing	Appr.Infra	GW use	IBTL+Apr.Infra	Efficiency	planned treatm.	improved treatm.	e-flow
State of Groundwater development (% critical areas)	GW overext.	88	88	79	83	88	88	88	95
Lowest discharge (m3/s)	Low Q	1502	1458	1622	1258	1483	1502	1502	1528
Volume of water stored in reservoirs (Billion m3)	Res.Store	52	55	53	41	53	52	52	20
Agricultural crop production (% of area harvested)	Agr.Harv.	87	89	74	92	89	87	87	84
Deficit irrigation water (%)	IRR deficit	31	31	47	30	29	31	31	39
Deficit drinking water (%)	DR deficit	34	34	35	35	34	34	34	39
Surface water quality index (-)	WQ index	4	4	4	4	5	4	4	5
Volume of groundwater extracted (Billion m3)	GW used	217	215	176	206	207	217	217	235
E-flow: Ecological status (-)	E-ecol	65	65	66	63	66	65	66	73
E-flow: Hydrological status (-)	E-hydr	47	46	49	44	47	47	47	56
E-flow: Socio-Economic status (-)	E-socio	66	66	67	68	66	67	69	75

Figure 5-4: Charts showing the percentage improvement (positive) or deterioration (negative) in basin-wide indicator scores for evaluated strategies. All scores are relative to the do-nothing strategy.

The strategies with planned treatment and improved treatment do impact basin water quality, but as the indicator is determined by the lowest value, this is not visible in the water quality indicator scores at the basin level. However, the ecological status and socio-economic status environmental flow indicators that include fish increase, primarily because of improved oxygen levels in the rivers.

The environmental flow strategy that reduces abstractions scores significantly better on the hydrological and socio-economic environmental flow indicator as it revives some of the river dynamics. However, as water will be less available for irrigation and other purposes, the groundwater extraction will increase, resulting in more over-extracted areas and a significantly higher deficit in irrigation and drinking water. The forced releases deplete most reservoirs.

5.3 Combination of Strategies

When a number of the suggested strategies are combined it is expected that this powerful approach will achieve significant benefits. For this assessment the interventions on approved infrastructure, IBTL, 20 percent efficiency increase in agriculture, reduced groundwater use in over-extracted areas and improved waste water treatment are combined in one run. Table 5-4 and Figure 5-5 show the results in terms of basin wide indicator scores.

Table 5-4: Overview of impact of combined strategy.

Indicator	Code	present	2040-RCP45 do-nothing	2040-RCP45 combination
State of Groundwater development (% critical areas)	GW overext.	41	88	79
Lowest discharge (m3/s)	Low Q	2683	1502	1422
Volume of water stored in reservoirs (Billion m3)	Res.Store	56	52	43
Agricultural crop production (% of area harvested)	Agr.Harv.	96	87	85
Deficit irrigation water (%)	IRR deficit	23	31	42
Deficit drinking water (%)	DR deficit	10	34	35
Surface water quality index (-)	WQ index	4	4	4
Volume of groundwater extracted (Billion m3)	GW used	99	217	163
E-flow: Ecological status (-)	E-ecol	69	63	66
E-flow: Hydrological status (-)	E-hydr	52	43	46
E-flow: Socio-Economic status (-)	E-socio	69	64	73

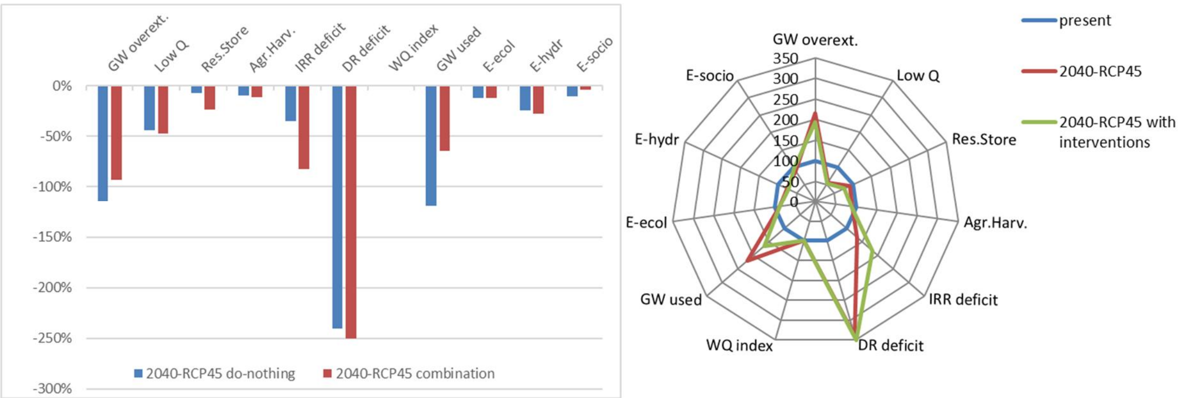

Figure 5-5: Charts comparing 2040_RCP4.5 and 2040_RCP with a combination of strategies relative to the present. Bars show the percentage deterioration (negative) in basin-wide indicator scores for evaluated scenario/strategy.

The main conclusion from the results is that the combination of interventions does improve the situation compared to the 2040_RCP4.5 scenario somewhat, primarily because it will produce more agricultural output with almost the same indicator values. However, the strategy is nowhere near sufficient to achieve the present conditions. In other words, the conditions in the basin will significantly deteriorate between now and 2040 even if all these interventions are implemented. Results would be better in terms of irrigation and drinking water deficits when groundwater abstractions are not limited in over-extracted areas. However, that would be a very unsustainable solution as groundwater would be seriously depleted leading to the same shortages at a later stage. More fundamental changes are necessary to improve the situation, and these go beyond technical solutions.

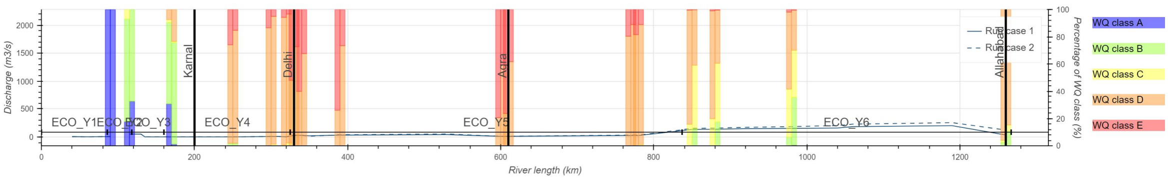

Figure 5-6: Water quality index distribution along Yamuna for 2040_RCP4.5 do-nothing (left bar) and with a combination of interventions (right bar) scenarios.

5.4 Discussion

The scenario assessment indicates a significant decrease in future water availability, water quality and ecological status if no additional interventions are made. Future changes are mainly determined by socio-economic factors, much less by climate change.

There is not one ‘silver bullet’ intervention that solves all problems. Combinations of different interventions are required. However, the set of currently considered far reaching interventions, that would already require huge investments, and would face significant technical challenges and opposition from stakeholders, is not enough to deal with future challenges regarding water availability, water quality and ecology.

The intervention that will result in the most beneficial impact is improvement of municipal waste water treatment. Whether central or decentral, whether high or low tech, reduction in pollution loads provides a positive return on investment both in availability of clean water for downstream uses, including ecosystem services, as well as a drastic reduction in water related illnesses and deaths. Note that the river-oriented indicators selected for this study do not reflect the beneficial health impacts achieved in towns as a result of proper sewerage and waste water treatment.

The next ‘no-regret’ intervention is increasing the efficiency of all water uses: irrigation, domestic and industrial water use.

All stakeholders must realize there simply will not be enough water to meet all the rising demands and there are no ‘easy’ technical solutions. Ambitious strategies need to be implemented that reduce demands in all sectors; at the same time trade-offs need to be made between different sectors. The agricultural sector will have to adapt to lower water availability in terms of crop choice, planting season and water efficiency. Farmers will need to develop a flexible approach; depending on the monsoon they may have to select irrigated or non-irrigated crops even when irrigated crops are already of high efficiency.

Every October, after the monsoon, the state and basin authorities could determine the water availability status in different regions and manage water demand and infrastructure differently for wet and dry years. Domestic and industrial demands for the year could be ‘reserved’ in reservoirs so that domestic and industrial supply can always be met in the downstream regions, allocating only the non-reserved volume to agriculture.

The consequences of these conclusions are far reaching and involve departments and ministries outside the traditional water resources realm. Non-technical interventions such as incentives to change cropping patterns and practices to reduce water demand are needed.

Even more fundamental, is probably the need to initiate a ‘more job per drop’ economy instead of focusing on crops. Service and industrial sectors consume much less water per employment and economic benefit generated. Urban centers need to be prepared for migration of rural people to service and industrial jobs in well planned cities with water supply and waste management, housing and transport smartly designed for all income levels. This will create room for a higher income per capita in the remaining rural community and allow for professionalization of the rural production by facilitating optimal technological means and capacity to invest. This will be required to maintain high agricultural production to meet demand while optimizing water consumption.

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Part B: Environmental Flow Assessment

7 Introduction

7.1 The Importance of Natural Flow Dynamics for River Ecosystems

A river's ecological functioning is largely governed by the dynamics in river discharge (Bunn and Arthington, 2002; Poff et al., 2006). Both low and high flow events perform important ecosystem functions. Normal base flows maintain suitable habitat for aquatic species while low base flows during droughts eliminate invasive species and concentrate prey to benefit predators. High pulse flows shape the physical characteristics of the river channel and connect the main channel with its floodplains. This allows sediment settlement in floodplains and creates a zonation in floodplain vegetation (Gran and Paola, 2001; Hupp and Osterkamp, 1996). Moreover, large floods provide migration and spawning cues and, like the low flows during drought, purge invasive species (Figure 7-1). This shows that all flow characteristics contribute to various important ecosystem processes and functions (Table 7-1). The awareness of the link between the river flow regime and its ecosystem functioning led to the concept of 'environmental flows' or 'e-flows'. E-flows are commonly defined as "The quantity, timing, and quality of freshwater flows and levels necessary to sustain aquatic ecosystems which, in turn, support human cultures, economies, sustainable livelihoods, and well-being." (Arthington et al., 2018).

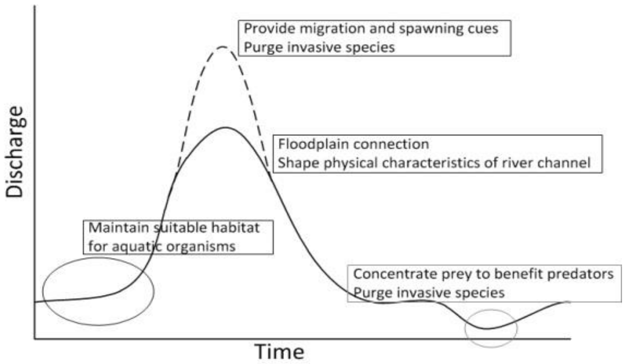

Figure 7-1: Schematic representation of the function of different flows. After Bunn and Arthington, 2002.

Box 1: intertwined ecological and socio-economic values in the Ganga basin

In the Ganga river basin, ecological and socio-economic values are closely intertwined. For example, fish production is important to sustain the poorest people in the basin. People upstream of the Farakka Barrage used to catch Indian shad (*Tenualosa ilisha*), but had to switch to other, smaller sized fish, as the Indian shad population has been dwindling due to the barrage (Sinha, 2014). Downstream of Farakka barrage, fisheries benefited from increased Indian shad presence (ICAR, 2015). Thus, the Farakka barrage deprived people upstream from an ecosystem service still available.

7.2 The Importance of River Ecosystems for Ecosystem Services

Besides ecological values, a river ecosystem provides goods and services like fish production, hydropower, irrigation and recreation; these ecosystem services depend on the flow regime and occasionally alter the flow regime (Box 1). Therefore, ecological and socio-economic values are closely intertwined and different stakes have to be weighed. A useful tool to asses these trade-offs is the ecosystem services approach.

It creates a focus to integrate economics and ecology connecting both to human welfare (Kozak et al., 2015) by exporting the benefits of the natural ecosystem to the human economic sector (Fisher et al., 2009). Ecosystem services are the result of the overall ecological functioning of a river. For example, to be able to profit from a river's potential fish production, the river must be capable of providing for good spawning areas and for survival of juveniles to actually realize the 'fish production' ecosystem service. Generally, four service categories are distinguished (Millennium Ecosystem Assessment, 2005):

1. Supporting services: primary production, soil formation, maintaining the balance in aquatic and riparian communities;
2. Regulating services: regulating local climate, diseases, water quality, river bank stabilization and soil moisture levels;
3. Provisioning services: providing for fish, medical plants and drinking water;
4. Cultural services: aesthetics, spiritual, recreational and educational facilities.

Table 7-1: Relations between river flow characteristics and ecological functions (Postel and Richter, 2003)

Flow type	Ecological functions
Low (base) flows - normal level -	- Provide habitat for aquatic organisms by maintaining suitable water temperatures and water chemistry - Keep fish and amphibian eggs suspended - Enable fish to move to feeding and spawning areas - Support hyporheic organisms living in saturated sediments - Provide drinking water for terrestrial animals - Maintain water tables levels in the floodplain and soil moisture for plants
Low (base) flows - drought -	- Purge invasive introduced species from aquatic and riparian communities - Concentrate prey into limited areas to benefit predators - Enable recruitment of certain floodplain plants
High pulse flows	- Shape physical character of river channel, including pools and riffles and determine size of stream bed substrates (sand, gravel and cobble) - Restore normal water quality conditions after prolonged low flows by flushing away waste products and pollutants - Aerate eggs in spawning gravels and prevent siltation - Maintain suitable salinity conditions in estuaries - Prevent encroachment of the channel by riparian vegetation
Large floods	- Drive lateral movement of river channel, forming new habitats, such as in secondary channels and oxbow lakes - Deposit gravel and cobbles in spawning areas - Provide migration and spawning cues for fish - Enable fish to spawn on floodplain and provide nursery area for juvenile fish - Provide new feeding opportunities for fish and waterfowl - Trigger new phase in life cycle - Deposit nutrients on floodplain - Recharge floodplain water table - Purge invasive introduced species from aquatic riparian communities - Maintain diversity in floodplain forest types through prolonged inundation - Distribute seeds and fruits of riparian plants - Provide plant seedlings with prolonged access to soil moisture - Flush organic materials and woody debris into channel to serve either as food or habitat structures

7.3 E-flow Misconceptions

A common misconception of an e-flow assessment is that the method will provide a minimum flow calculated as a fixed percentage of the river discharge.

An e-flow assessment is river-specific and requires a balancing of interests of various different stakeholders. Almost any change in flow regime will alter the ecosystem to some extent, and it is therefore not possible to decide on a fixed minimum flow regime that keeps the ecosystem 'healthy'. A discussion between scientists and stakeholders is required to decide the amount of ecosystem change that is acceptable. It requires a balancing of different societal interests: changes in the flow regime will lead to changes in the ecosystem and the ecosystem services provided for society. However, these changes are also meant to benefit society e.g., by providing electricity through hydropower or water for irrigation. The benefits of abstractions and river regulations need to be balanced against the loss of ecosystem services. For certain rivers or river stretches the benefits of regulation may be preferred over the benefits of ecosystem services; in other river stretches the ecosystem services may outweigh the benefits of regulation. Ultimately, an e-flow is a *societal choice* and the result of a negotiated weighting of ecological and socio-economic benefits. Thus, the purpose of an e-flow assessment is to inform the societal process on the status of the ecosystem condition and related services for different possible flow regimes and to ensure a transparent and evidence-based comparison and trade-off. This is conveyed very clearly in the ‘ELOHA’ framework (**E**cological **L**imitations **O**f **H**ydrological **A**lteration; Poff et al., 2010), which suggests two separate processes: a scientific process in which the relationships between river flow variations and the condition of the ecosystem and availability of services is assessed and a societal process in which stakeholders jointly set objectives and agree on the desired flow regime.

Box 2: E-flow methods

Hydrological methods estimate flow requirements in terms of discharge-based statistics, which are generally derived from historical flow records. Among the most used methods are the *Tennant method* (Tennant, 1976) which proposes a fixed percentage of flow and the *Indicators of Hydrological Alterations* (Richter et al., 1996), which shows deviations in ecologically-relevant flow statistics.

Hydraulic methods focus on *changes* in various hydraulic river variables. A common method is the *Wetted Perimeter Method* (Reiser et al., 1989) in which flow changes on a fixed location are used to describe relationships between the river flow regime and some ecological components.

Habitat methods asses E-flows based on biotic responses to flow characteristics. Those methods quantify the effects of changes in the flow regime on species or groups of species. Those species may either be economically profitable, such as fish, or indicators of water quality and/or of spatial connection of different riverine attributes, such as floodplains or lakes. Examples of methods are the *Instream Flow Incremental Methodology* (e.g. Mosley 1983) and the *River System Simulator* (Alfredsen, 1998).

Holistic methods are a combination of the above methods and are nowadays the common approach. In these methods, the flow regime is coupled to ecological functioning and the interests of stakeholders. Only within these kinds of settings, i.e. frameworks with a sound eco-hydrological foundation, river flow regimes can be restored properly (Stewardson and Gippel, 2003; Richter, 2010; Poff et al., 2010). Examples of those methods are the *Building Block Method* (King et al., 2008), *the Drift method* (Brown et al., 2000) and the *ELOHA approach* (Poff et al., 2010).

7.4 Assessing Ecosystem Responses to Flow Regime Changes

Over the last decades, many methods have been developed to assess e-flows, overviews of these methods are provided by amongst others Tharme (2003), Acreman and Dunbar (2004) and Magdaleno (2009). Box 2 gives a brief overview of different e-Flow methods: Hydrological, Hydraulic, Habitat focused, and Holistic. In general, an e-flow assessment requires the following steps:

- Analyzing long term changes in the flow regime to provide understanding of the pristine situation and how human actions and climate change led to the present situation. Hence, this analysis reveals the alteration of the flow regime;
- Identifying both the physical and chemical aspects and ecological processes required for specific ecosystem services to gain insight into the interaction between various components of the e-flows and ecosystem services;

- Recommending alternative water management strategies based on the identified e-flows, as input for the negotiation process.

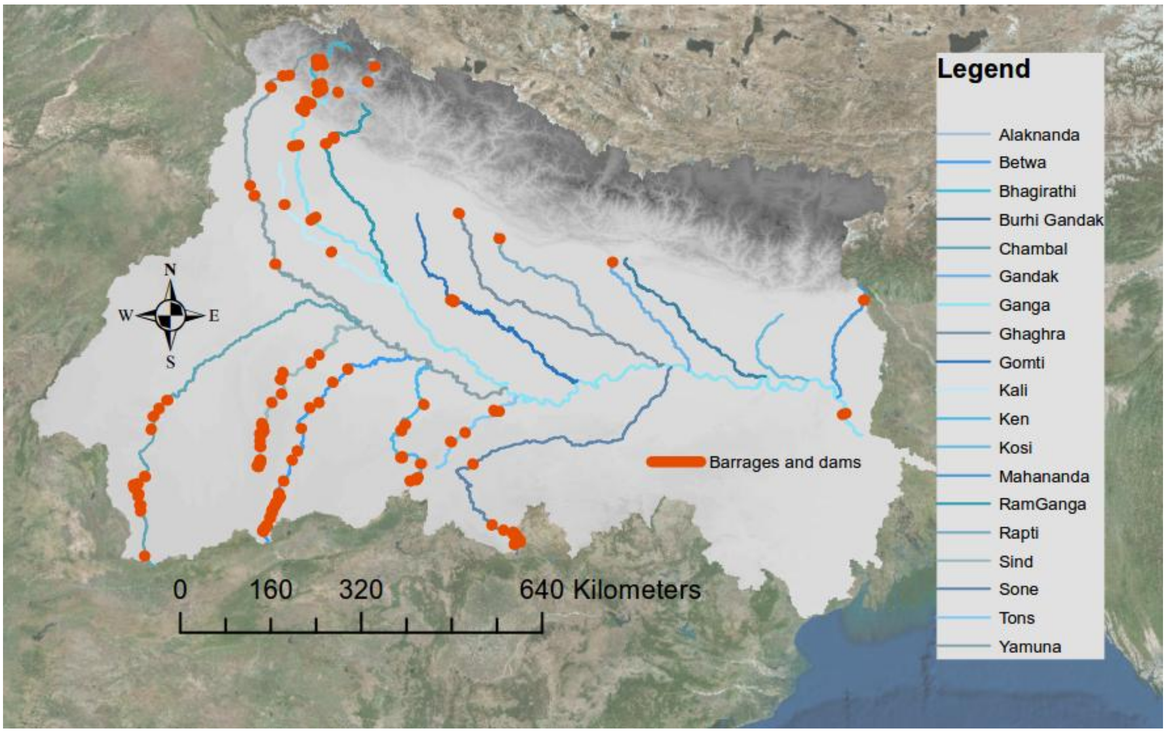

Figure 7-2: Overview of (larger) dams and barrages in the Ganga River Basin.

Figure 7-3: Left: Gharial (photo courtesy Steve Bassett on Flickr), right: bathing in the Ganga River near Varanasi (photo courtesy Julian Huang on Flickr)

7.5 The Ganga River Basin

The flow regime within the Ganga river basin is characterized by significant inter-annual and intra-annual variability. By abstracting water and building dams and barrages, humans have impacted the natural flow regime. Water is abstracted mostly for agricultural use, but recently the share of water abstracted for industrial and urban use has increased (World Bank, 2014). Dams and barrages were built as water reservoirs to redistribute water and for hydropower generation (Figure 7-2). These structures affect the magnitude, timing and frequency of flows (Bharati et al., 2010). The changes in flow regime impede ecological functioning of the Ganga river basin; as a result, the basin's ecological health has deteriorated significantly. In addition, a decrease in water quality, originating from inputs of toxins from industries and nutrients from agriculture, contributes to ecosystem decline (O'Keeffe et al., 2012).

Impoverished ecological health has far-reaching consequences for the inhabitants of the Ganga river basin, as it decreases the production of ecosystem services. For example, communities relying on floodplain agriculture need floods to bring in water and nutrients, but when the water is polluted, yields decrease (O'Keeffe et al., 2012). The ability to sustain suitable habitat for many unique species, like the Ganga river dolphin and the Gharial (Figure 7-3 left) and to provide sufficient clean water supply during spiritual and cultural expressions (Figure 7-3 right) are ecosystem services that have been dwindling because of the Ganga basin's impoverished ecological health.

7.6 Recent E-flow Work in the Ganga River Basin

A study by IWM (2010) in the Ganga river basin investigated several scenarios and strategies, i.e. effect of the Ganga Barrage, operation rules of the Kosi high dam and climate change on hydrological and socio-economic indicators such as water diversion volumes and generated hydropower. The study showed that reservoir dams dampened the amplitude of annual high and low flows, thereby decreasing the extent of inundated land. Moreover, all reservoirs influenced the hydrograph in a similar way but the impacts decreased more in the downstream area of the Ganga river basin. Although the effects of climate change could be best alleviated upstream, the largest effects were expected downstream of the dam. A major recommendation for Ganga river basin development was to include socio-economic issues for a holistic view of various development scenarios.

These recommendations were incorporated in a study that focused on the upper Ganga river basin, the 800 km-reach from Gangotri to Kanpur (O'Keeffe et al., 2012). The Building Block Methodology (BBM, Box 2) was employed and hydraulics, hydrology, fluvial geomorphology, water quality, biodiversity, livelihood and spiritual/cultural issues investigated. Working groups were assembled to investigate each of these indicators; the result was the definition of e-flows for normal, dry and wet years, expressed as a percentage of the natural Mean Annual Runoff (MAR) on a monthly basis. Due to the qualitative nature, the findings of this study cannot be linked to quantitative changes in discharges resulting from scenarios and strategies.

7.7 This Study

This e-flow assessment has three objectives: to evaluate the current state of the Ganga river basin, to assess the impact of potential future scenarios and river management strategies and to make recommendations for improved analysis and adaptive river management.

This is accomplished by exploring the impact of changes in water quality and water quantity on the ecological and socio-economic status of the Ganga river basin. An integrated River Basin Model was developed and modelled water quality, surface water and groundwater interactions, and water abstractions and diversions (Deltares, 2018). The model was coupled to an ecological habitat module and a module designed to calculate ecosystem services.

This innovative method confirmed the recommendations of previous studies; it also gave rise to a basin-wide, integrated and quantitative assessment of the ecological and socio-economic effects of various strategies under different socio-economic and climate change scenarios. Chapter 8 describes the assessment approach, Chapter 9 presents the assessment results, from which main findings are drawn in Chapter 10. Chapter 11 considers the way forward, acknowledging the multitude of uncertainties that hamper the present environmental flow assessment.

8 Technical Approach

8.1 Indicators for E-flow Assessment

Hydrological, ecological and socio-economic indicators are necessary for assessing the impact of changes in flow regimes and water quality (see Appendix A). These indicators were selected during stakeholder workshops and are sensitive for changes in magnitude, timing, duration and frequency of discharges and changes in water quality (BOD and DO). All indicators are linked to components of the Integrated River Basin Model (Deltares, 2018, Figure 8-1).

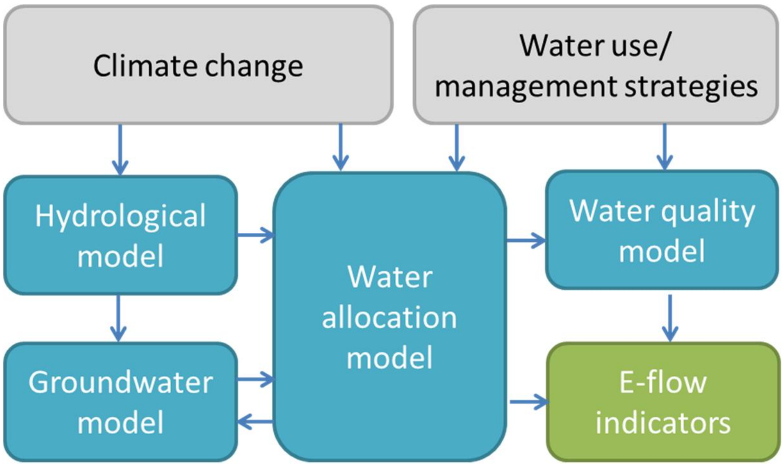

Figure 8-1: Flow diagram with the components of the river basin model and the link to the e-flow indicators, scenarios and strategies

To calculate the hydrological indicator, ten ecologically-relevant hydrological sub-indicators were identified to give an indication of changes in magnitude, duration, timing and frequency of both low and high discharge events compared to the pristine situation. These indicators provide a first step in understanding how different developments e.g., river regulation, increased water abstraction, or land use change, have impacted the Ganga river ecosystem. The indicators help to identify hotspot reaches that merit further investigation.

The ecological sub-indicators are expressed as changes in habitat suitability compared to the pristine situation for several fish species, the Ganga river dolphin, the Gharial and the Indian Flapshell turtle. Habitat suitability was calculated with response curves containing environmental thresholds for water quality and water depth. For socio-economics, the sub-indicators are fisheries, for which habitat suitability information is extracted from the ecological sub-indicators, ritual bathing and floodplain agriculture. Detailed information on the indicators, sub-indicators, underlying parameters and response curves can be found in Deltares (2018 and 2018a). In the e-flow assessment the socio-economic evaluation only includes services in the river and the active floodplain. Several other services that depend on water abstraction: irrigation, drinking water, and industrial supply are analyzed and discussed in the scenario analysis part (Part A) of this report.

8.2 Different Zones in the Ganga River Basin

Because of the large heterogeneity in the Ganga river basin, the rivers and tributaries are divided into 70 ‘eco-zones’ (Figure 8-2). These zones represent river reaches with relatively homogeneous geomorphological, ecological and anthropogenic characteristics (see details in

Deltares, 2018). This permits a site-specific evaluation of the effects of strategies and scenarios and pinpoints areas for extra attention.

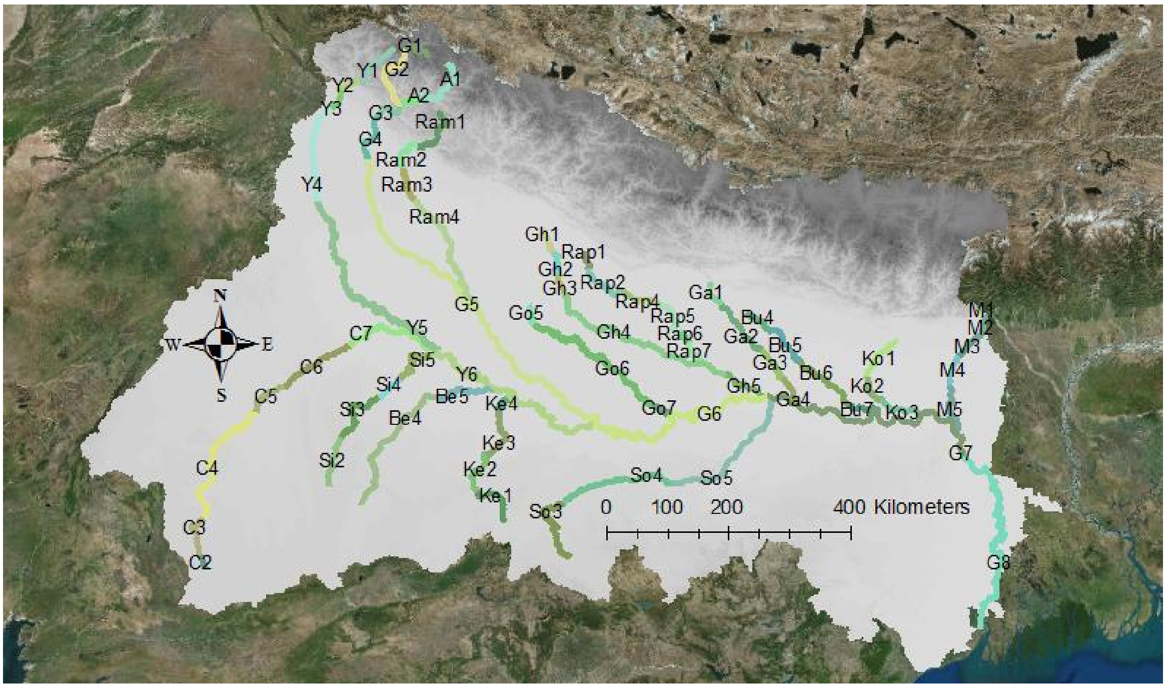

Figure 8-2: Zonation of the Ganga River and its tributaries into eco-zones with relatively homogeneous geomorphological, anthropogenic and ecological characteristics. Zones are coded with first letters of tributaries and numbered upstream to downstream per tributary. A list of zone names and start and end points is included in Appendix B. A detailed description of the zones is given in Appendix F.2 of the technical report (Deltares 2018b).

8.3 River Health Objectives

River health objectives are important to assess whether the current or a future ecological status of a river meets the desired status. To describe both desired river health and actual/future health a classification following the approach of the Water Framework Directive (WFD, European Commission, 2003) is adopted in which status is expressed as agreement with a reference condition (Table 8-1). This reference condition can be an earlier condition of the same river or the current state in a reference river, which could be a river with comparable characteristics but with limited human influence. In the WFD, the goal for a good ecological and hydrological status is expressed as a deviation from species habitat suitability in the reference condition for fish, macro-invertebrates and aquatic flora.

Table 8-1: Classes that express the hydrological, ecological and socio-economic agreement with reference conditions

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

In the WFD methodology, system status is considered sufficient if the indicator scores fall in the top two classes (A and B), which translates into more than 60 percent agreement with the reference situation. The lower two classes (D and E) reflect an insufficient system status while Class C is considered a transition class. For the Ganga, a stakeholder process is required to derive river reach specific health objectives. These river health objectives should reflect the societal importance of the river and may vary across the basin: a river stretch through a nature conservation area with threatened species may have higher objectives than a river stretch flowing through an urbanized area and which is already severely modified. To set these objectives, insight in also required in the socio-economic feasibility – setting river health objectives requires a balancing of ecological and other uses of the river. The analysis in this report (including the other report parts) provides a first insight in instream and off-stream costs and benefits of alternative river management strategies. This insight can serve as input to setting balanced and spatially varied river health objectives. **For the analysis in this report the minimum river health objective for all river stretches was set to be class C, so no 'insufficient condition' in any of the river stretches (eco-zones).**

To assess the extent to which the river health objectives are met, all indicators are calculated per eco-zone and expressed as changes compared to the modelled pristine situation, a situation without human land- and water use and without infrastructure in which the ecosystem is in a natural state. The indicator scores per eco-zone are expressed as a percentage of agreement with the pristine situation (Table 8-1).

A return to the pristine situation is not the goal for the Ganga river basin; the pristine situation is the most logical reference situation for understanding how much the Ganga ecosystem has changed. Current understanding of ecosystem responses and data availability do not allow for an absolute assessment of the level of ecosystem health and its services. Even if it were possible to express the ecosystem components as absolute values, a benchmark is required to evaluate if these conditions are sufficient.

8.4 Scenarios and Strategies

Current water shortage and water quality issues may change as a result of both socio-economic developments and climate change. Impacts on the river ecosystem were therefore tested for three future scenarios for the year 2040 (see Chapter 2):

1. Socio-economic development: this scenario includes population projections based on the official method, increase in agriculture demand to 180 percent of the present demand and increase in industrial demand to 400 percent of the present demand;
2. RCP4.5: this scenario uses climate projections from the RCP4.5 scenario using downscaling by IITM in Pune, on top of the socio-economic developments until 2040;
3. RCP8.5: this scenario uses climate projections from the RCP8.5 scenario using downscaling by IITM in Pune, on top of the socio-economic developments until 2040.

Water shortage and water quality problems are presently encountered; this situation will become more acute in the future. To reduce these problems, several strategies have been identified and tested for their impact (see Chapter 3). Several of these measures have an objective of reducing water shortages for irrigation by adding new infrastructure or by increasing irrigation efficiency. Other strategies aim to improve water quality. The E-flow strategy prioritizes water in the river over abstractions, with the purpose of protecting the river ecosystem and its services.

The following strategies were analyzed in the Present scenario and the 2040-RCP4.5 scenario for their impacts on the river ecosystem:

- Approved infrastructure: including all new infrastructure projects that have been approved prior to 2018;
- Conjunctive use: reducing groundwater abstractions in currently over-abstracted locations;
- Increased efficiency: enhancing efficiency of both conveyance and field application from groundwater and surface water irrigation;
- NMCG planned treatment: actions planned as part of the National Mission Clean Ganga (NMCG) program;
- Improved treatment: includes NMCG planned treatment and additional surface water treatment capacity in both rural and urban settings;
- E-flow: The strategy analyzed here is a first analysis of how the river ecosystem and its services respond to prioritizing the river over other uses. A target is set of 41% of pristine monthly discharges at the major rivers in the Ganga basin. This strategy aims at achieving at least a moderate hydrological status. Note that an e-flow regime is ultimately a balanced and agreed upon flow regime.

All scenarios and strategy results are individually expressed as percentage agreement with the pristine situation. Subsequently, to analyze the specific effect of the scenarios and strategies, all ‘do nothing’ scenarios were compared amongst each other and all strategy results were compared to the corresponding ‘do nothing’ scenario.

9 Environmental Flow Assessment for the Ganga River Basin

9.1 Present River Status Compared to Pristine

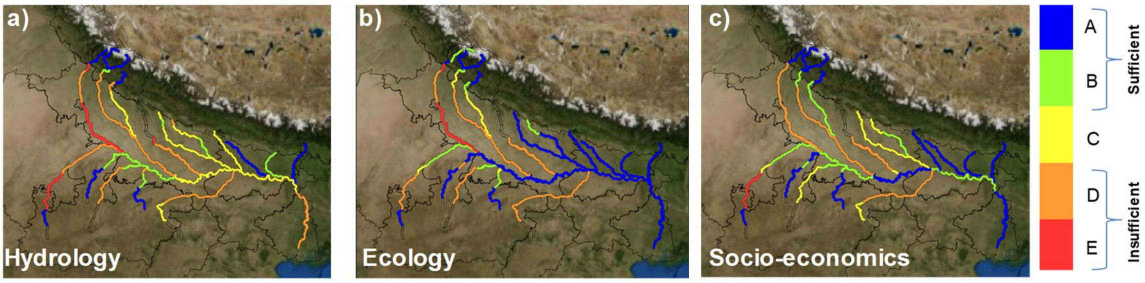

Figure 9-1: Overview maps with the changes in hydrological (a), ecological (b) and socio-economic (c) indicators in the present scenario compared to the pristine scenario (scores are defined in Table 8-1).

In the present scenario, the Ganga basin has both zones where the **flow regime** is relatively unaltered compared to pristine conditions and zones with severe flow regime alteration. Particularly the middle/lower reaches of the Ganga, Yamuna, Chambal, all studied reaches of Gomti, and some reaches of Ramganga, Rapti, Betwa, Ken and Son, have highly changed flow regimes due to dams, weirs and water abstractions (Figure 7-2, Figure 9-1a). Upper reaches of the Ganga, Yamuna, Ramganga, Chambal, Sind and Ken as well as the entire tributaries of Alaknanda, Burigandak and Mahananda continue to have a relatively natural flow regime. Around 50% of the modelled zones can be considered to have a sufficient flow regime. The flow regime has been severely altered in around 25% percent of the zones.

This alteration is reflected in changes in frequency of specific flow components. Particularly magnitude and frequency of low and high flow events have changed. Shifts in the timing of months with maximum discharge generally show small changes between pristine and present which means that the seasonality of the flow remains relatively unaltered. To illustrate these changes, Figure 9-2 shows the long-term variations in monthly discharge for the Ganga in the stretch from Allahabad to Chhapra (G6) for the pristine and present scenarios, and Table 9-1 shows the results for the individual indicators. These individual indicators show that in zone G6 low, average and high flows are reduced in the present scenario. As a result, the duration of the low flow situation is prolonged. These hydrological changes in zone G6 resulted in class C. Appendix C includes graphs with indicator tables for all zones.

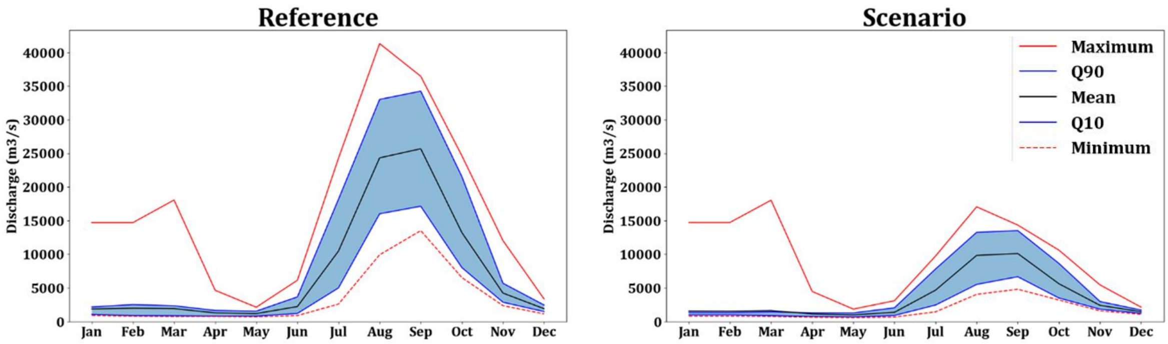

Figure 9-2: Variation in monthly discharge for 1980-2014 in eco-zone G6 from Allahabad to Chhapra. Left: pristine scenario, right: present scenario.

Table 9-1: Hydrological indicator values for eco-zone G6.

Indicator	Pristine	Present	Change (% or number of months)
Magnitude			
20 % non-exceedance annual minimum (m3/s):	817	722	-12
Median annual minimum (m3/s):	1048	954	-9
Average annual median (m3/s):	2478	1571	-37
Median annual maximum (m3/s):	28555	11780	-59
80 % non-exceedance annual maximum (m3/s):	34131	13484	-60
Timing			
Most frequent month of maximum:	Sept	Sept	0
Duration			
Average no. of months with Q < Q25 (reference):	3	5	2
Frequency			
Relative frequency: 80% exceedance (min):	0.8	0.69	-14
Relative frequency: 50% non-exceedance (min):	0.49	0.71	45
Relative frequency: 50% exceedance (max):	0.49	0.00	Not exceeded anymore at all

Almost 75 percent of the modelled zones in the Ganga basin have a sufficient **ecological status;** however, the status is insufficient in almost 20 percent of the zones (Figure 20-1b). In general, the Yamuna shows the worst ecological status of all rivers; where half the zones, all in the middle reach, have badly deteriorated compared to the pristine situation. The middle reach of the Ganga River also has a lower ecological quality. Furthermore, the complete Gomti and Son rivers have substandard ecological scores, while the middle reaches of the Chambal, Sind and Betwa Rivers contain ecological zones with lower quality.

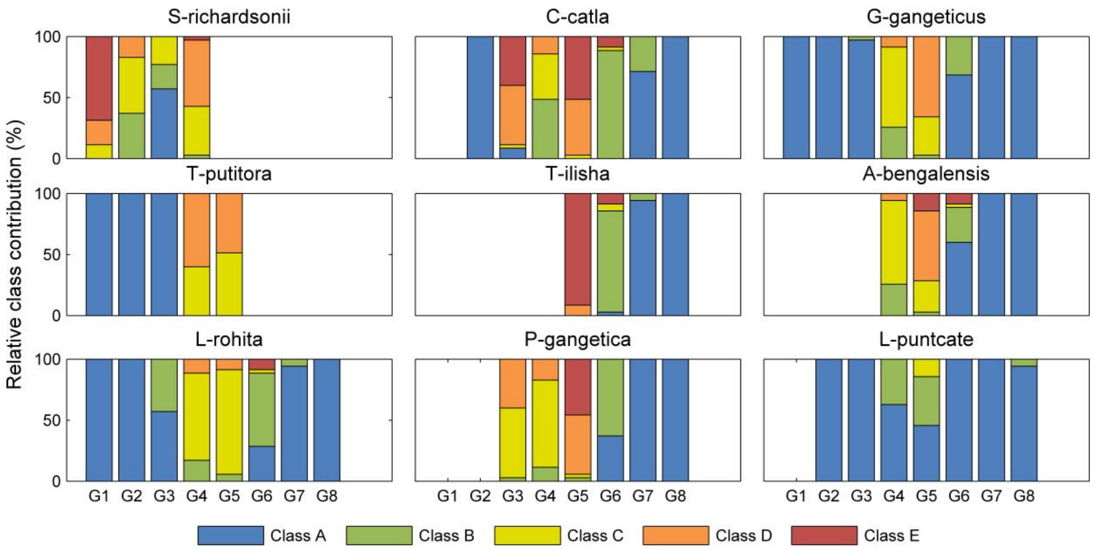

Figure 9-3: Relative class distribution of species (from 1980 to 2014) per eco-zone in the Ganga River.

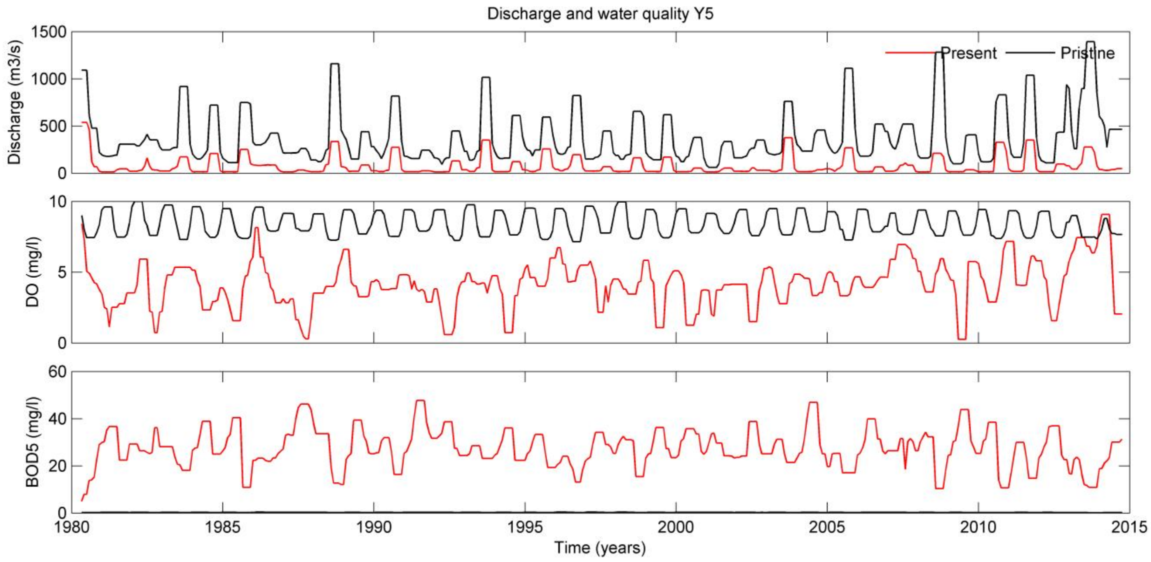

Figure 9-4: Example of discharge and water quality values that differ between the present and the pristine situation for eco-zone Y5, in the middle of the Yamuna River. Lines are plotted as 7 months moving median. Note that pristine BOD5 is zero.

Different species are affected in different seasons, based on their life events and life stages. Almost all species occurring in the middle reach of the Yamuna, from Paonta Sahib to Bhareh, have low ecological scores. In the reach from Poanta Sahib to Wazirabad (Y3 and Y4) low scores are mainly due to water deprivation (Appendix C). In the zone from Wazirabad to Bhareh (Y5), low concentrations of dissolved oxygen are an additional cause of decline (Figure 9-4, middle and lower panels). This can be related to several large cities in this zone, including New Delhi, which dramatically increase pollution loads. In the Ganga River the zones from Jonk (Rishikesh) to Allahabad (G4 and G5) have low ecological scores (Figure 9-3), which are caused by changes in discharge (Appendix C). In the Gomti from Hindaura to Bijaipur (Go5 and Go6) water depth is the main limiting factor, but oxygen becomes increasingly limiting more downstream. In the Chambal from Khejariya to Itawa (C4) and in the middle reach of the Betwa, water depth is the limiting factor, while in the complete Son River and in the Si4 from Dabra to Medpura a combination of water depth and oxygen are limiting factors for a good ecological score.

In the present situation, 70 percent of the eco zones still show a sufficient **socio-economic** state compared to the pristine (Figure 9-1c), while 13 percent of the eco zones show an insufficient state with a deviation of more than 60 percent compared to the pristine situation. The zones of sufficient state are found in both the upper and the lower reaches of Ganges and Yamuna. Also all modelled zones of Ramganga, Gandak, Burigandak, Mahananda, Sind and Ken show a sufficient status.

The only insufficient zone in the Ganga is the zone from Bijnor to Allahabad (G5), where the state is insufficient for bathing and fisheries, while the state for agriculture fall just within the sufficient category. (See Appendix E). Bathing suitability is mainly limited by poor water quality in this zone.

The insufficient status of the Yamuna from Paonta Sahib until Bhareh (Y3, Y4 and Y5) is determined by low quality of the conditions for both bathing and fisheries. For the stretch from Paonta Sahib to Wazirabad (Y3, Y4) water depth was the limiting factor for bathing suitability. For the stretch from Wazirabad to Bhareh (Y5) water quality is limiting. This is the zone along which New Delhi is located with high emissions of polluted water. With three culturally significant sites, Vrindavan, Mathura and Agra, located in this zone, it is important to restore good water quality for religious ceremonies. In addition, this zone is insufficient for fisheries as all fish species are impacted (Figure 9-3).

The socio-economically most impacted zone is found in the middle reach of the Chambal (C4), where scores on all three socio-economic indicators are insufficient.

Overall, the results reveal that within the Ganga basin zones can be found that are in a sufficient and even near-pristine status, but also zones that are severely altered and where ecological and socio-economic values have been impacted compared to the pristine situation. The results also show that there is not a clear linear relation between hydrological alteration and ecological and socio-economic values. This might be explained by the fact that hydrological alteration comprises a range of hydrological indicators that are not all used as input in the responses curves. Discharges are processed into water depth values, which are subsequently used in the response curves. Water depth does not have a linear relation with discharge, since it depends on the geomorphological characteristics of the river. However, the complete range of hydrological sub-indicators give a total picture of flow alteration which could reflect other ecosystem responses that are currently not modelled due to data limitations, i.e. riparian vegetation. The ecological and socio-economic scores combine water quantity and water quality parameters in different ways, which results in spatial variations of suitability for different species and functions.

9.2 Impacts of Socio-economic Development and Climate Change Scenarios

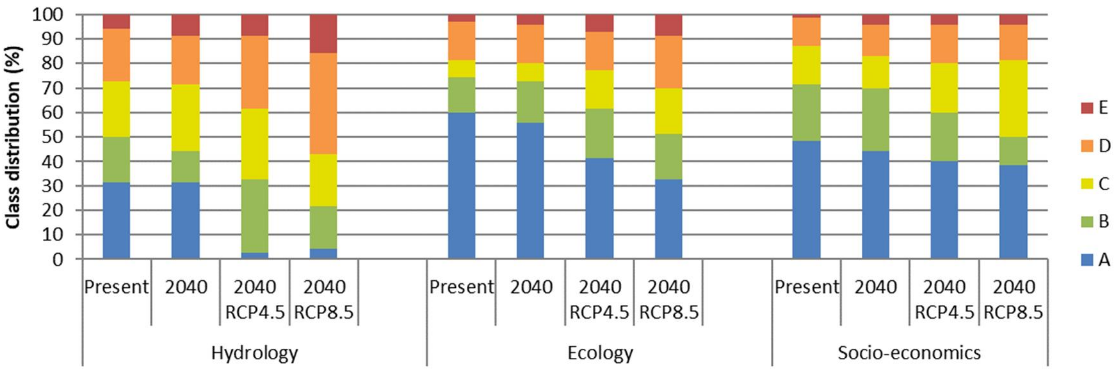

Figure 9-5: Scenario results of socio-economic development (2040) and average (RCP4.5) and extreme climate change (RCP8.5) compared to the present situation for hydrology, ecology and socio-economics.

Figure 9-5 displays the distribution of classes over all 70 zones of the Ganga basin for each of the scenarios and the three indicators. Classes per scenario per zone can be found in Appendix F.

Indicators of hydrological change show a deteriorating river condition in all analyzed future scenarios (Figure 9-5). The total percentage of zones with sufficient quality becomes smaller in 2040 due to socio-economic developments. Under climate change, this situation further worsens, with lowest results for the situation in 2040 in which both socio-economic developments and severe climate change (RCP 8.5) take place. High reductions in low and high flows are the main causes of these lower future hydrological scores.

Flow regimes of both Ganga and Yamuna are severely affected by some of the future scenarios. Middle reaches of the Ganga (from Bijnor to Farakka, G5-G7) either go to insufficient or to the lowest class. Middle and lower reaches of Yamuna (from Yamuna Nagar to Allahabad, Y4-Y6) also deteriorate to insufficient or from already insufficient to the lowest class. Many zones in the other tributaries deteriorate one class or more, reaching insufficient status in many places under one or more of the scenarios. Lowest classes are furthermore reached in Ramganga from Kalagarh to Ali Rajapur (Ram2 – Ram3), and individual reaches of Gomti, Ken and Sind.

Ecological effects of future socio-economic developments and climate change are also predicted to have a negative effect on ecology (Figure 9-5). In the current situation, almost 75 percent of the basin has a sufficient ecological state. This declines slightly due to socio-economic developments in 2040, but with additional climate change the ecological scores in 2040 are projected to decline to 60 percent in the RCP4.5 scenario and 50 percent in the RCP8.5 scenario. In 2040 the ecological deterioration is mostly located in the middle of the Yamuna from Nagar to Wazirabad (Y4) mainly due to decreased water quality. Additionally, the lower reach of the Ken tributary shows lower ecological scores compared to the present situation due to reduced water quality.

In the RCP4.5 scenario, the situation deteriorates to the lowest class in the middle reach of the Ganga (G5) due to a combination of discharge reduction and deteriorating water quality compared to the 2040 scenario. The Ganga from Allahabad to Chhapra (G6) shows a decreasing trend as well due to combined pressures. Also the Ramganga, Chambal, Betwa, Ken and Son show zones with decreasing ecological quality.

Moreover, in the RCP8.5 scenario, conditions further deteriorate in the middle reach of the Ganga from Allahabad to Chhapra (G6, Figure 9-6), in the lower reach of the Yamuna, in the middle reach of the Ramganga, in the Rapti, Burigandak and lower reach of the Ken. Generally, these changes in discharge and water quality negatively affect all modelled species, depending on the sensitivity of the environmental parameters and the magnitude of change.

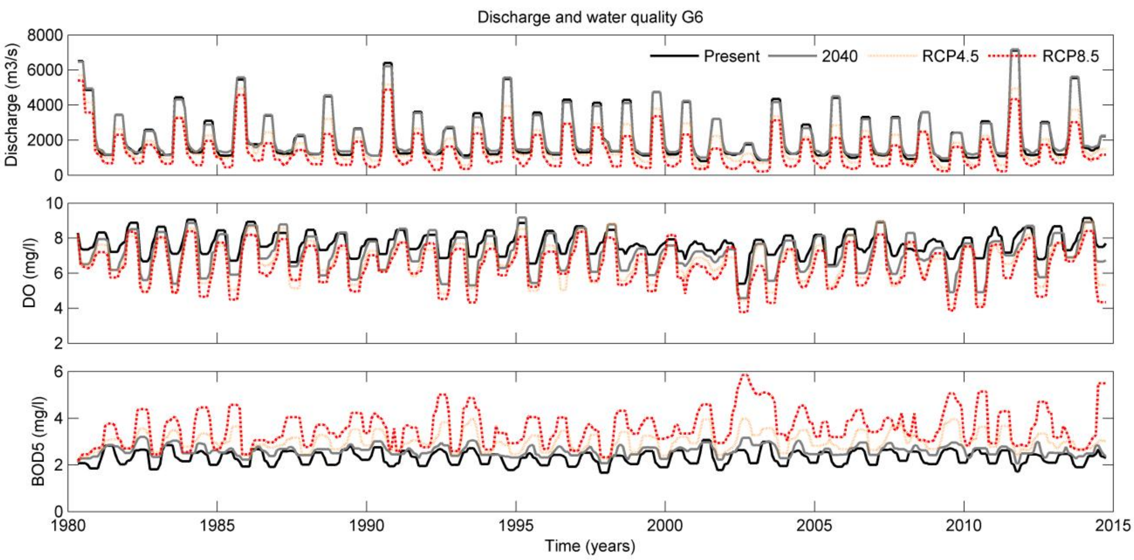

Figure 9-6: Example of discharge and water quality values that differ between the scenarios and the current situation for eco-zone G6, in the middle of the Ganga River. Lines are plotted as 7 months moving median.

The conditions for socio-economic use of the Ganga river deteriorate under all three scenarios. However, in 50% of the zones, the socio-economic conditions do not change at all under the different scenarios. The socio-economic development scenario leads to only a small increase in insufficient conditions. Combined with the RCP4.5 climate change scenarios the number of zones with sufficient conditions further reduces. The RCP8.5 scenario leads to a small improvement compared to the RCP4.5 scenario (Figure 9-5). Although the number zones with insufficient conditions does not change much, the scenarios do lead to a shift in classes between the different sufficient classes, and thus overall do lead to a reduction in socio-economic value.

Changes in the Ganges and Yamuna are limited, with only a few zones that reduce to a lower class in only some of the scenarios, without reaching insufficient conditions. The zones that are already insufficient do not change. In other parts of the basin several tributaries have zones that degrade from sufficient to class C: Ramganga, Ghaghra, Rapti, Burigandak, Chambal, Sind, Betwa, and Ken. And in a few tributaries some zones reach insufficient status or go from already insufficient to the lowest class: Gomti, Rapti, Chambal, Betwa, and Son.

9.3 Impacts of Strategies

The individual strategies have limited impact on the e-flow indicators. Results are discussed per strategy for the present and the RCP4.5 2040 scenario. Figure 9-7 summarizes how selected strategies influence the class distribution of the 70 eco-zones for hydrological, ecological and socio-economic indicators. The classes per strategy for all zones are included in Appendix G for the present situation and in Appendix H for the RCP 4.5 2040 scenario. The overall finding is that these individual strategies have limited impact.

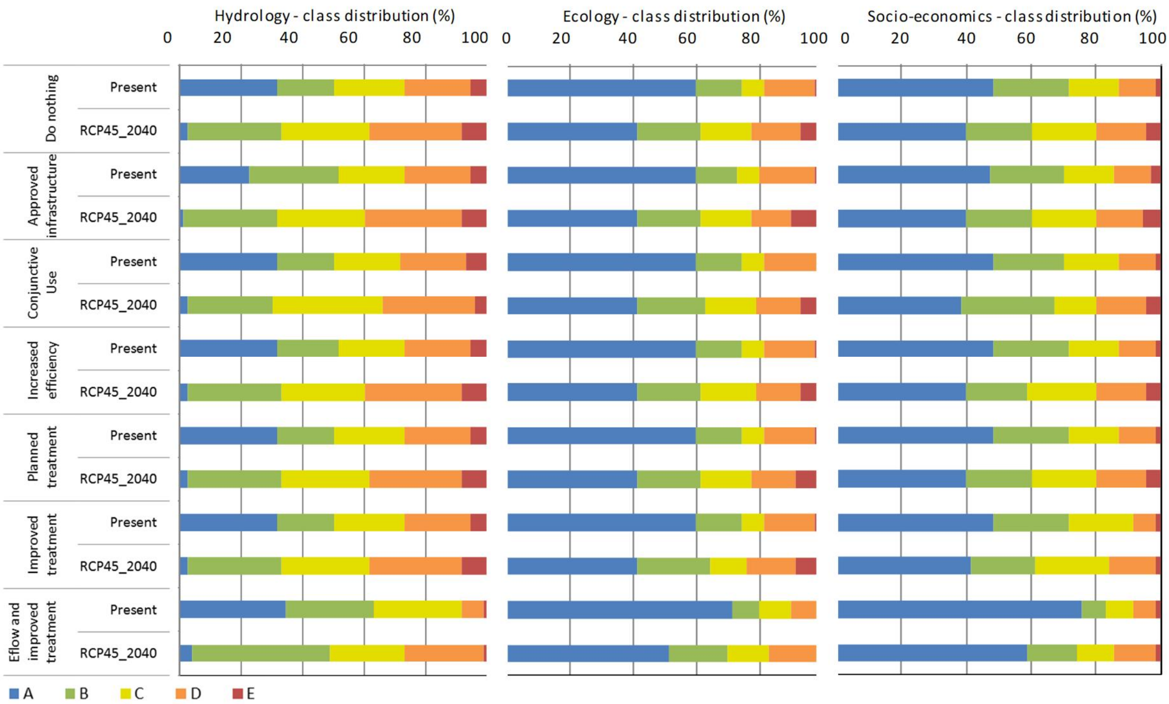

Figure 9-7: Comparison of strategies under different scenarios of socio-development and climate change for hydrology, ecology and socio-economics.

Approved infrastructure
The ‘approved infrastructure’ strategy consists of new weirs and related abstractions for agriculture, including some inter-basin transfers. Inter-basin transfers can improve discharge conditions in some reaches while degradation occurs in other reaches, as is demonstrated in the results. Overall, the ‘approved infrastructure’ strategy has little impact in most rivers both in the present scenario and under the RCP4.5 scenario. The flow regime is affected in a few zones, mainly in a negative way. However, these flow regime changes do not everywhere translate into lower scores on the ecological and socio-economic indicators.

Conjunctive use
In the ‘conjunctive use’ strategy, irrigation with groundwater is restricted to times with no surface water availability; this should stabilize the groundwater tables. Thus, this strategy may result in increased surface water abstractions and reduced return flows from groundwater irrigation. The volume of water for irrigation is likely to be similar, but the impact of groundwater use on the river system is more spread over time. Additional use of groundwater during dry periods may increase river discharge through increased return flows. This strategy has impacts in only a small number of tributaries. These impacts are largely positive for all indicators. However, lower reaches of Yamuna, Ganga, Burigandak, Gomti and Chambal experience negative impacts for some of the indicators.

Increased efficiency
The ‘increased efficiency’ strategy increases the efficiency of irrigation which means that lower volumes of water are withdrawn from both surface water and groundwater, thus resulting in more natural flows. The impact of this strategy is very limited. The flow regime of only a few zones is impacted. Under the present scenario two zones are positively impacted in Ghaghra and one negatively in Rapti. Under the future scenario only the downstream reach of Yamuna is impacted negatively. More zones experience impacts on ecological indicators. These impacts mainly occur under the present scenario and are largely positive. Socio-economic impacts are only found under the future scenario: 1 zone in Rapti is impacted negatively. A possible explanation of negative impacts can be that some reaches no longer receive return flows from water abstracted from groundwater or from other rivers.

Planned treatment
The ‘planned treatment’ strategy results in the removal of some pollutants and an improvement in water quality. This means that the hydrological indicators remain unaltered. The results show that the strategy has no impact on the socio-economic indicators either. The impact on the ecological indicators is positive under the present scenario, for few zones that are impacted. Under the RCP4.5 scenario only the downstream reach of the Gomti is affected, in a negative way.

Improved treatment
The ‘improved treatment’ strategy adds additional treatment capacity to the already planned treatment, aimed at further improvement of water quality. Under this strategy hydrological indicators remain unaltered. With this combined treatment, many more zones are impacted. These impacts are largely positive.

E-flow
In the e-flow strategy the Ganga River is prioritized as a water user over being a water source for irrigation. This strategy should be considered an exploration of what is required to recover the e-flow indicators to a sufficient status. A more dynamic flow regime was developed not deviating more than 60% of pristine flow in any month, maintaining the variability within the years as well as between years. With this strategy around 30% of the zones improved in all

three e-flow indicators for both present and future scenarios. In 6 or 7 zones the desired minimum class C was not reached in the present scenario, where water quality is still a limiting factor or due to model uncertainty. In the 2040 RCP4.5 scenario, rainfall and evaporation patterns change, which make it harder to meet the e-flow requirements and more zones remain in insufficient status.

10 Main Findings and Recommendations

10.1 Main Findings

The Ganga river basin shows a severely altered state compared to the pristine situation due to alterations of the flow regime and poor water quality. Model results show that reduced discharges caused by water abstractions and dams are the main driver behind deteriorating ecological and socio-economic quality. Reduced dissolved oxygen concentrations and high biological oxygen demand are an additional pressure, mainly in the middle reaches of the Ganga and Yamuna rivers where large polluting cities are located.

All socio-economic and ecological values in the Ganga river basin are expected to be negatively affected by future socio-economic developments and will further deteriorate under climate change. However, there are some exceptions where climate scenarios project increased discharges in the modelled Himalayan Rivers that have positive effects. Figure 10-1 shows the cumulative negative effect in zones where future scenarios decrease in hydrological, ecological and socio-economic quality to the two lowest classes, i.e. from class A-C to class D or E or from class D to class E. This shows which zones are negatively impacted by future socio-economic development and climate change, and where implementation of additional measures might be necessary.

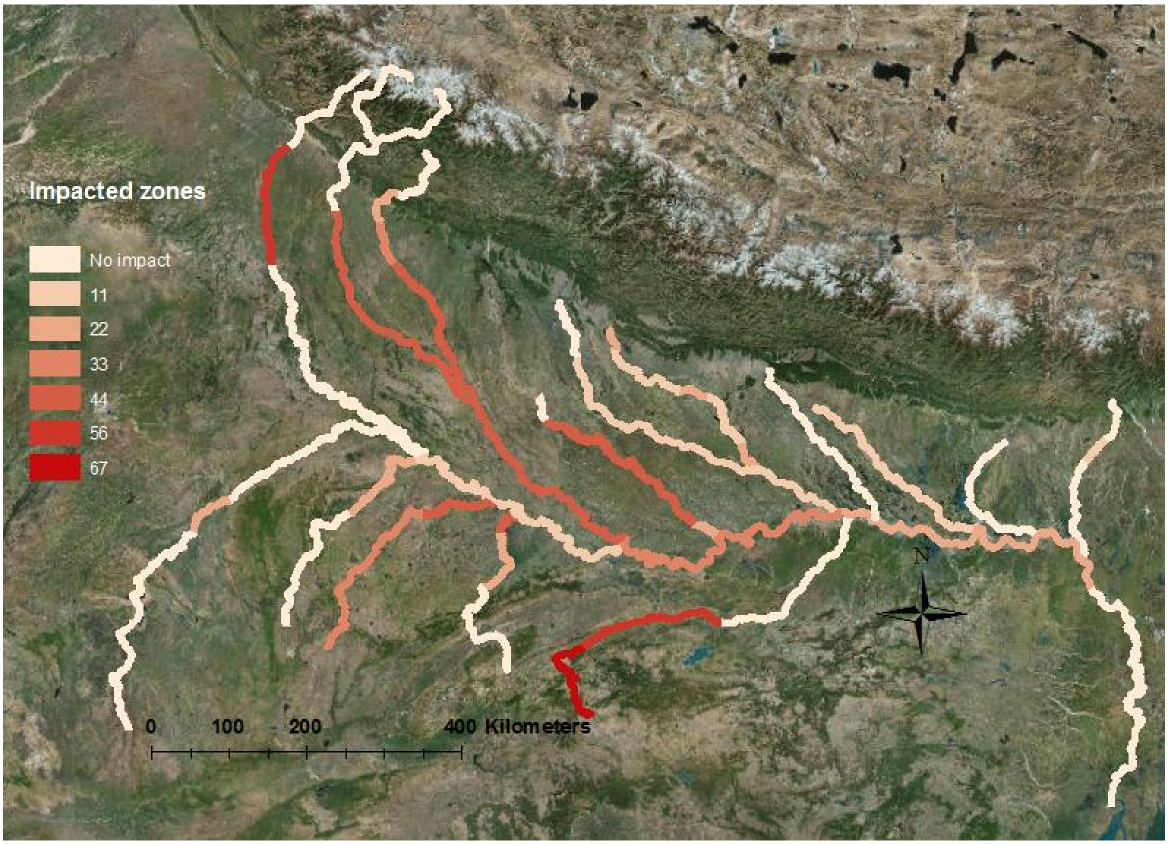

Figure 10-1: Zones that are negatively impacted by future scenarios, expressed as the percentage of scenario-indicator combinations per zone that become insufficient or decrease to the lowest class.

Compared to the impacts of the scenarios, the impacts of the strategies are limited. Strategies have positive impacts in a limited number of zones. Figure 10-2 shows the cumulative positive effect in zones where strategies increase hydrological, ecological and socio-economic quality to sufficient quality, i.e. from class D-E to class A-C or from class C or B to class B or A respectively. This shows that the positive effect of the proposed strategies is limited in the zones that are most impacted, which are the middle reaches of the Ganga (G5), the Yamuna (Y4), the Gomti (G6) and the Betwa (Be4). This suggests that especially in these zones, additional measures such as water treatment or irrigation efficiency should be applied to prevent further deterioration. Off-stream water use and groundwater pumping must be reduced and local species habitats must be restored in order to further improve Ganga ecosystem health and to create a climate resilient system. Clear choices need to be made reflecting how the Indian society values both their off-stream water use and their instream ecosystem and related services.

Impacts of future scenarios and strategies on environmental flows reflect the sensitivity of species and services to the physical and chemical parameters that are now included in the river basin model. When new species, services and response relations are added, the amount and distribution of impacted zones, both negatively and positively, might be different. Chapter 11 discusses an adaptive management framework to improve future e-flow assessments and corresponding river management.

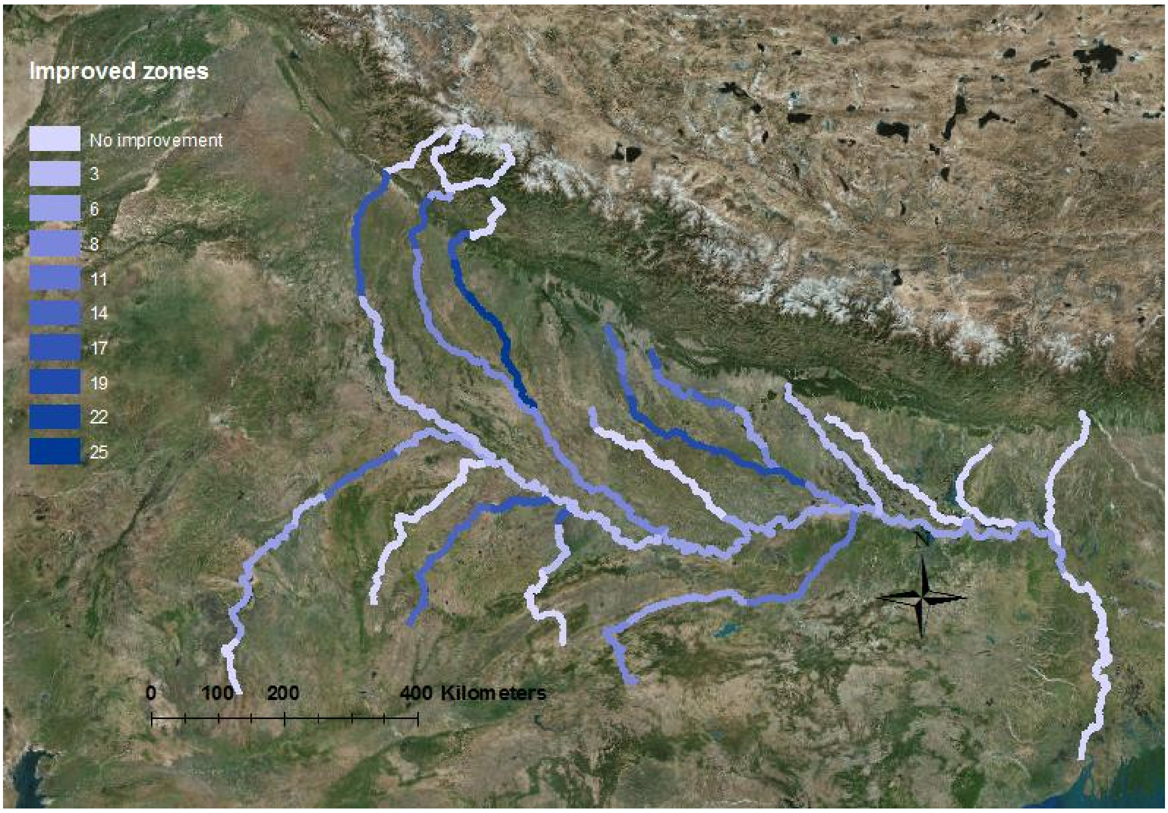

Figure 10-2: Zones that are positively impacted by strategies, expressed as the percentage of strategy-indicator combinations per zone that become sufficient or increase to the highest class.

For the e-flow assessment in this report an e-flow strategy that maintains 41% of monthly pristine discharges and natural dynamics was analyzed. The strategy showed that a reduction of more than 50 percent of the diverted irrigation water is required to achieve a sufficient status, which still deviates significantly from pristine. In addition to the reductions in diversions additional water quality measures are required. However, the same strategy would be even more difficult to be implemented under RCP4.5 climate change scenario due to changes precipitation and evaporation (Table 10-1).

Table 10-1: Number of zones that are no longer or still insufficient under the e-flow strategy.

	Hydrological indicators		Ecological indicators		Socio-economic indicators	
	Present	**2040 RCP4.5**	**Present**	**2040 RCP4.5**	**Present**	**2040 RCP4.5**
No longer insufficient after e-flow	13	9	6	6	4	5
Still insufficient after e-flow	6	19	7	12	6	10

10.2 Recommendations for E-flow Regimes in Selected Regions and the Basin as a Whole

Considering the enormous required reduction in diversions, it may not be feasible to make the flow regime ecologically sufficient in the basin as a whole. Certainly, hydrological measures alone are insufficient because water quality is also a limiting factor in many zones. Additional measures to improve water quality or to construct specific habitat conditions, such as deep pools or connections to flood plains will be required in zones where flow regime improvement alone turns out to be insufficient. In case it will prove to be difficult to implement the changes to achieve a minimum of ‘Class C’ or ‘no zones with insufficient conditions’ it is not recommended to take general ‘watered-down’ measures. This will probably not lead to significant ecological rejuvenation while the costs to society are high leading to risks of media and public dissatisfaction.

However, specific zones with valuable ecosystem services or high biodiversity values, such as natural parks, species reserves, or bathing sites, can be targeted to achieve higher river health objectives. In such cases tangible results are achievable and interventions may be socially acceptable when stakeholders will be able to see the results of interventions. When this approach is accepted it can slowly be expanded to include other zones. Environmental flows interventions require an informed societal choice, which means that river health objectives need to be set in consultation with stakeholders of both instream and off-stream water uses.

Based on these considerations, the following e-flow recommendations are made:
- Decide on river health objectives per river zone. Class C as a minimum river health objective is recommended for each zone. When that is not yet achievable, focus on specific zones rather than lower overall objectives;
- Set monthly e-flow regimes that correspond with these classes; taking care to include variability both within year as well as between years;
- Design accompanying measures for water quality improvement and habitat construction.

11 Adaptive Management

The assessment of environmental flows for the Ganga river basin has been restricted due to limitations in understanding flow-ecosystem-service relationships, as has been the case with most environmental flows assessments conducted world-wide. Instead of focusing first on additional data collection and analysis, it is generally recommended to begin implementing improved river management practices, in parallel with monitoring the responses of the ecosystem and the availability of ecosystem services (Hirji and Davis, 2009). This 'learning while doing' process also updates both analysis and river management. This chapter describes actions to reduce information gaps in the current e-flow assessment, followed by specific recommendations for monitoring. Effective use of the monitoring results requires procedures and responsibilities for updating both the assessment and river management actions.

11.1 Reducing Information Gaps for E-flow Assessment

Although this e-flow study is innovative in quantitatively coupling changes in discharge to species responses and ecosystem services, there is a major lack of data which influences the sensitivity of the model outcomes.

To improve the accuracy of the e-flow assessment, refinements can be made at five levels:
1. Improving the physical description and zonation of the river basin;
2. Improving physical parameters – ecosystem (service) response curves;
3. Broadening the set of sub- indicators;
4. Describing reference conditions;
5. Constructing discharge–inundation relations.

11.1.1 Improving the Physical Description and Zonation of the River Basin

An accurate physical description of the river basin is important to define the environmental boundaries in which species live and services are provided. From upstream to downstream, river characteristics change from fast flowing, steep slopes with large sediment fractions towards slower flowing lowland rivers with sandier substrate; a range of other planforms and flow-characteristics are found in the transition from upstream to downstream. Obviously, a river is a continuum, but zones can be designated to provide areas in which species and services react relatively homogeneously to discharge changes. This study created a river zonation based on slope inflections, geomorphological characteristics and anthropogenic impacts, mainly based on aerial imagery from Google Earth. This zonation procedure resulted in zones of varying length. For example, the Ganga River has eight zones with zones in the middle and lower reaches of several hundred kilometers in length. In the current methodology all zones have the same weight; this means that a very large zone with poor quality has the same weighted value as a small zone with good quality. Adjusting the weighting process based on river length of the zone would yield more accurate results.

The processing of simulated discharge into water depth as input for the species response curves also has limitations; at least one, but preferably more cross sections are necessary. Because the number of cross sections for the basin was limited, many zones were assigned cross-sections from other, comparable, zones (Deltares 2018a, Appendix F.3).
As a result, the modelled discharge and water depth values from these artificially defined zones could be out of balance, influencing the accuracy of the results. Thus, adding more

detailed information on geomorphological characteristics and a finer spatial resolution in the zonation will help to identify specific areas with suitable habitats for specific species.

11.1.2 Improving Physical Parameter–Ecosystem (Service) Response Curves

For those species and services included in the e-flow assessment, the data of the environmental parameters, serving as input for the response curves for species and services, is extracted from the river basin model. Only limited data was available to construct meaningful response curves for most species. Response data on water quality was lacking for several fish species and for the Dolphin, Gharial, and the Turtle. Generic European dissolved oxygen guidelines were applied to several species; in cases where the generic guidelines are not available, those species become insensitive to measures that affect water quality. Obtaining data on the timing of specific life events was problematic; when this information is included in the response curves, responses to timing of flow events can be monitored, and species will respond more effectively to strategies that intervene at specific moments in the species life cycle. Sediment properties are useful in refining response curves to determine spawning habitats for fish and basking habitats for reptiles. Response curves for substrate can be tied to several fish species; if these data are added to specific eco-zones, the corresponding response curves can be applied in the model.

Connectivity is an important parameter as several species in the model are migratory fish that inhabit different sections of the river during evolving life-stages. A barrage or dam within a migratory route will negatively impact the species distribution and population density. This is especially the case for catadromous and anadromous fish species; for example, the catadromous *A. bengalensis* breeds in the ocean and migrates up the river; this migratory pattern is hampered by the Farakka barrage and the distribution of this eel will be limited. The inclusion of information on migration pathways coupled with the reachability of certain zones will improve the validity of response curves for disconnected zones. In addition, strategies that affect connectivity, e.g., fish passages, can be analyzed more effectively.

Response curves provide relative comparisons between the present and the pristine situation. Response curves can only be validated by field observations; when validated with field data, response curves can be refined for defining absolute habitat suitability predictions.

The socio-economic response curves for bathing water quality, floodplain agriculture and fisheries were based on stakeholder suggestions from the workshops. Response curves should constantly undergo a process of testing and refining for which service users are best placed to provide invaluable input with respect to practical requirements. Collection of this input can start in selected zones with high human dependence on the river ecosystem and high ecosystem service degradation risk.

11.1.3 Broadening the Set of Sub-Indicators

A list of IUCN protected species was derived following several stakeholder workshops with Indian experts (Appendix I). Unfortunately, only a small sub-set could be included in the assessment because sufficient data was limited (Appendix A). However, the list serves as the starting point for researching which environmental parameters are important and for deriving the appropriate response curves for the selected species. This will also decrease the inequality among species groups, of which fish are now currently dominating.
Additionally, riparian and aquatic vegetation are important groups, since vegetated areas provide shelter for species, buffer temperatures and affect hydro-morphological processes in the river.

Impacts on all indicators in all zones were assessed. However, it is possible that certain food species or ecosystem services are less important. Additional research should assess indicator importance in terms of economic or livelihood value. Hydrological alteration is an important factor in understanding basin mechanics. An informal social-economic exploration could be conducted in zones that show high hydrological alteration. Talking with inhabitants along the river and in nearby villages would provide additional insight into the main use of the river and how the ecosystem has changed over time. Ecosystem services are important for the livelihood, i.e., income, health, mental well-being, of basin inhabitants. Any survey of the key services should understand the availability of these services over time in relation to river characteristics.

Adding more response curves for species and services refines the sensitivity to environmental change; however, this tends to create stricter habitat or service availability with the potential to lower ecological and socio-economic scores.

11.1.4 Describing Reference Conditions

The e-flow assessment compares the present and future states of hydrological, ecological, and socio-economic values to a pristine situation. The pristine situation provides a reference to which all results can be compared; however, it is a situation that is unattainable nor is it the main goal. In some cases, strong deviations from the pristine situation will be revealed. In reality, this divergent case may be sufficient to providing adequate habitats and services. Thresholds should reflect the minimum requirements for sustaining healthy populations of species and for providing the necessary ecosystem services. This may result in a more realistic reference situation which can be spatially heterogeneous. This realistic reference situation could be considered “good enough” for the valued species and services. This approach will require large scale research on species carrying capacity and the local population’s reaction to ecosystem services.

11.1.5 Constructing Discharge–Inundation Relations

Inundation dynamics is a promising method of coupling quantitative data to ecology and ecosystem services.
Data derived from satellites are used to assess the extent to which various land categories, e.g., wetland, cropland, natural vegetation, cropland mosaic, urban areas, are flooded during a specific period. This information can be coupled to damage, e.g., flooded agriculture and flooded urban areas or coupled to riparian vegetation dynamics, e.g., flooding duration and timing.

During the study, a small pilot investigated if this method could be used to derive quantitative relations between flooding extent and different land use types. All calculations were performed on the Google Earth Engine platform.

The following analytical actions were applied:
- Correct cloud cover on satellite images based on the reflectance value per pixel;
- Separate water from land using the Normalized Difference Water Index (NDWI);
- Identify croplands, wetland and urban areas from land use map and calculate flooding extent per land use type;
- Derive relation between flooding extent per land use type and modelled discharges.

It was possible to derive inundation maps (Figure 11-1), to calculate flooding extent per land use type (Figure 11-2) and to identify general flow-inundation response categories for each flow output node (Figure 11-3).

The flow-inundation response categories are:
- Direct flow-inundation response;
- Direct response and extended inundation until the new high flow period;
- Weak response between flow and inundation; and
- Phase lag between high flow and high inundation.

The type of flow-inundation response depends on many system characteristics, like topography, rainfall ponding and infiltration. Additional research should reveal why a certain zone has a certain flow-inundation response.

Figure 11-1: Example of differences in inundated area between dry- and wet period at the location where the Ghaghra river flows into the Ganga river.

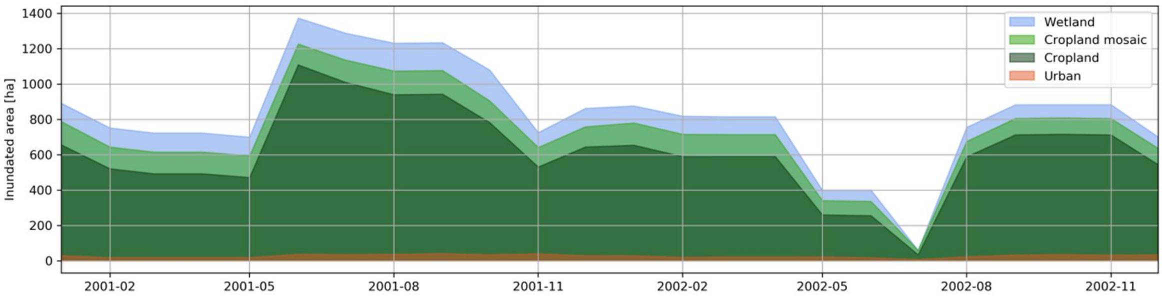

Figure 11-2: Inundated area per land-use category at the location where the Ghaghra river flows into the Ganga river.

However, it was not possible to derive reliable discharge inundation formulas for inclusion in the river basin model. The amount of cloud cover on the Landsat 5 and Landsat 7 satellites during the monsoon period hampered the detection of water and created distorted inundation dynamics. In the pilot, a moving average window of 4 months, based on 2 images per month, was deemed necessary during the cloudy monsoon season; this resulted in the delayed response and reduction of peak inundation. These formulations can be improved by including data from other missions like the ESA Sentinel 2 (since mid-2015) and NASA Landsat 8 (since mid-2013) or SAR (radar) missions such as the ESA Sentinel 1A/B mission (available since end-2014). Since radar can penetrate clouds, individual images can be considered. These recent options will provide more images per month which should help to clarify the applicability of discharge-inundation relations.

Unfortunately, this new data could not be used in this study since the river basin model only runs until 2014. Future studies should extend the time range of the model and could improve formulations based on these new satellite and radar images.

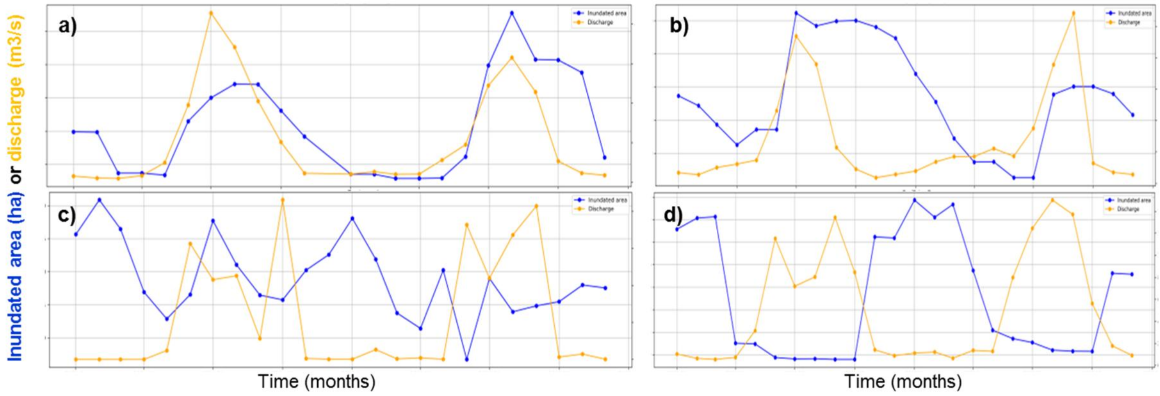

Figure 11-3: Different types of discharge–inundation relations that could be observed in the Ganga river basin. a) direct flow–inundation response, b) direct response and extended inundation until next high flow period, c) weak flow–inundation response and d) lag phase between high flow and high inundation.

11.2 Monitoring

Spatial and temporal resolution is important for improving e-flow assessments. *Table 11-1* summarizes the proposed set of monitoring parameters and suggestions for spatial and temporal resolution, expressed in specific measurable physical, chemical and ecological components.

In addition to the parameters, species and services to be monitored, data should be gathered on migratory pathways for fish and coupled to the current reachability of the eco-zones. Rather than monitoring all parameters in each zone, it may be more expeditious to focus on a combination of the highest impacted zones: the middle reaches of the Ganga and Yamuna; high value zones e.g. protected zones, natural parks, cultural sites; areas with river-dependent rural livelihoods.

11.3 Procedures and Responsibilities for Adaptation

Adaptive management is an iterative process in which stakeholders and river managers review the impacts on the river ecosystem and ascertain the possibilities and limitations of river regulation and water use. Adaptive management requires that monitoring results are analyzed and used to update river management. Ultimately, the environmental flow regime for the Ganga will be a societal choice based on balancing stakeholder interests. This means that stakeholders are to be involved in the adaptive management process.

Adaptive management will succeed if the process is institutionalized and ownership is accepted by the responsible stakeholders:

- **Communication** among stakeholders is crucial for implementation of strategies. It must be understood that strategies may not be definitive but will be strengthened and expanded based on new insights. It is important that all stakeholders, governmental, non-governmental and local citizens, have access to the strategies and related uncertainties when planning activities and investments;
- **Monitoring** is an ongoing activity. Agreement must be reached on how monitoring data are collected and processed. Data must be transparently available to ensure that the river management remains iterative;
- **Updating and expanding response curves** is also an ongoing activity. The existing response curves require updating and additional curves must be developed and

integrated into the model post-processing tool (see Deltares, 2018). It is advisable to monitor two full years before undertaking the first update;

- **Updating ecological flow assessment for scenarios and strategies**. As response curves are updated and new response curves created, the analysis presented in this report will bear repeating. If new scenarios and strategies are to be analyzed, the full modelling suite will need to be run; if not, only the E-flow post-processing requires rerunning;
- **Decision regarding adapting current management approaches**. The E-flow regime is a basin tool for all stakeholders. The impacts on other off-stream users such as hydropower and industries must be considered. As the assessments of scenarios and strategies become updated and possibly new strategies developed, the relevant stakeholders and experts must jointly agree on the need to adjust river management practices.

Table 11-1: Summary of important physical, chemical, ecological and socio-economic parameters to monitor in order to improve future E-flow assessments.

	Spatial and temporal resolution	**Important to**
Physical and chemical parameters		
Sediment distribution	At least at one location in each eco-zone, but preferably several samples over the lateral and longitudinal gradient, preferably once every several years.	Refine zonation, use response curves for *T. putitora, S. richardsonii* and *G. gangeticus*, can be used for newly created response curves
Cross sections	At least at one location in each eco-zone, but preferably several samples over the lateral and longitudinal gradient, preferably once every several years.	Refining of zonation and better prediction of water depth as input for response curves
Dissolved oxygen	Continuously at several locations in each eco-zone in different discharge periods	Refine response curves in combination with observed species to
Species and services		
Presence and abundance of species currently included in the E-flow assessment (Appendix A)	At several locations in each eco-zone in different discharge periods for at least several years in a row	Validation of response curves, creating new response curves by linking species occurrence to measured physical or chemical parameters
Presence and abundance of species that were selected during the stakeholder workshop (Appendix I)	At several locations in each eco-zone in different discharge periods for at least several years in a row	Creating new response curves by linking species occurrence to measured physical or chemical parameters
Riparian and aquatic vegetation	At several locations in each eco-zone in different discharge periods for at least several years in a row	New response curves, validation of inundation extent- discharge relations
Socio-economic river services	Inventory of actual use of river for human livelihoods and well-being, its importance in terms of number of people that makes use of this and the relevance to their livelihoods/the availability of alternatives	Improving existing response curves and/or developing new response curves.

Adaptive management of the Ganga river basin is the responsibility of water management authorities at the state and basin level. The authorities will involve other organizations with specific capabilities to collect and process data and to update the analysis. The key to success of Adaptive Management of the Ganga river basin will be the open dialogue with the many stakeholders and experts to discuss updated insights and to determine how best to adjust river management practices to meet the changing conditions of this vital resource, the Ganga river basin.

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Part C: Groundwater-Surface Water Interaction Assessment

13 Introduction

13.1 Objective

Groundwater plays an important role in the Ganga basin and, at greater than 70%, is the main source of irrigation water (Thenkabail et al., 2005). In addition, groundwater is also pumped for domestic and industrial use. The quality of health and the environment depends on the right quality and quantity of groundwater. For the responsible organizations to develop effective water plans and water management practices, it is necessary to understand the hydrologic system and the interaction of surface water and groundwater. A future-proof approach can only be realized if there is acceptance how the water system works by key organizations combined with the necessary technical skills.

At a world scale the Ganga river basin is one of the most deteriorated river basins. The basin's water system is over-exploited, mainly because of groundwater extractions for irrigation. The water system, shallow groundwater and river water, is highly polluted from overuse of fertilizers and other agro-chemicals (pesticides) and discharge of untreated waste water and industrial water. In the IWMI (2007) water scarcity study the Ganga river basin was classified as "economic water scarcity" indicating that water is available, but that access is limited.

A recent study by Richey et al. (2015) shows severe indications of physical stress. Renewable groundwater stress was quantified using satellite remote sensing based on gravity anomalies (GRACE). Based on this classification the Ganga basin is one of the most stressed basins in the world.

Earth Security Group published a Global Depletion of Aquifers index in 2016. The Ganga river basin had the following characteristics: (a) high recharge rate, (b) withdrawal vs. recharge is variable and, (c) the key pressure is water pollution.

Not only is groundwater quantity under serious stress, but also water quality is deteriorated by badly or untreated waste water effluent, industrial water discharges, and high fertilizer use. The related high nutrient contents of the river system cause ecological problems as evidenced by the development of a hypoxic zone in the Ganga delta area and the Bay of Bengal.

All these world scale analyses indicate that the basin is suffering serious water problems but there is no consensus as to which stress is the most important. At a country scale the Central Groundwater Board (2014) was less pessimistic about the groundwater state of the Ganga river basin; only the western, upstream part was considered "Semi-critical to over-exploited" (Figure 13-1).

Improving the understanding of groundwater-surface water interactions across the Ganga river basin is a project objective. By employing groundwater modelling/analysis and river modelling it is possible to assess the implications of changed surface water management on groundwater use.

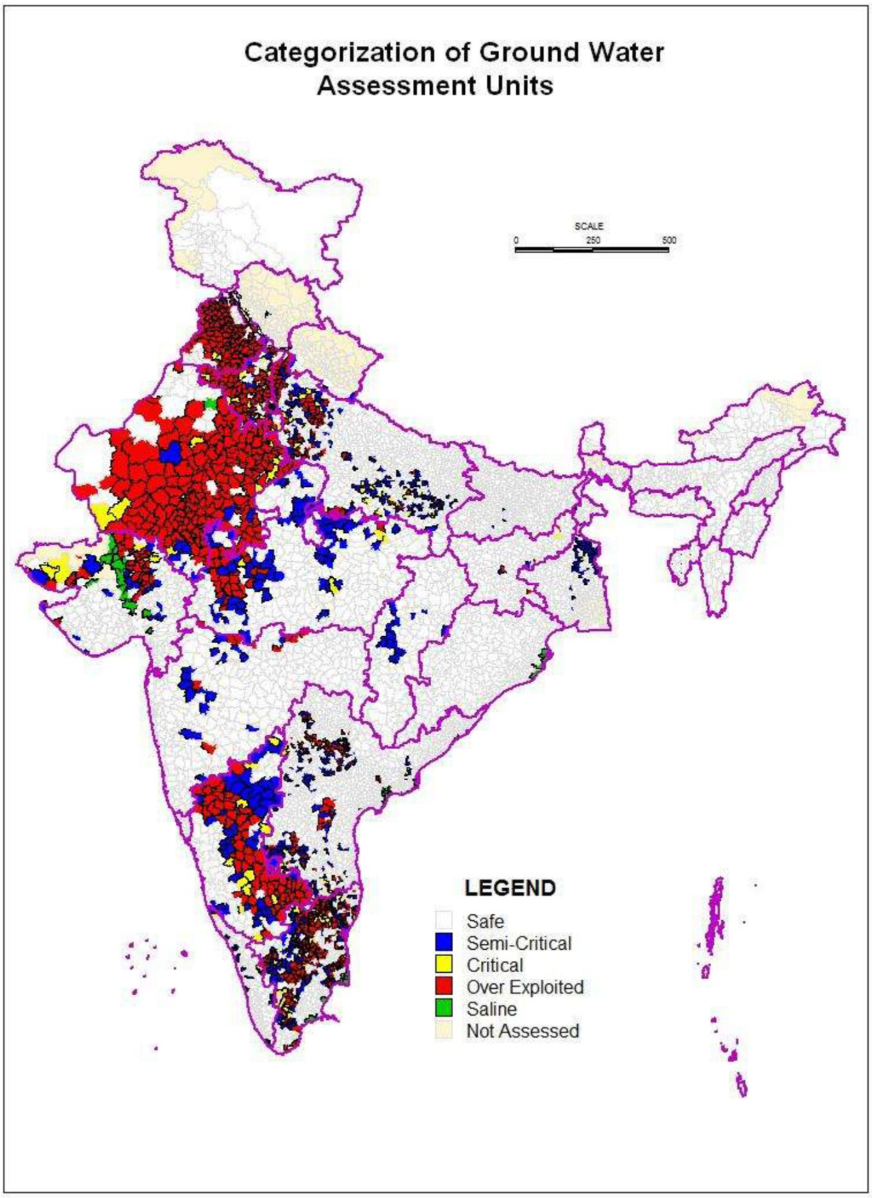

Figure 13-1: The status of groundwater in India (CGWB, 2014)

13.2 Methods

This study is focused on surface water and groundwater upstream of Farakka, and is based on:

- Groundwater Ganga river basin literature;
- Current and historical maps;
- The iMOD and Ribasim (Deltares, 2018) groundwater and river basin model study;
- Other existing model studies.

The water system, groundwater and surface water, is analyzed and described. Conclusions are drawn and synthesized into a general system description.

14 Regional Hydrogeology and Groundwater Situation

14.1 Physical Geography and Hydrogeology

Physical geography: Historical maps present an impression of the water situation from the late 1700s. Renel's map of 1794 (Figure 14-1) depicts a natural meandering network of numerous streams with most of the land devoted to agriculture. The map suggests bulging groundwater levels between the main rivers. Groundwater levels at the groundwater divides were considerably higher than river levels, indicating significant groundwater recharge by rain. Renel's map also shows a long, wet forest zone at the foothills of the Himalaya Mountains with numerous small streams and rivers originating from this area.

It appears that this area possessed a sponge function, creating longer time base flow conditions. The Ganga basin groundwater system completely changed after the construction of the irrigation canal system around 1854. Before this construction, groundwater was only recharged by rain and outflow from streams and rivers. After the introduction of the irrigation infrastructure, canal outflows and extra irrigation loss became important for groundwater recharge. In the second half of the twentieth century numerous deep wells were installed thus significantly increasing groundwater pumping and dramatically changing the groundwater system.

Figure 14-1: The historical map of James Renel (1794).

Hydrogeology: An analysis of hydrogeological information is summarized in Figure 14-11. A deep alluvial valley, including faults, lies between the Himalaya area in the north and the solid craton rocks in the south. The northern Piedmont Fan area and the covering Mega Fans form an important hydrogeological area. The coarse sediments of the Piedmont Fan, interfingering into the Alluvial plain deposits in a relative humid area with very high hydraulic conductivities, provide excellent groundwater recharge conditions with the possibility of recharging the deeper parts of the alluvial deposits at a regional scale (Figure 14-2). Similar but smaller circumstances exist at the transition zone of the craton and the Ganga plain. Groundwater management is critical to protecting these recharge functions for deeper groundwater and the ecological flow downstream.

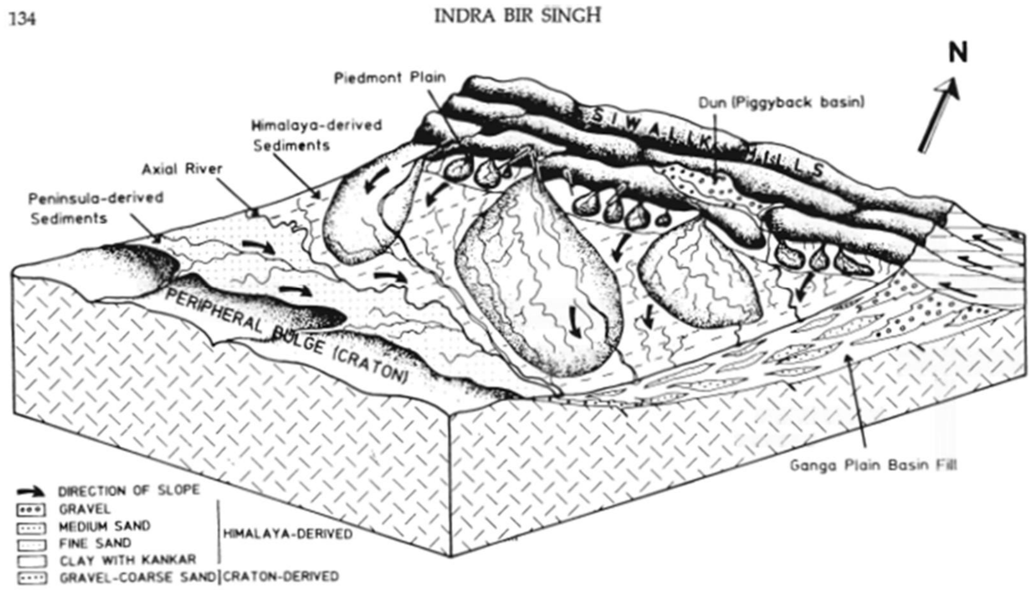

Figure 14-2: Distribution of main hydro-geological (geomorphological) units in the Ganga Basin: Piedmont Plain, Mega Fans, shallow and deep alluvial plain, southern marginal alluvial plain, southern craton (Singh, 2003).

Appendix K presents an extended description of the physical geography and geology of the Ganga basin.

14.2 Available Groundwater Information

In general groundwater descriptions are based on data of the CGWB groundwater monitoring network and groundwater models which were partly calibrated (validated) with these monitoring data. There exist little additional research results about groundwater age to validate groundwater flow models. The characteristics of the groundwater monitoring network are:

a. The entire Ganga river basin has 5745 groundwater monitoring wells (Figure 14-3), most maintained the CGWB and 303 by the National Hydrograph Network Stations (Government of India, 2014). Only 2186 observation wells deliver pre- as well as post-monsoon information. Most observation wells monitor shallow, phreatic groundwater. About 690 observation wells are so-called “lithology” wells meaning they observe aquifers of which 46 are exploratory wells, 635 observation wells, and 9 piezometer wells (Figure 3-15). Nearly half of the lithology wells are shallower than 50 meters (Figure 14-5). The spatial distribution of the deeper wells is very heterogeneous.
b. The density of the monitoring network is approximately 1 well every 250 km^2. In West-Bengal the density is higher, 1 monitoring well at 120 km^2.
c. Of the monitoring locations, 1839 observation wells produced time series suitable to validate/calibrate the groundwater model.
d. There is scant information to determine if the observation locations are representative. Various factors can impact the measurements. Especially land use around the

observation well, or distance to a surface water body such as a pond, canal, or river can have a large impact on the measurements. It is likely that most of the observation wells are located in or near cities and villages where urban groundwater can be influenced by local pumping and infiltration of waste water from cesspits.

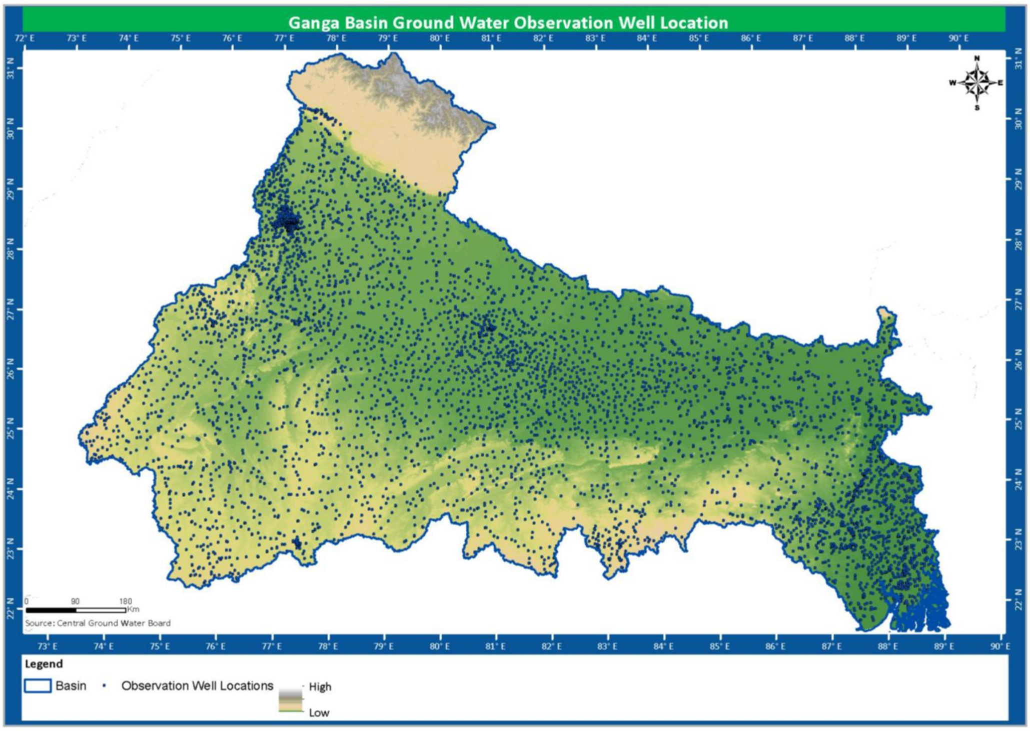

Figure 14-3: Location of ground water observation wells (India-WRIS Ganga Basin Report, 2014).

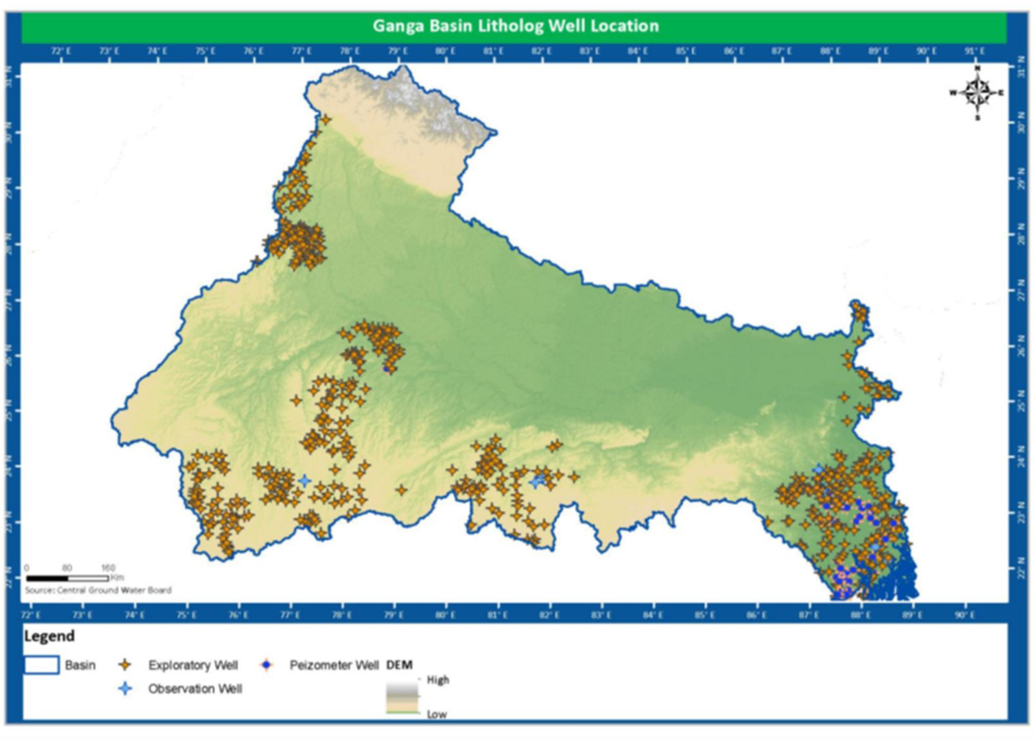

Figure 14-4: The heterogeneous distributed deep lithology well locations (India-WRIS Ganga Basin Report, 2014).

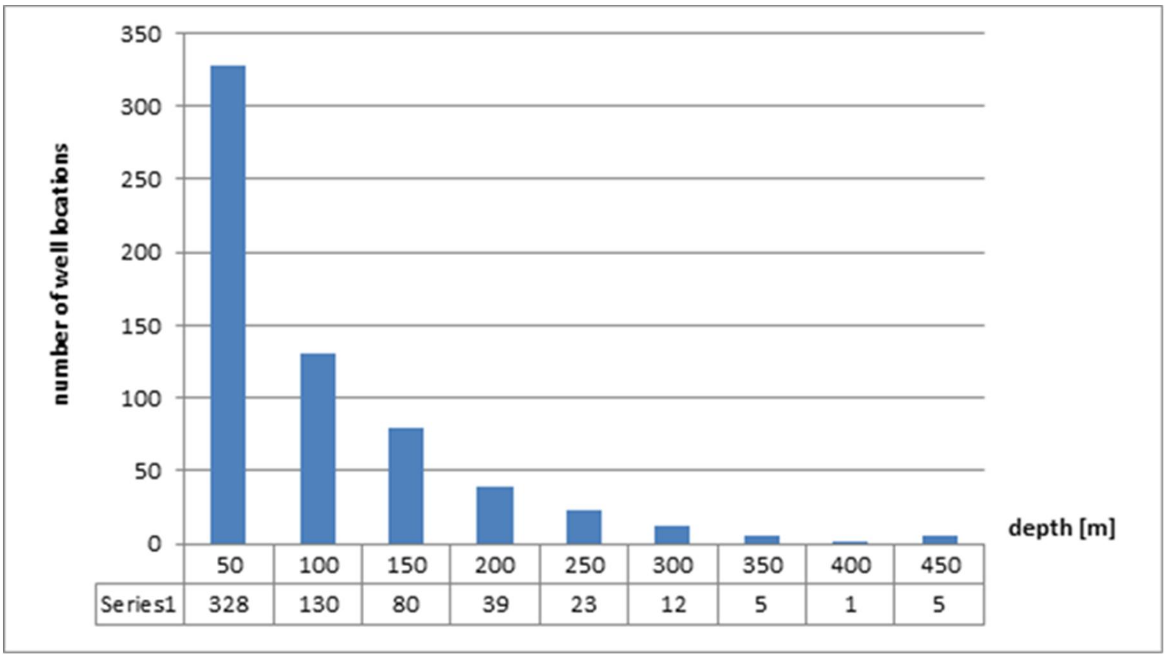

Figure 14-5: Depth distribution of Lithology wells (IIT, 2014).

14.3 Differences in Groundwater between Villages and Cities

Because of the lack of knowledge about the location and the land-use situation around monitoring wells, and our field experience that most observation wells are near or in villages and cities, in this paragraph we explain the difference between ground water recharge in rural areas and cities.

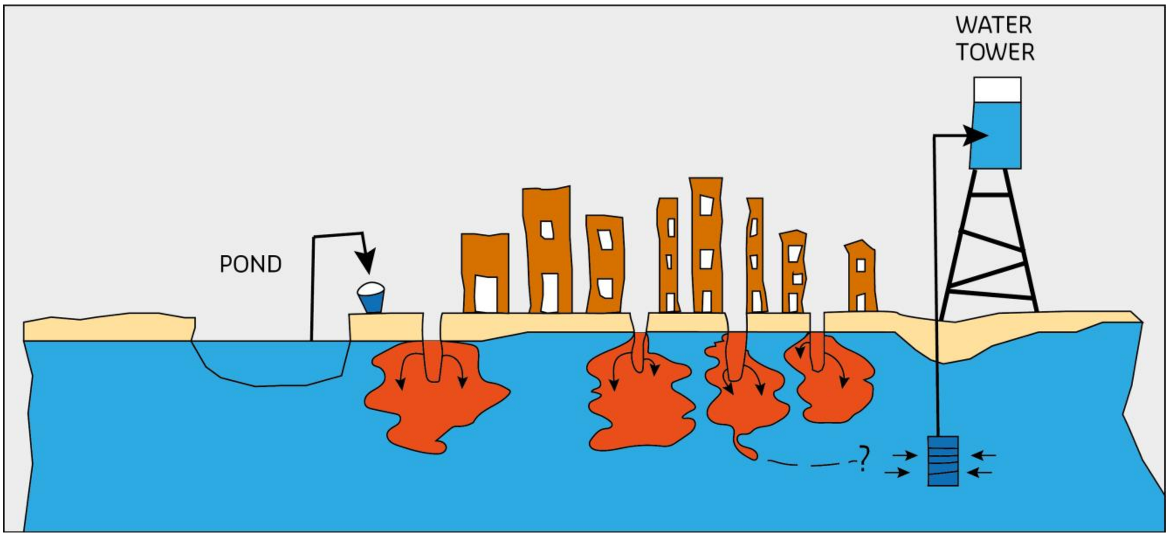

Figure 14-6: Domestic water and groundwater in a rural village. Groundwater is also recharged by waste water.

In smaller rural villages, the surface is still permeable and rain can infiltrate. Waste water is often discharged into the subsurface by means of cesspits, which in turn can pollute the drinking water (Figure 14-6). Many times, a balance exists between the amount of pumped groundwater and returned water after infiltration in cesspits. There are many examples where groundwater levels decrease after modernization of the waste water system because treated waste water is no longer recharging the groundwater but is discharged into the sea, rivers or canals.

The situation is very different in larger cities. The surface is usually impermeable because of constructions and pavement; rain is normally drained from the city. Waste water is often collected and transported to a waste water treatment plant or directly discharged into a drain or river. In addition to pumping for public drinking water supply, numerous private wells for drinking water and industry exist. Thus, cities are characterized by high groundwater extraction and low recharge. Only losses in the drinking water distribution systems may provide a small amount of recharge.

In the light of this analysis there is a serious need to evaluate the monitoring network. Monitoring wells must be labelled by land-use situation: (1) agriculture, (2) rural/villages (including village characteristics, e.g. sanitation situation, local wells, water use), (3) cities and (4) natural. Distances to local surface water, e.g. ponds and streams should be determined.

14.4 Shallow and Deep Groundwater Flow

A recent study by Joshi (2018) in the Ghaggar River catchment provided a better understanding of groundwater recharge and groundwater flow near the Himalayan foothills. In this area most groundwater is recharged by rain. Groundwater less than 80 meters in depth is relatively young and recharged locally; groundwater deeper than 80 meters is much older and is recharged in the fan area (Figure 14-7). These results support the earlier conclusion that the foothill areas and mega fans are important for the recharge of deep groundwater.

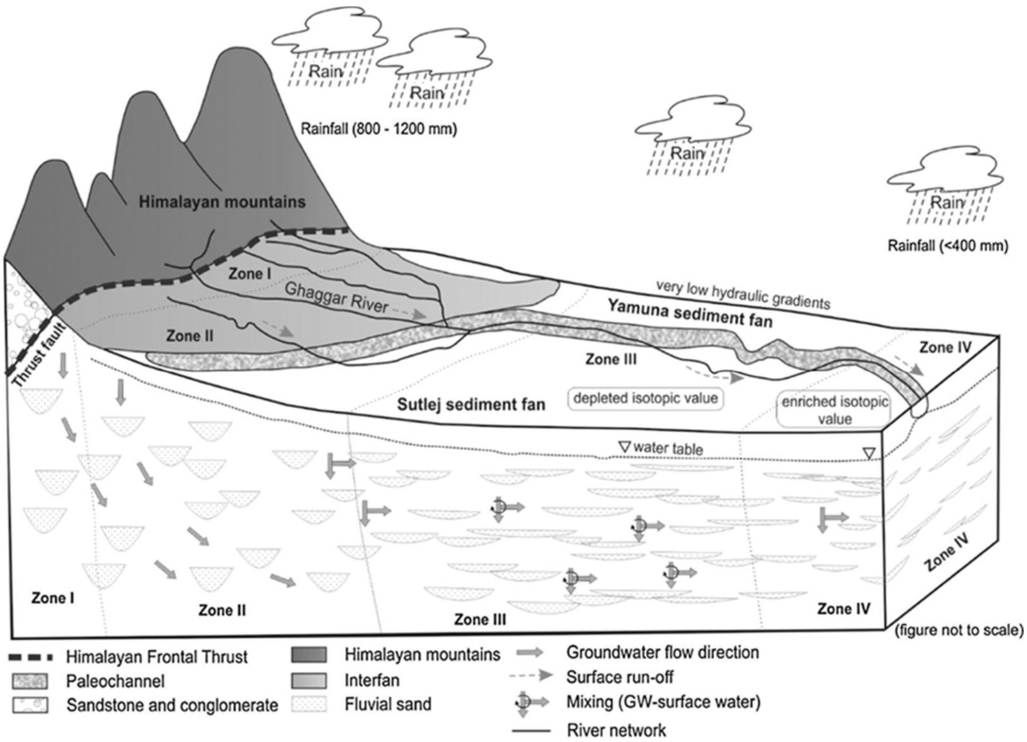

Figure 14-7: Groundwater flow based on isotope data (Joshi, 2018).

Understanding the relation between shallow and deeper groundwater was also studied by Taylor et al. (2014) in the Bengal Mega-Delta part of the Basin and by MacDonald et al. (2010) in the Indo-Gangetic Basin. In both studies the boundary between “shallow” and “deep” groundwater is defined at 150 m. MacDonald et al. (2010) concluded that excessive groundwater abstraction poses a great threat to the water quality of deep groundwater. Tayler et al. (2014) supports this conclusion of increased vertical leakage by deep groundwater pumping (increasing every year to support irrigation). In the Bengal Delta deeper groundwater is free of excessive arsenic and is threatened to become polluted by agriculture pollution. Both authors point out the lack of deep groundwater data. Therefore, Tayler et al. (2014) installed several deep nested (3 observation wells) to a maximum of 320 m. below surface. In general, little knowledge exists of groundwater deeper than 150 meters.

14.5 Modelled Groundwater Flow

Although the iMOD numerical groundwater model does not consider the deepest parts of the Ganga basin, it provides a good overview of the groundwater flow system. Figure 14-8 presents a groundwater level contour map indicating the groundwater flow directions. The map shows a general west-east flow direction, but also a south to north and north to south flow at the craton and foothill bedrock-alluvium transition zones respectively.

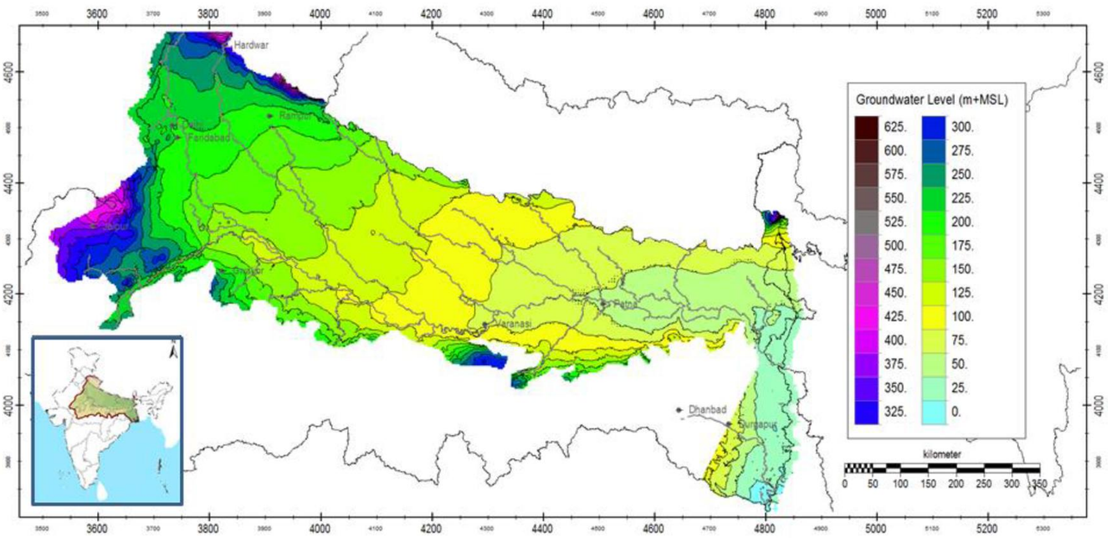

Figure 14-8: Location of the model area (inset after Sharma and Paithankar, 2014) and the resulting groundwater levels in m +MSL for 1st of January 2010 (Vermeulen et al., 2017).

Figure 14-9 shows a cross-section with calculated groundwater flow lines between the Himalaya and the craton area. The distribution of flow lines indicates that most of the recharge by rain, canals, rivers, and irrigation loss is captured by groundwater pumps. Most water remains in the zone up to 150 meters below the surface. The distribution also shows the recharge function of the northern Piedmont Fan zone; but the regional function for recharge of deeper aquifer is very small and not very clear. It seems logical that this recharge system is disturbed by the dense system of groundwater pumps.

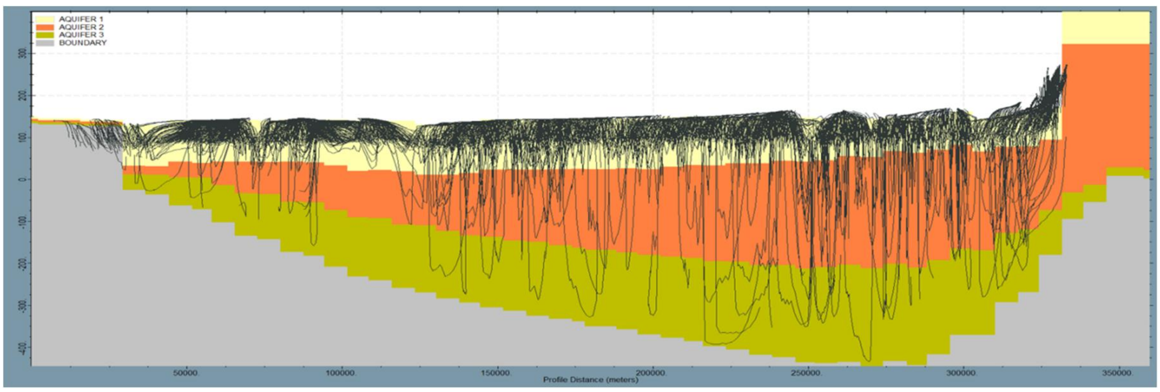

Figure 14-9: A north-south cross-section with calculated groundwater flow lines (iMOD).

Figure 14-10 presents the flow line calculations horizontally. The map shows that nearly all flow lines, starting at the surface, direct towards an extraction well. Between the surface and about 50-150 meters depth exists one large man-made groundwater flow system, partially re-cycling infiltrated-pumped groundwater. These modeling results correspond with the isotopes results from Joshi (2018).

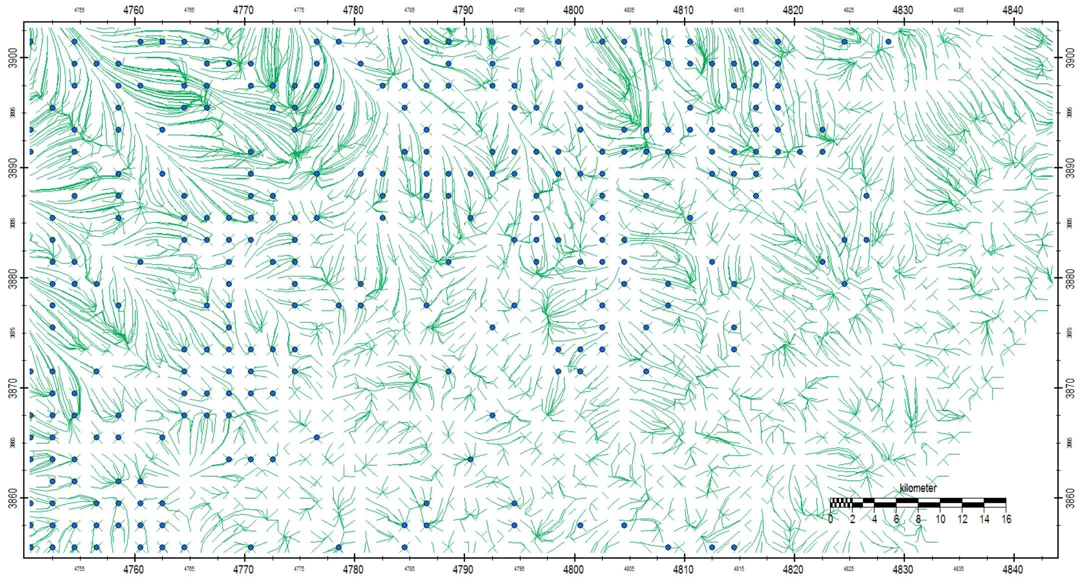

Figure 14-10: Groundwater flow lines: Note that lines starting at the land surface direct towards groundwater extraction wells.

14.6 Hydrogeology Conclusions

The hydrogeological information discussed in the foregoing paragraphs is summarized in a generalized regional hydrogeological model, see Figure 14-11. The figure shows the thick alluvial valley between the Himalaya area, including faults, in the north and the solid craton rocks in the south and the approximate depth of the hard rock basement. The northern Piedmont plain area and the covering mega fans form an important hydrogeological area. The coarse sediments of the Piedmont Fan, in a relative humid area with very high hydraulic conductivities, provide excellent groundwater recharge conditions, possibly also recharging the deeper parts of the alluvial deposits at a regional scale. At the transition zone of the craton and the Ganga plain similar but smaller circumstances exist. Groundwater management to protect these recharge functions for deeper groundwater is very important. As described earlier, there is little knowledge about the hydrogeological characteristics of the very deep and very thick layer of Proterozoic sediments between the alluvial deposits and the hard rock base of the alluvial deposits.

The groundwater flow information discussed in the preceding chapters is conceptualized in Figure 3.23. It seems clear that the Ganga basin groundwater system includes a relative shallow completely man-made flow system with a depth of 0-150 meters. In this system the water loss from rain, canals, rivers and irrigation is nearly completely pumped-up and used primary for irrigation. What does this continuous re-use system mean for water quality in the future? Most likely the total dissolved solids including pollutants of this shallow groundwater body will increase in time due to the continuous pumping-evaporation-infiltration cycle. Because of increased deep groundwater pumping this boundary, presently at approximately 150 meter depth, is expected to lower, and the quality of deep groundwater, which is still relative clean and often free of arsenic, will deteriorate by agriculture pollutants.

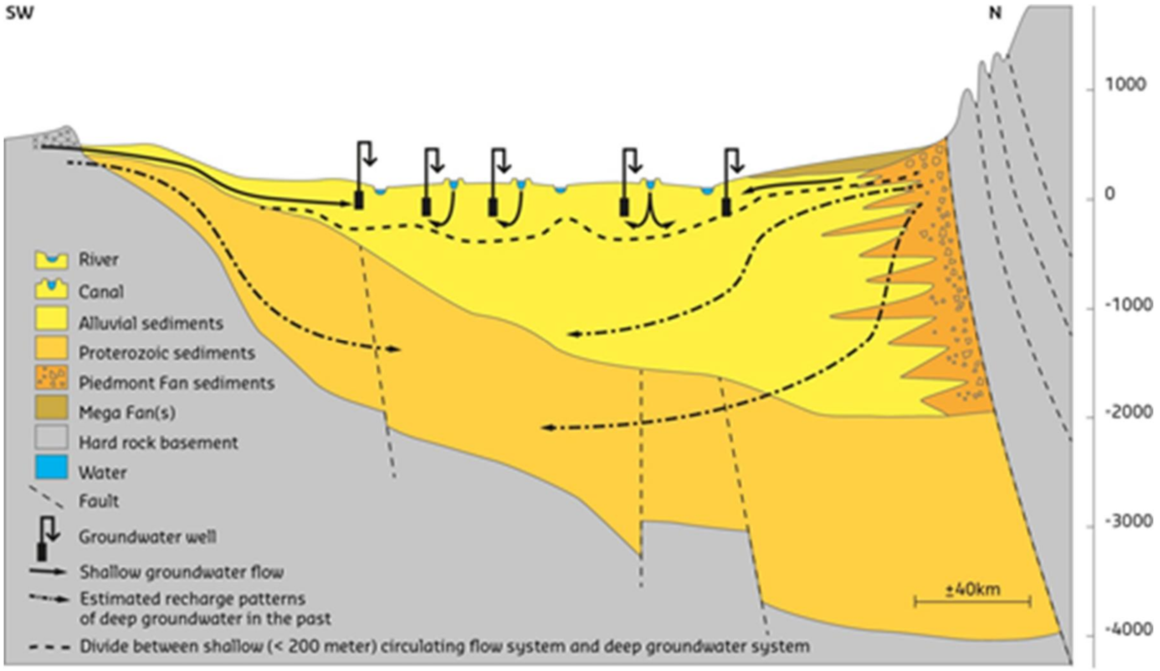

Figure 14-11: Conceptual geology and groundwater flow conditions in Ganga basin.

The northern Mega Fans and Piedmont Fan area, and the southern craton transition zone, are important for recharge of deeper groundwater, but it appears that this natural system is strongly disturbed by pumping. The deep oil and gas boreholes demonstrate that groundwater can be fresh at even 700 meters depth. There is no evidence that this groundwater is still actively recharged. This can be considered “paleo-groundwater” under the present recharge and flow conditions.

This leads to the following conclusions:
1. The shallow part of the Ganga river basin seems to be a completely man-made groundwater flow system. Nearly all water loss from infiltrating rain, rivers, canals and irrigation is pumped up again in groundwater wells;
2. The impact is of this recycling flow situation on groundwater quality is unclear;
3. The boundary between shallow relative young and deeper older fresh groundwater is at 80–150 meters depth and will move downwards because of increasing deep groundwater pumping;
4. The northern Piedmont Fan and mega fans are potentially important natural infiltration areas; however, the mechanics and efficiency of this system are unclear.
5. Groundwater flow at hundreds of meters depth is unknown. Flow will be low because of the very shallow gradients and present recharge conditions have not been determined.
   a. A number of issues regarding the groundwater flow system of the Ganga basin remain to addressed: What is the origin of deep (300–5000 meter) groundwater? Is the origin saline or fresh?
      i. Is deeper groundwater still recharged? And where?
      ii. Did this water body develop during wetter paleo conditions?
      iii. How can Isotope age data be extrapolated?
   b. If fresh water exists in deep groundwater, how can this water body be sustainably exploited? What are the main recharge areas of shallow groundwater, up to a depth of approximately 200 meters?

i. What is the importance of the Piedmont Fan area and the Mega Fans? How can the recharge functions be optimized and protected? Recharge by canal loss and irrigation loss is based on numerical approaches. How can model results be verified by groundwater measurement, e.g. use of isotopes?

15 Saline and Fresh Groundwater

15.1 Introduction

Salinization processes in the lower delta of the Ganga are an increasing and very disturbing issue (Gain et al., 2007). These delta problems are related to climate variations and to upstream water management decisions Lower Ganga flow into the delta increases salt intrusion of surface water. Upstream of Farakka salinity is problematic for agriculture, soil and health. Therefore, it is necessary to identify the extent of salinity in the basin before proceeding with further groundwater development or a change in management practices. The distribution and origin of brackish and saline groundwater of the whole basin is not completely understood; however, the CGWB has prepared a regional analysis for Uttar Pradesh (CGWB).

15.2 Inland Salinization Processes

Brackish soil water or groundwater can have many origins. It can be related to the natural climate and/or geology, but it can result from man-made alterations to the water system. In many of the world basins, the Mississippi and Rhine being prime examples, deeper geological deposits are of marine origin and after thousands to millions of years are no longer fresh. Sometimes parts of these basins are intruded by sea water causing groundwater salinization. In the Ganga basin upstream of Farakka, both these issues are lacking: the basin built up above sea-level and deposition took place by fluvial processes. No marine transgression has affected the Ganga plain foreland basin throughout its depositional history (Singh, 1996). Therefore, brackish or saline water has other origins. It should be noted that in most studies “salinity” is presented as Total Dissolved Solids (TDS) and is determined on the basis of Electrical Conductivity of water and by geophysical borehole measurements. As a result, “salinity”, a high electrical conductivity, is not necessarily “sodium chloride” related. The possible origins of salinity are described below.

a. Evaporate paleo-soils: This is the most likely explanation for saline groundwater at greater depths in the southern part of the basin. There may have been arid climate circumstances at the time of deposition, and water minerals in lakes and soils became concentrated by evaporation. Later these layers were covered by new sediments, and this process would repeat. Over time these salt deposits can be flushed, creating (vertical) density flow conditions and developing saline groundwater bodies. The more arid southern part of the basin was most vulnerable to this process. In modern times this brackish saline water can be activated by pumping, and even after use for irrigation can salinize shallow groundwater.
b. Active soil salinization: This process is similar to (a), but it is caused by human interaction with soil and water use. For example, water logging and irrigation in a strong evaporating environment often causes serious soil salinization. Drainage of these soils during the Monsoon period can transport these salts into deeper groundwater or surface water drainage systems.
c. Ion selective clays: Ion selective membrane processes are often mentioned as possible explanation of saline groundwater. Based on this theory clay layers act as ion-selective membranes and due to hydrostatic pressure minerals concentrate at one side of the clay layer (Neuzil, 2000; Shekhar et al., 2015).
d. Geochemical activity: When the sedimentation process was rapid, as in the late Pleistocene period, (Singh, 2003), minerals were less weathered and dissolved than during periods with slow sedimentation processes. Therefore, the “fast” sediment layers

can still be more geochemical re-active and develop high TDS water types. Where this is the dominant process, Calcium, Magnesium, and Bicarbonates are the main ions, not Chloride or Sodium.

e. Fractured bedrock: Because the ONGC deep boreholes show a thick body of saline water above the bedrock, the origin could be saline water stored in the fractured bedrocks caused by marine influences before the sedimentation phase of the basin development.
f. Faults: Although rare, another possibility could be of geological origin: fluids arriving from very deep transported by faults into the alluvium deposits.

15.3 Regional Distribution of Saline Groundwater

The electrical conductivity map of Figure 15-1 shows groundwater salinity classified in three broad categories:
(1) Fresh groundwater: less than 750 µS/cm;
(2) Slightly saline groundwater: 750 – 2250 µS/cm; and
(3) Saline: > 2250 µS/cm.

In the upper reaches of the Ganga river basin, groundwater is fresh. In addition, almost all areas between the Himalaya and the Ganga river have fresh groundwater. Almost half of Jharkhand and West Bengal have fresh groundwater while the remaining area has brackish water. Madhya Pradesh has fresh groundwater resources.

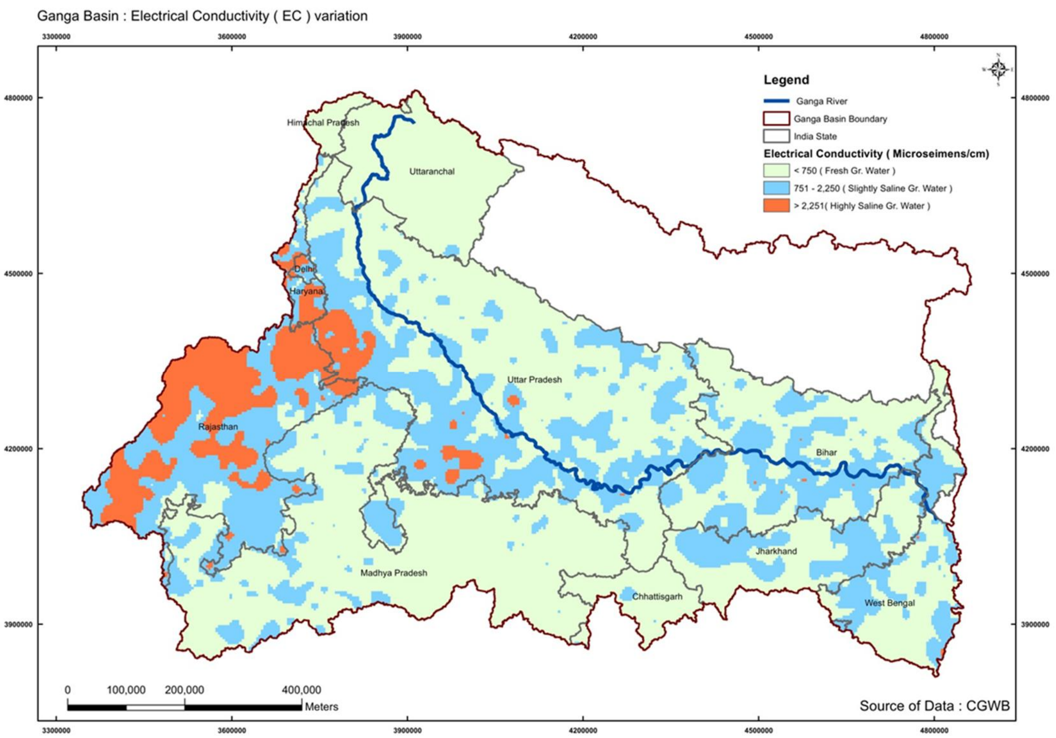

Figure 15-1: The groundwater electrical conductivity map based on CGWB monitoring network (CGWB).

Most of the western part of the basin, i.e. Delhi, Haryana, Rajasthan and the adjacent part of Uttar Pradesh, has highly saline groundwater. About 65 percent of the basin has fresh groundwater, 25 percent brackish, and 10 percent has saline groundwater.

15.4 Saline Groundwater in Deep and Very Deep Groundwater

Knowledge about the distribution of brackish and saline groundwater in the deeper aquifers improved considerately after the CGWB (2012) study of the inland groundwater salinity in Uttar Pradesh. Figure 15-2 and Figure 15-3 show the areal extent and depth of saline contours, supporting the earlier observation that saline groundwater is mainly distributed in the southern part of the basin. The cross-section (Figure 15-4) presents a better view of the vertical distribution of fresh and saline water. In this area saline groundwater can be found between 100-300 meters below the surface.

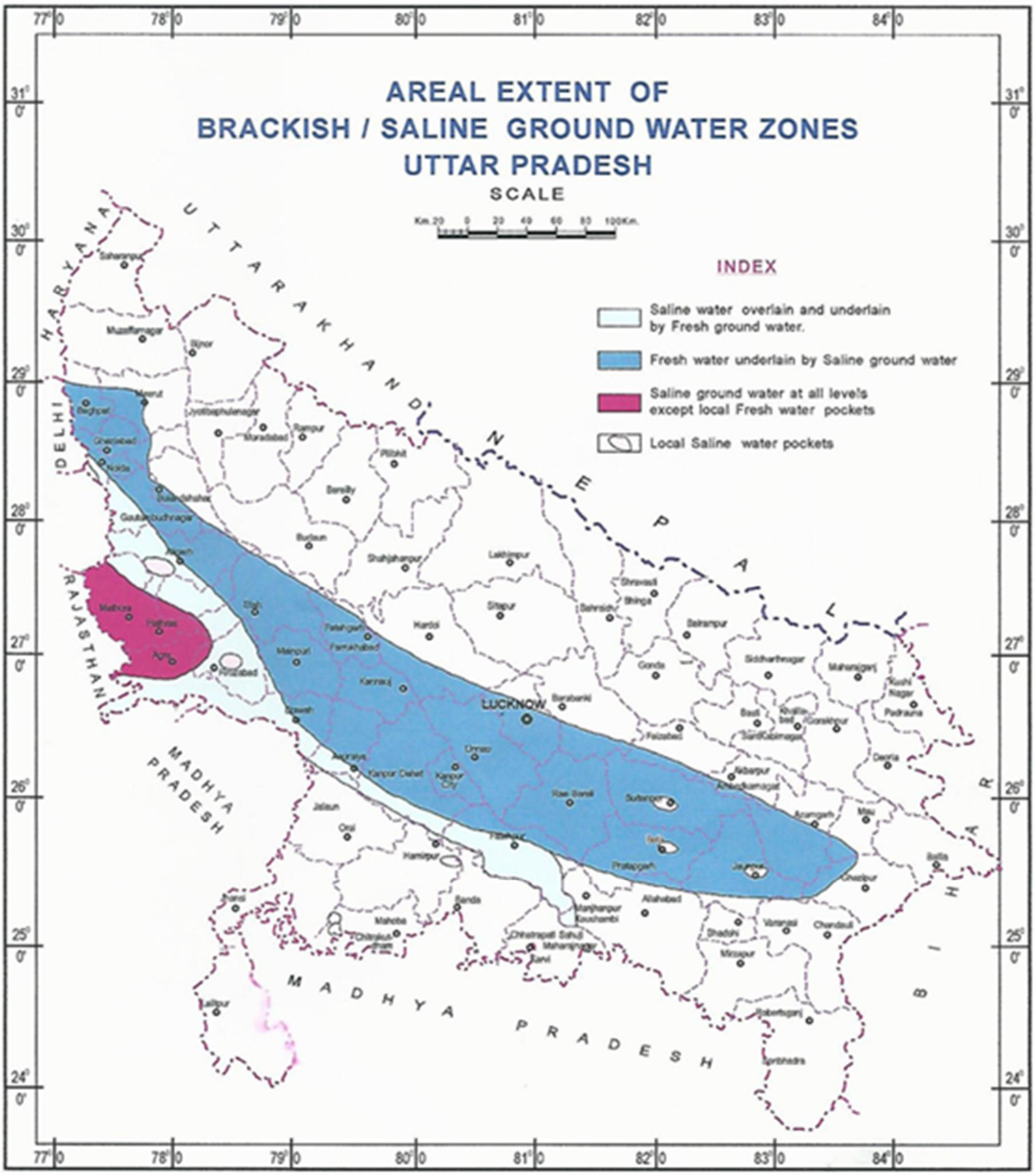

Figure 15-2: Inland groundwater salinity in Uttar Pradesh (CGWB, Trivedi & Chandra, 2012).

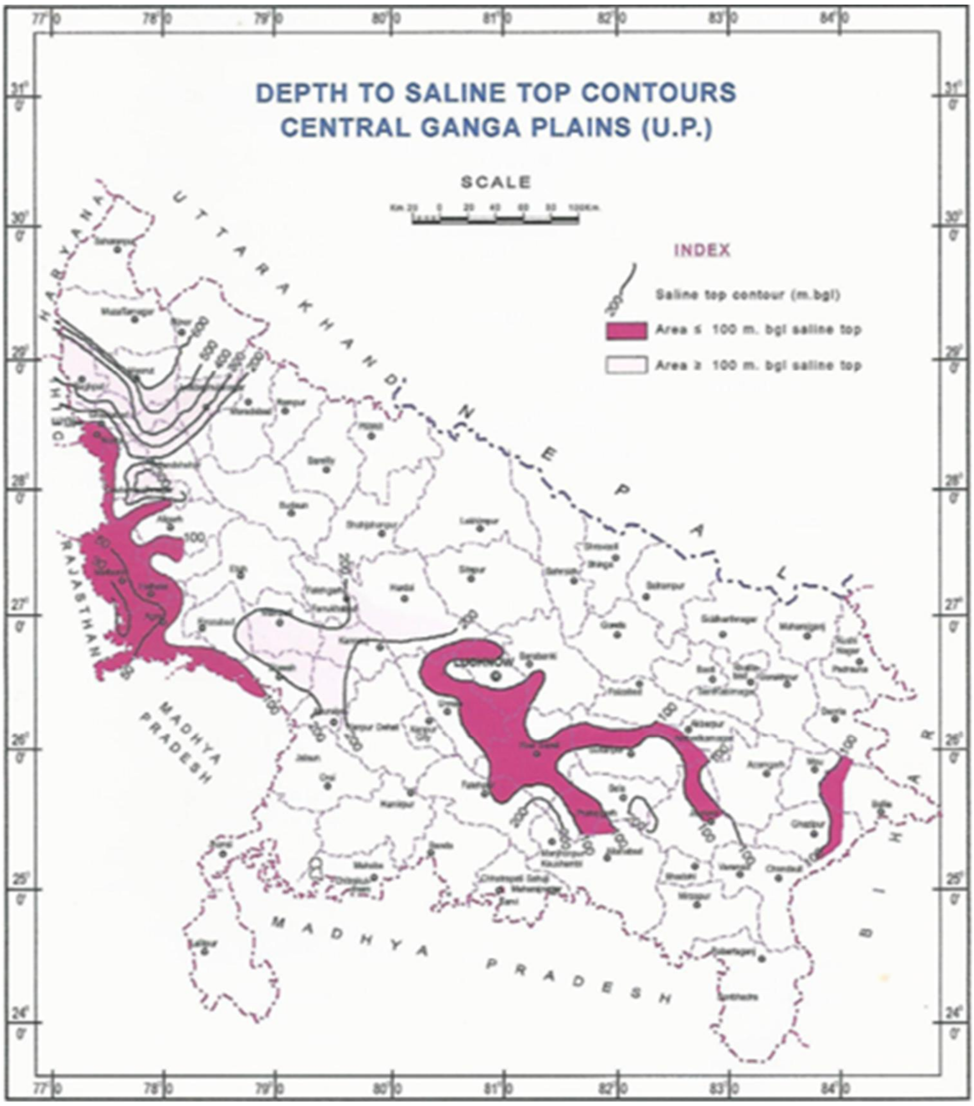

Figure 15-3: Depth to saline contours of Uttar Pradesh (CGWB; Trivedi & Chandra, 2012).

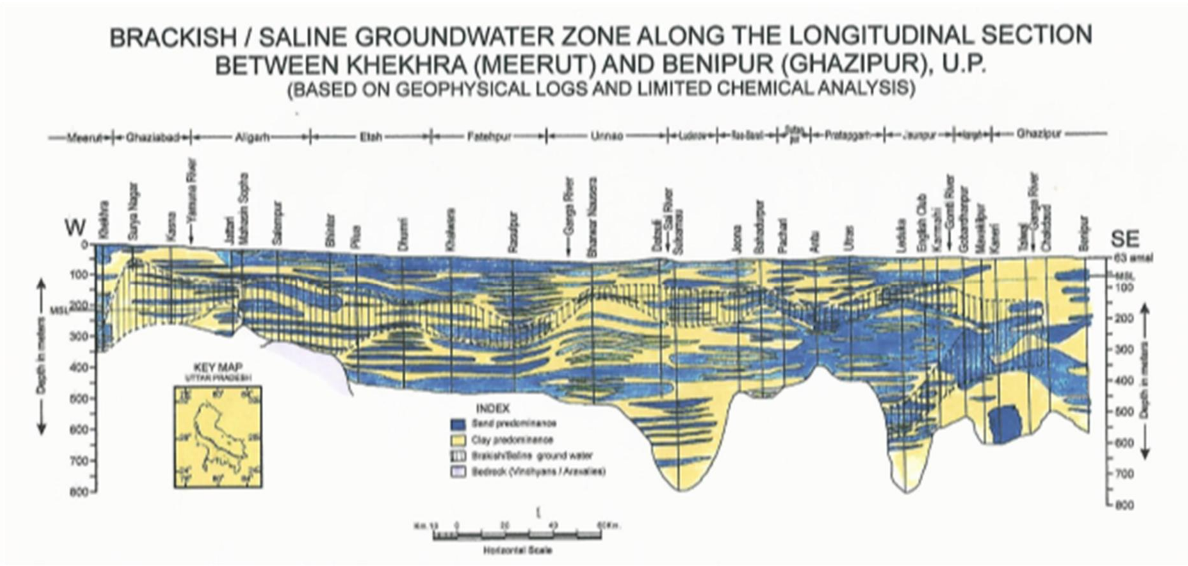

Figure 15-4: Cross-section with distribution of fresh and saline groundwater (CGWB; Trivedi & Chandra, 2012).

Little is known about groundwater deeper than 200-300 meters below the surface; therefore, information of fresh-saline groundwater interaction is minimal. A few ONGC deep boreholes provide additional information. Three very deep boreholes, Ganga Nagar 900 m, Rajasthan 840 m, Ujhani 1200 m, and Anola 1200 m show thick (550-700m) fresh groundwater bodies floating on saline water zones (Figure 15-5). Ujhani and Anola are near the Ganga river. These three results (figure 4-5) suggest the possibility of a saline groundwater body directly above the bedrock, but also the existence of a huge fresh groundwater body in the basin. Water samples of the deep saline water can increase knowledge of the interaction of fresh and saline water.

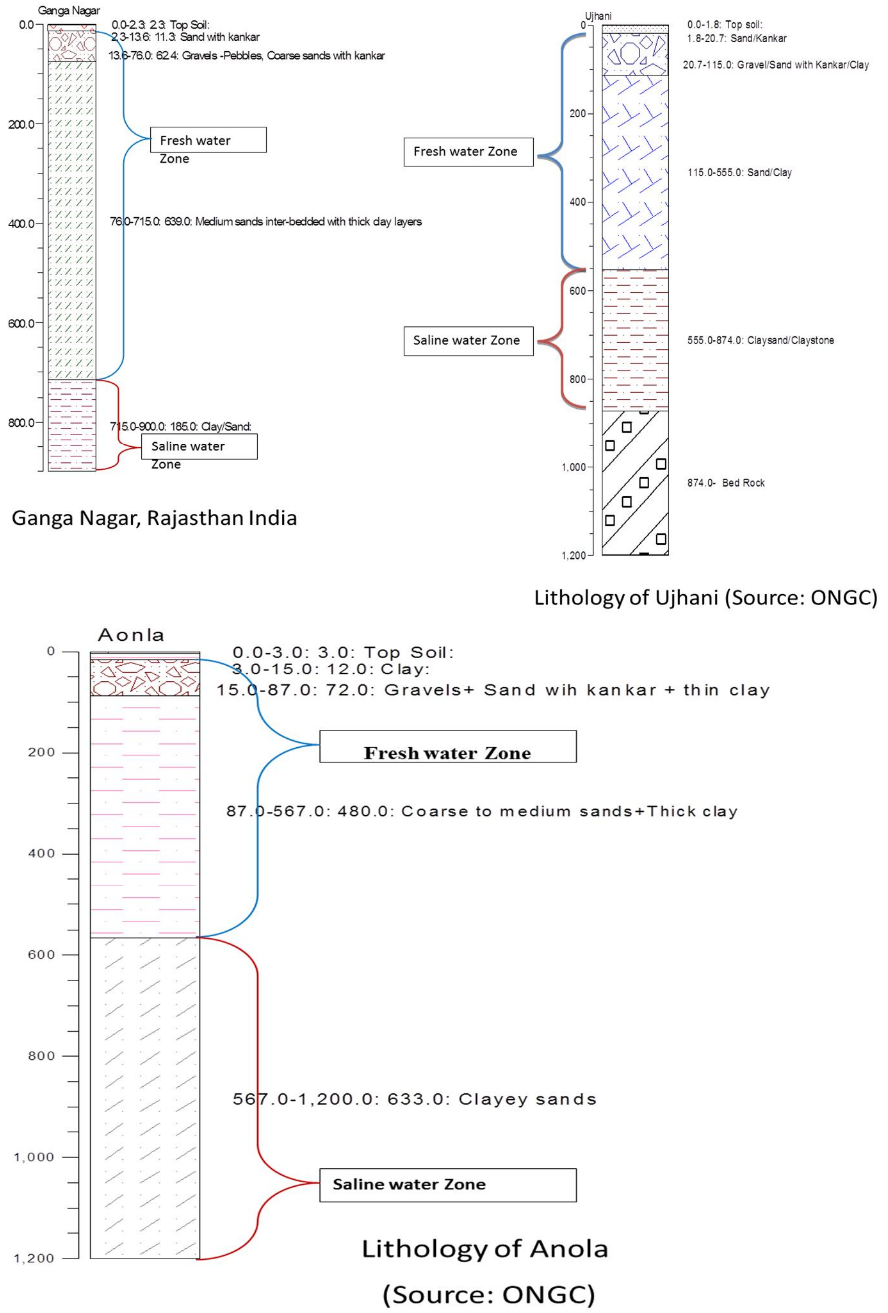

Figure 15-5: Fresh – saline groundwater interface in deep ONGC boreholes (ONGC/CGWB).

15.5 Fresh-Saline Groundwater Conclusions and Recommendations

The contours of the distribution of fresh-saline groundwater are fragmented. Only in Uttar Pradesh is the distribution mapped. A few deep borings also determined saline water at hundreds of meters depth. The genesis of this deep saline groundwater is not well understood because the basin deposits are not of marine origin, and the alluvial basin was never flooded with sea water.

Salinization in the Ganga river basin is a serious issue. In the western and southern part of the basin a huge volume of “shallow” (50-300 m) brackish or saline groundwater can be found. Fresh groundwater can be found above and below this saline water body. To achieve sustainable groundwater management, it is very important to understand the fresh-saline groundwater interaction during exploration:

- Because most ground water observation wells are relative shallow (<250 m) while the depth of the basin is several kilometers, little is known about the actual distribution and size of the fresh groundwater body, at a Ganga river basin scale, as well as at a depth scale.;
- A few deep boreholes show the existence of saline groundwater below the fresh water body at more than 500-700 m depth. Additional deep existing boreholes should be studied, and water samples should be collected to improve the knowledge base.
- The origin of salts is not well understood. Basin wide hydro-chemical and isotopes studies can solve this knowledge gap.
- Decreased Ganga discharge will increase salt intrusion of surface water in the Ganga delta area.

It is recommended to improve the knowledge on the distribution of fresh and saline groundwater. This can be accomplished by using helicopter electro-magnetic (EM) surveys and by studying existing deep borehole information or by installing additional very deep boreholes.

16 Groundwater Quality Considerations

16.1 Introduction

Groundwater quality is monitored by the CGWB with over 6,500 observation wells in the Ganga basin. Wells are to be monitored every year in April–May. The origin of this monitoring network is mainly drinking water related. The monitoring wells are mainly shallow dug wells, hand pumps, or springs. Most wells are located in an urban and rural villages environment making the monitoring results not particularly representative for understanding regional groundwater quality. Geogenic or “natural” pollution and man-made pollution are major factors affecting groundwater quality.

16.2 Geogenic Pollution

Arsenic, Fluoride and Uranium are chemical components of geological origin that occur in some regions of the Ganga basin at levels that make human use undesirable in those locations.

Arsenic

Arsenic is a natural constituent of the earth’s crust and is the 20th most abundant element. The average concentration of Arsenic in the continental crust is 1–2 mg/kg. Arsenic is released in the environment through natural processes such as weathering and volcanic eruptions, and the element may be transported over long distances as suspended particles and aerosols through water or air. Arsenic emission from industrial activity also accounts for widespread contamination of soil and groundwater environment.

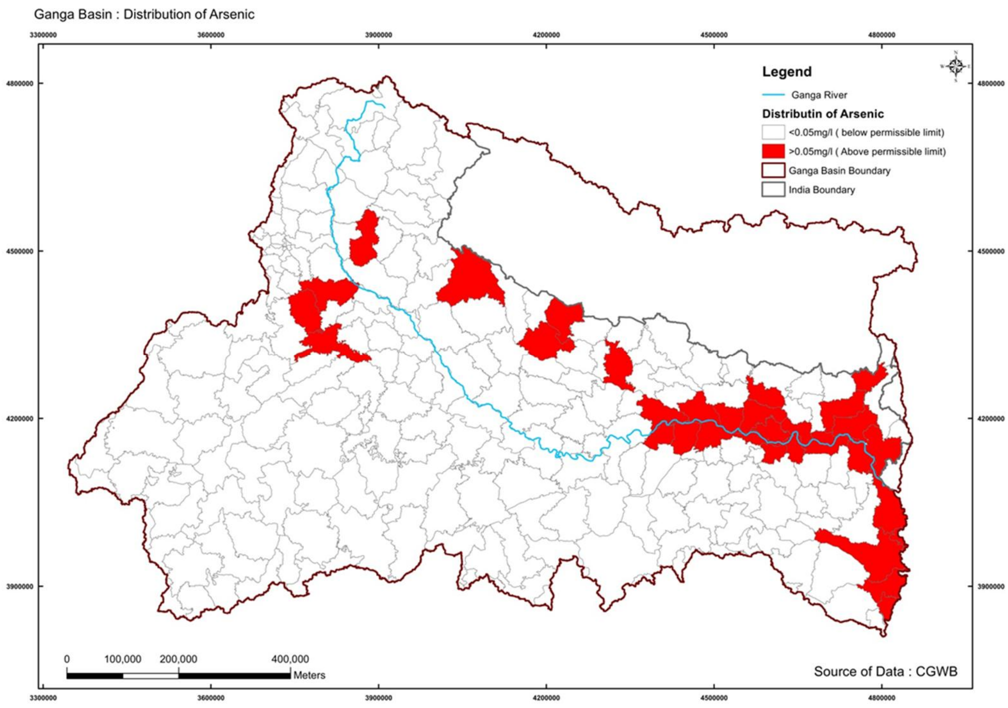

Figure 16-1: The distribution of areas affected with Arsenic (CGWB, 2014).

The Arsenic problem in groundwater was first recognized in West Bengal in the late 1980s and the health effects are now reasonably well documented. Long-term exposure to Arsenic from drinking-water and food can cause cancer and skin lesions. It has also been associated with cardiovascular disease and diabetes. In utero and early childhood exposure has been linked to negative impacts on cognitive development and increased deaths in young adults (WHO). More recently, the scale of the problem in other states with similar geology like Assam, Bihar, Uttar Pradesh, Tripura, Manipur, Arunachal Pradesh and Nagaland, has also been reported. The affected aquifers of the region are mainly Holocene alluvial and deltaic sediments (Singh, 2006), similar to those in large parts of Bangladesh. The distribution of Arsenic in the Ganga basin is depicted in Figure 16-1. The basin has been broadly categorized into two categories: districts where arsenic has been reported higher than the permissible limit (0.05 mg/l) and districts where it is reported below the limit. Most arsenic affected areas are located in West Bengal and Bihar along the Ganga River.

Recent estimates suggest that elevated concentrations of Arsenic exist in groundwater in nine districts of West Bengal, namely Murshidabad, Malda, Nadia, North Parganas, South Parganas, Bardhaman, Howrah, Hoogly and Kolkata. Nearly 50 million people living in 3,200 villages in nine of the total 18 districts of West Bengal, covering 38,865 km2, are exposed to drinking water containing Arsenic above 50 mg/l. Rice and vegetable fields irrigated by shallow groundwater receive a large amount of Arsenic in the affected districts of North 24-Parganas and Murshidabad in West Bengal. Hot spots of Arsenic contamination in the upper, mid and lower plains of the Ganga have also been reported in the Ganga–Ghaghra Plain, Ballia district, eastern Uttar Pradesh, Bhojpur, Buxar and Shahebganj districts, Bihar and Jharkhand situated on the western banks of the Ganga.

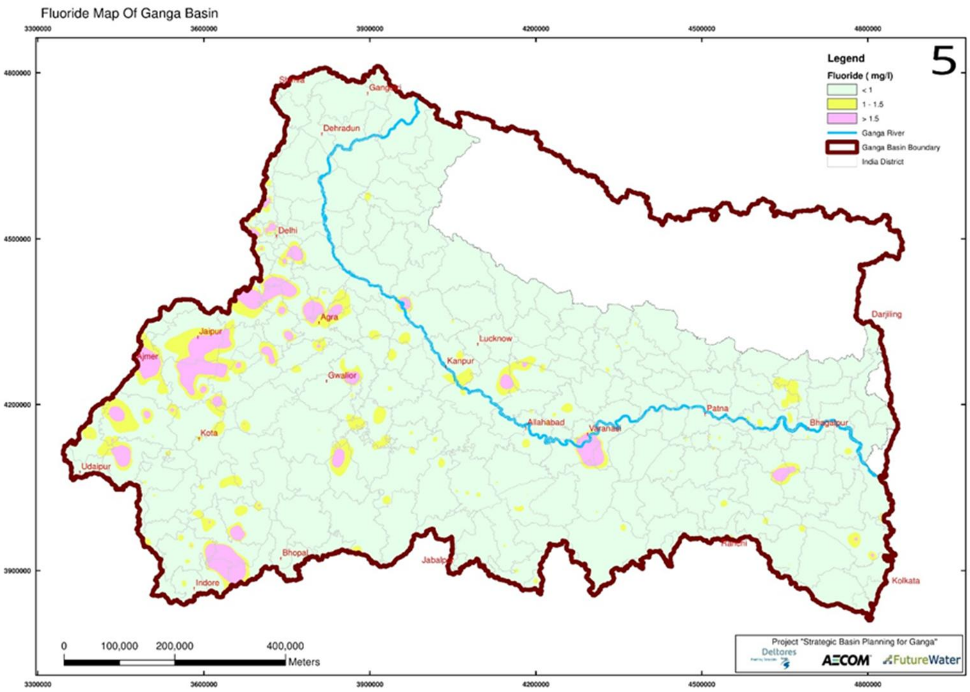

Figure 16-2: Distribution of Fluoride affected regions (data CGWB).

Although arsenic pollution is geogenic, problems arise when the water is used as a source of drinking or irrigation water. Especially rice tends to take up arsenic because of the anaerobic paddy soil culture (Food Standards Agency, Signes-Pastor et al, 2016). Irrigation supply by arsenic rich groundwater aggravates this process. Often, arsenic mobilization and pollution of shallow wells is related to manmade interferences like lowering water levels causing oxidation of arsenic-rich pyrites, creating reductive dissolution of iron hydroxides and releasing adsorbed arsenic induced by organic pollution, e.g. organic waste, fertilizers. Deeper aquifers in Bangladesh part of the Basin seem to be free of excessive arsenic (Tayler et al, 2014, Singh, 2006). Therefore, a better understanding of the spatial and depth distribution of arsenic, mobilized or non-mobilized, is needed to improve water management and/or land use strategies. For example, deep groundwater could be protected and used in the first place as strategic drinking water source. Rice paddies should be irrigated by water poor in arsenic.

Fluoride
Fluoride is another natural geogenic contaminant in groundwater that can create serious health problems. Fluoride concentrations more than 1.5 mg/L may cause dental and skeletal fluorosis. The map of Fluoride zones in the Ganga basin is given in Figure 16-2. The map shows the areas where groundwater has concentrations below the desirable limit of 1 mg/L, between the desirable and the permissible limit of 1,5 mg/L, and areas above the permissible limit. In general, the western parts of the basin, especially Rajasthan, are most affected by Fluoride. Aside from this Fluoride “hot spot”, only about 10 percent of the Ganga river basin is affected by high concentrations of Fluoride.

Uranium
Coyte et al. (2018) recently discovered that groundwater at many sample sites in the Ganga river basin exceeds the permissible standard for Uranium (> 30 microgram/L, WHO standard). The main source of the Uranium contamination is natural, but human factors such as groundwater table decline, enhancing oxidation, and nitrate pollution may be exacerbating the problem.

16.3 Groundwater Quality Changes by Human Activities

Groundwater quality is affected by several human processes. The most important are:

- The use of agro-chemicals including fertilizers and pesticides in agriculture areas;
- Infiltrating polluted water from rivers and canals;
- Urban pollution: leaking sewer pipes, cesspits, oil, polluted runoff, also causing changes in the redox or pH situations and therefore affecting dissolution of natural minerals like Arsenic;
- Industrial pollution;
- Anthropogenic polluted dry and wet deposition.

The Ganga river basin uses fertilizer amounts similar to intensive agriculture areas in the EU and USA (Potter et al., 2010). With the increasing frequency of harvests per area during the last decade, fertilizer use is rapidly growing. Because fertilizer use cannot be optimized in a way that no nutrients will be lost, high amounts of nutrients enter the rivers and the groundwater. The CGWB water quality monitoring program with observation wells up to 100 meters in depth indicates that groundwater is polluted or strongly influenced at many locations. Samples indicate that the pollution threshold is frequently exceeded. The CGWB records lack sampling information: type of well, depth of filter, land-use around the well, distance to the nearest surface water body; without such basic data interpretation of results is difficult. Also, knowledge about the origin of groundwater is not available, whether it is infiltrated rain water, infiltrated canal or river water, or infiltrated irrigation water.

Elevated levels of Dissolved Organic Carbon, Nitrogen, and Phosphorus are the main cause of poor water quality and loss of aquatic habitats in the Ganga river basin (Trivedi, 2010). Waste water discharges, including domestic waste and sewage, effluents from commercial and industrial establishments, and urban run-off, combined with agricultural run-off and aquaculture waste which may also contain fertilizers, are major threats in terms of nutrient pollution. This damages not only biodiversity but also human health through illnesses contracted from contaminated water. There may be a loss of income generated from tourism and fisheries because of poisoning and/or mortalities of fish and invertebrates resulting from the biological degradation of organic matter which can lead to hypoxia and anaerobic conditions.

Nutrients such as Nitrogen and Phosphorus encourage algal growth that may smother corals and cause algal blooms; dead hypoxic zones may be created in the delta and Bay of Bengal.

16.4 Vertical Groundwater Quality Zoning

Based on the existing information, and without considering geogenic pollution, a general vertical zoning of main water types can be drawn (Figure 16-3). Mapping and analyzing the distribution of these water types will increase understanding of the groundwater flow system.

The following general water types can be classified, from surface to bottom (Figure 5.4):

- Polluted groundwater: this water type possesses at least one chemical parameter that exceeds a chosen threshold, e.g. WHO drinking water. The depth of this zone differs according to flow situation and pollution load. Even in areas with natural vegetation a shallow polluted zone can develop because of dry/wet deposition and soil acidification;
- Anthropogenic influenced groundwater: this water type clearly shows anthropogenic influences, but these do not exceed standards;
- Pristine groundwater: this water type is without any human influence and can be found at greater depths, but also in groundwater discharge areas;
- Brackish-saline groundwater: in general, this water type can be found below the pristine zone. In the Ganga river basin this water type can also be found as “isolated” water bodies surrounded by fresh water due to dissolution of local/regional salt sediments, i.e. evaporates, paleo soils.

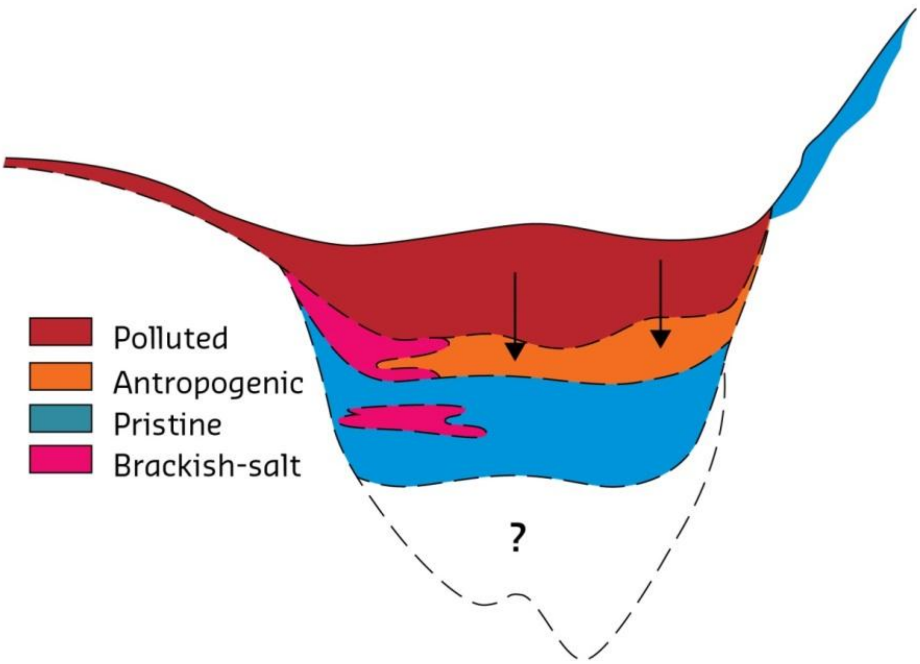

Figure 16-3: A general picture of the distribution of groundwater types in the Ganga river basin.

16.5 Conclusions and Recommendations

Groundwater quality is threatened at a regional scale by man-made pollution, as well as by natural geologically induced concentrations of Arsenic, Fluoride, and Uranium. The spatial distribution of pollutants is unclear. This is related to the distribution, in space and depth, of water quality observation wells. Nearly all samples show anthropogenic influence. Nitrates are also found in deeper groundwater. The data support the conceptual groundwater flow idea of an active, circulating (groundwater pumping-irrigation-infiltration of irrigation water-groundwater pumping) flow system in the upper 100-150 m. With depth information of the existing monitoring wells and information of water quality and isotopes data from deeper wells this zoning theory can be improved. Most likely this irrigation circulation system will decrease groundwater quality over time. The boundary between anthropogenic and pristine groundwater will move downwards when pumping of deep aquifers increases (Tayler et al. (2014) and MacDonald et al. (2010)).

Whether present monitoring is suitable for an assessment of groundwater quality is uncertain. Most observation wells are in cities or villages and often demonstrate the impact of urban pollution, including infiltrating waste water. Interpretation of existing monitoring data can be improved by additional data collection: (a) distance from canals/rivers, (b) land-use around the well (Ø 25 m. Ø 100 m), (c) irrigation type, (d) pumping discharge.

To effectively monitor groundwater quality, it is recommended to rationalize the monitoring network based on criteria such as: land-use, soil type, geology, irrigation situation, groundwater flow situation whether infiltration or seepage, and aquifer depth. The spatial distribution of monitoring locations, both horizontally and vertically, should be improved to support water management strategies. A base-line hydro-chemical assessment of deep groundwater is needed considering the local high Uranium contents recently discovered in northern India.

17 Regional Groundwater Water Balance

17.1 Introduction

Figure 17-1 summarizes all water balance terms in the agriculture area. It should be noted that these water balance terms are strongly variable during the year. Rainfall (P) is only significant during the monsoon period, but evapotranspiration (ET) occurs during the entire year. Therefore, calculating "precipitation surplus" (PS=P-ET-OF) is a very difficult task. Overland flow (OF) towards the drainage system can be considerable during the monsoon period; during that time the storage capacity in flooded rice paddies is very low and a high volume of rain water will be drained and discharged into the rivers. More than 80 percent of the total Ganga discharge is produced during the monsoon period. Better, alternative methods to determine PS are the use of lysimeters or tracers and isotopes. The recharge of shallow groundwater is also very dependent on canal loss and irrigation loss. The recharge of groundwater into the deeper aquifers is "total shallow recharge minus groundwater drainage" and will partly be influenced by groundwater pumping. The following water balance terms can be distinguished:

- direct overland flow (O.F.) into drainage system;
- shallow soil and subsurface recharge by rain (precipitation surplus (PS) = rainfall minus evapotranspiration);
- shallow soil and subsurface recharge by infiltrating surface water (canal loss or river loss);
- shallow soil and subsurface recharge by irrigation loss (I.L., sources: groundwater, surface water);
- aquifer groundwater recharge (total shallow soil and subsurface recharge minus drainage into surface water system);
- groundwater pumping.

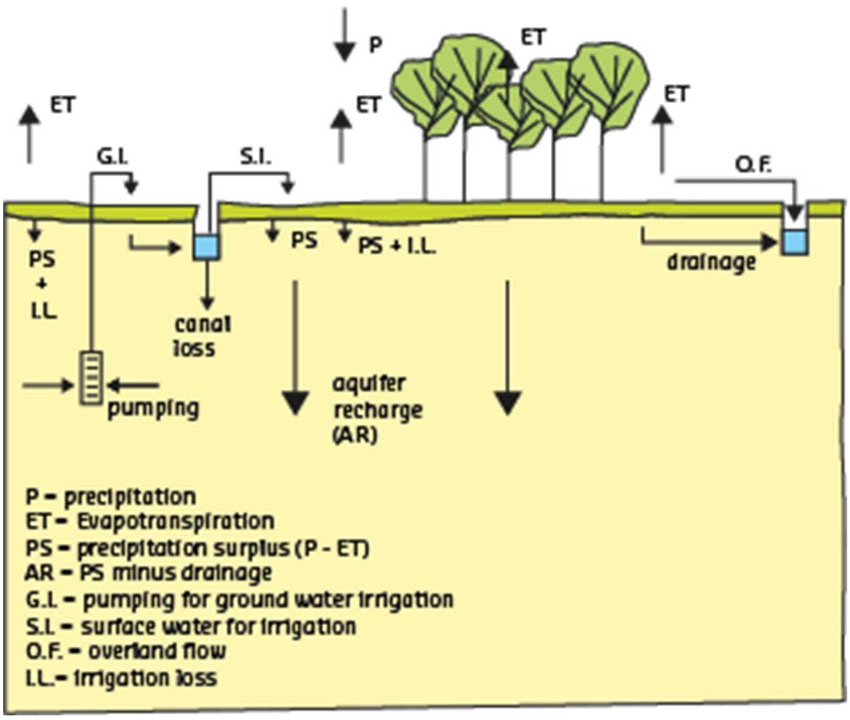

Figure 17-1: Water balance terms in agriculture area.

Climatically, the basin area is semi-arid to sub-humid and experiences three major conventional seasons. The three seasons are: Summer season, which starts from March and extends up to the month of June. Monsoon season which starts vigorously by the end of June and continues up to September. The eastern part of basin receives monsoon rains by second week of June whereas monsoon rains don’t reach the eastern part of the basin, i.e. Haryana and Rajasthan, until the end of June or in first week of July. Winter season in the basin starts in October and continues up to February. Indian Meteorological Department (IMD) has further sub-divided the winter season into two: the season of retreating monsoon from October to December and the cold season starting from January to February. These seasonal variations in the area have been broadly based on rainfall and temperature in different months at different places and altitude variations. Figure 17-2 presents the rainfall distribution. Rainfall significantly increases with rising elevation in the northern Himalaya area whereas the yearly rainfall amount decreases in the western part of the basin.

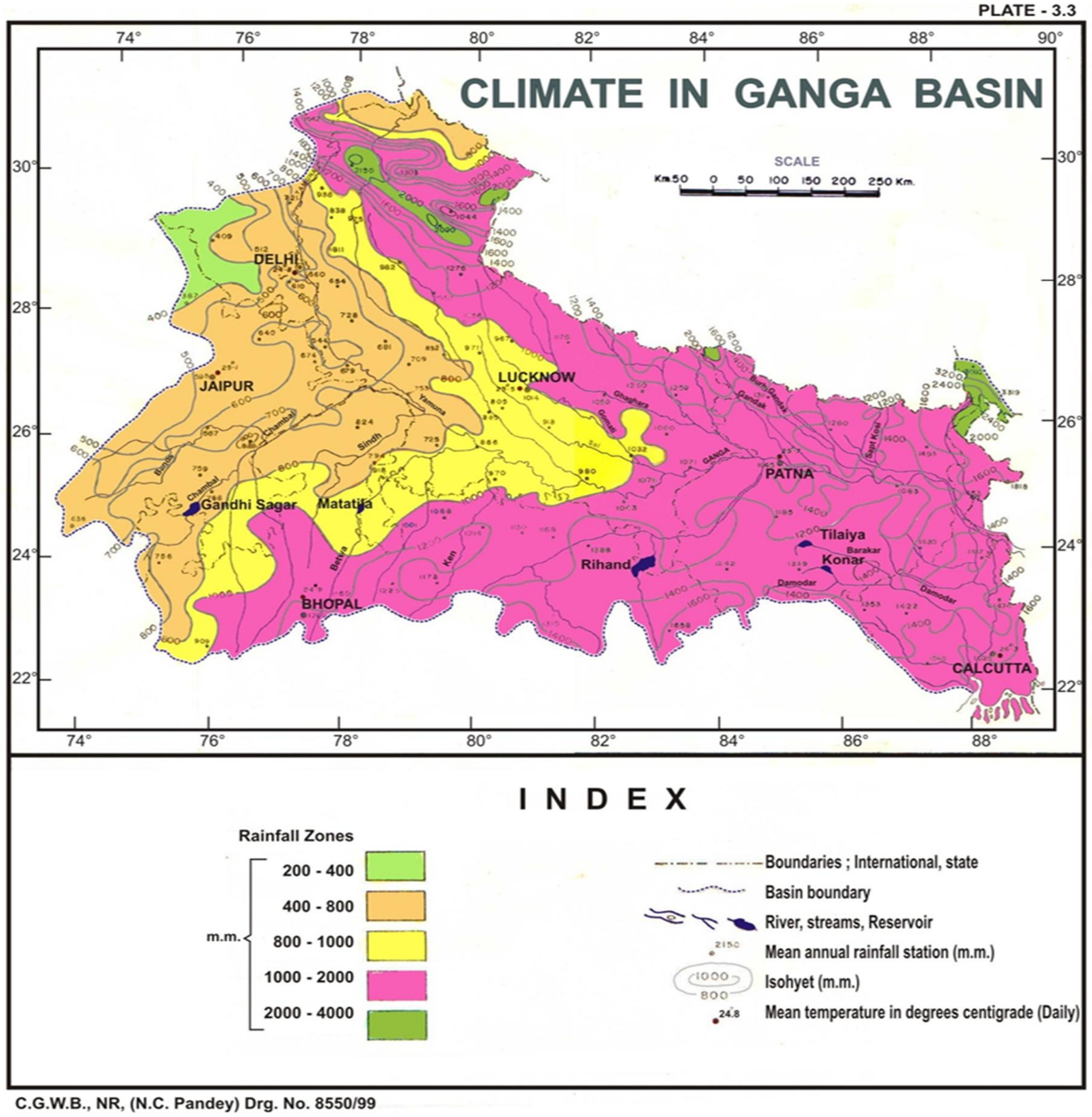

Figure 17-2: Rainfall distribution (CGWB, from IIT, 2014).

17.2 Precipitation Surplus and Groundwater Recharge

Estimating groundwater recharge in this monsoon system is rather difficult. On a yearly scale, evapotranspiration is much higher than rainfall during the monsoon period.

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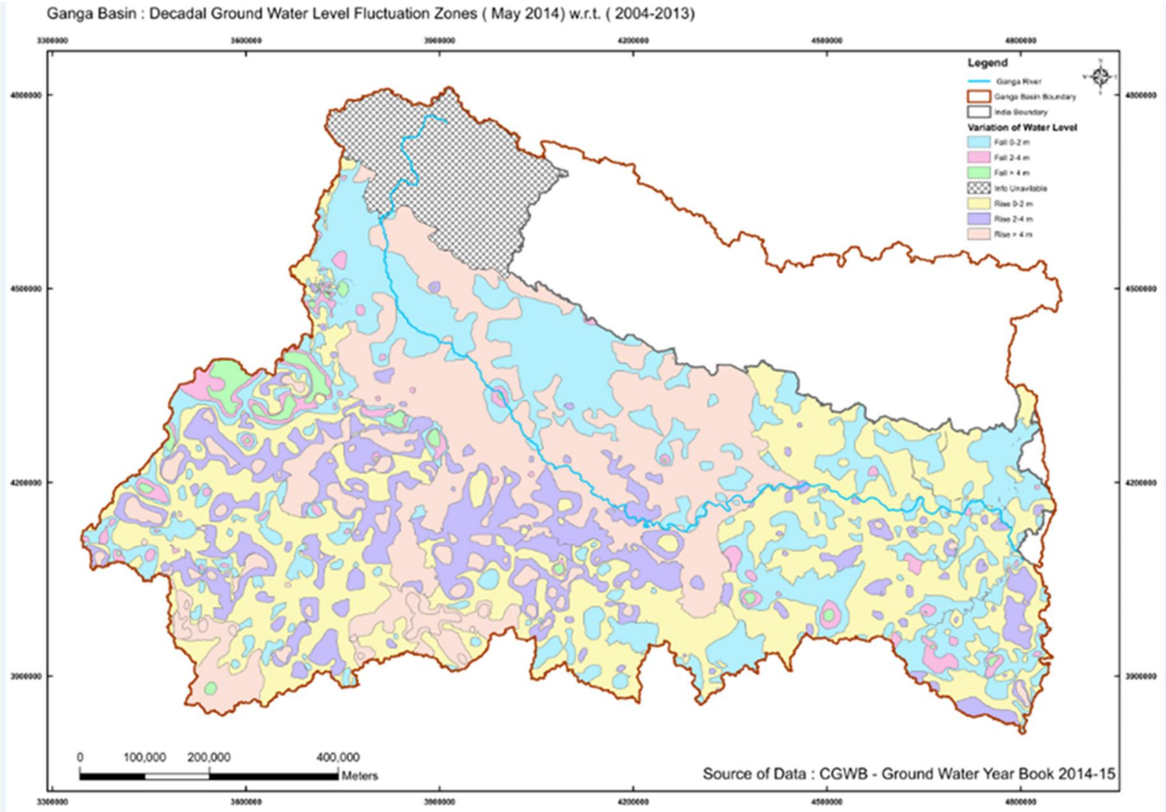

Figure 17-3: Groundwater level variations (CGWB, 2014).

The Central Groundwater Board and the British Geological Survey produced a series of groundwater recharge maps: Figure 17-4 – Figure 17-7 (CGWB, 2014; Bonsor et al, 2017)). Based on analysis of seasonal and yearly fluctuations in CGWB groundwater monitoring data (Figure 17-3), all recharge sources, e.g. rain, canal and irrigation loss, were included. The estimated groundwater storage fluctuations were translated into recharge estimates. The maps suggest high recharge in general and the BGS calculates very high recharge in the western part of the basin, the area with the lowest rainfall, but with an intense network of irrigation canals and groundwater pumps. There are inconsistencies in the BGS and CGWB results, thus suggesting a need to evaluate the methodology.

BGS uses the CGWB monitoring data in an analysis that concludes that because of the irrigation canal network, the Ganga river basin is not suffering groundwater over-exploration, except in the western part. The analysis also concludes that groundwater levels are rising at many locations. This again raises the question of how representative are the monitoring locations. Most of the monitoring wells are located in villages or near canals. In rural villages groundwater levels are rising due to infiltration of waste water from cesspits. As the population grows, urban groundwater recharge increases. Unfortunately, groundwater pollution keeps pace.

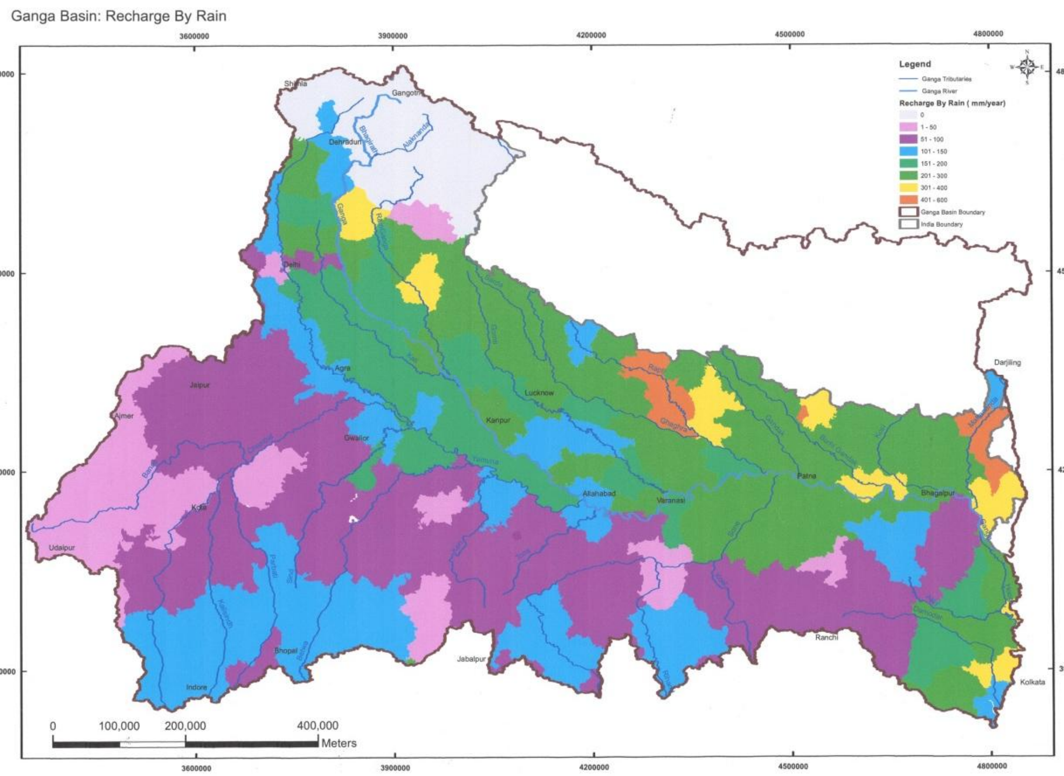

Figure 17-4: Calculated groundwater recharge by rain based on groundwater monitoring data (CGWB, 2014).

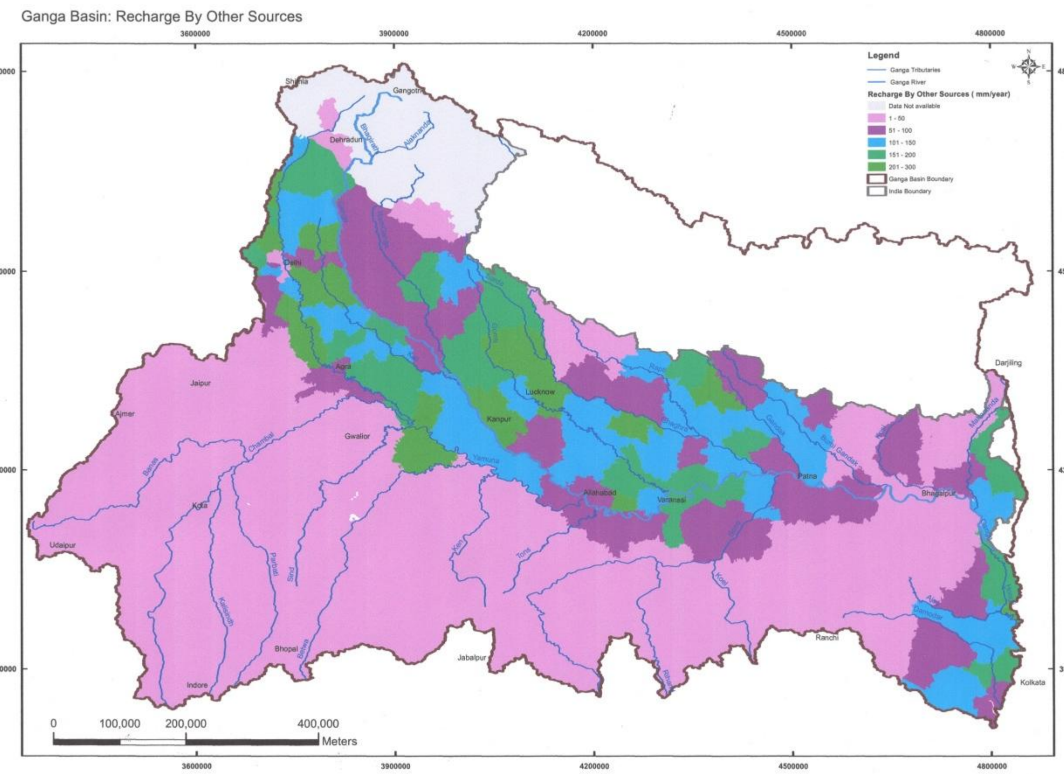

Figure 17-5: Calculated groundwater recharge by other sources based on groundwater monitoring data (CGWB, 2014).

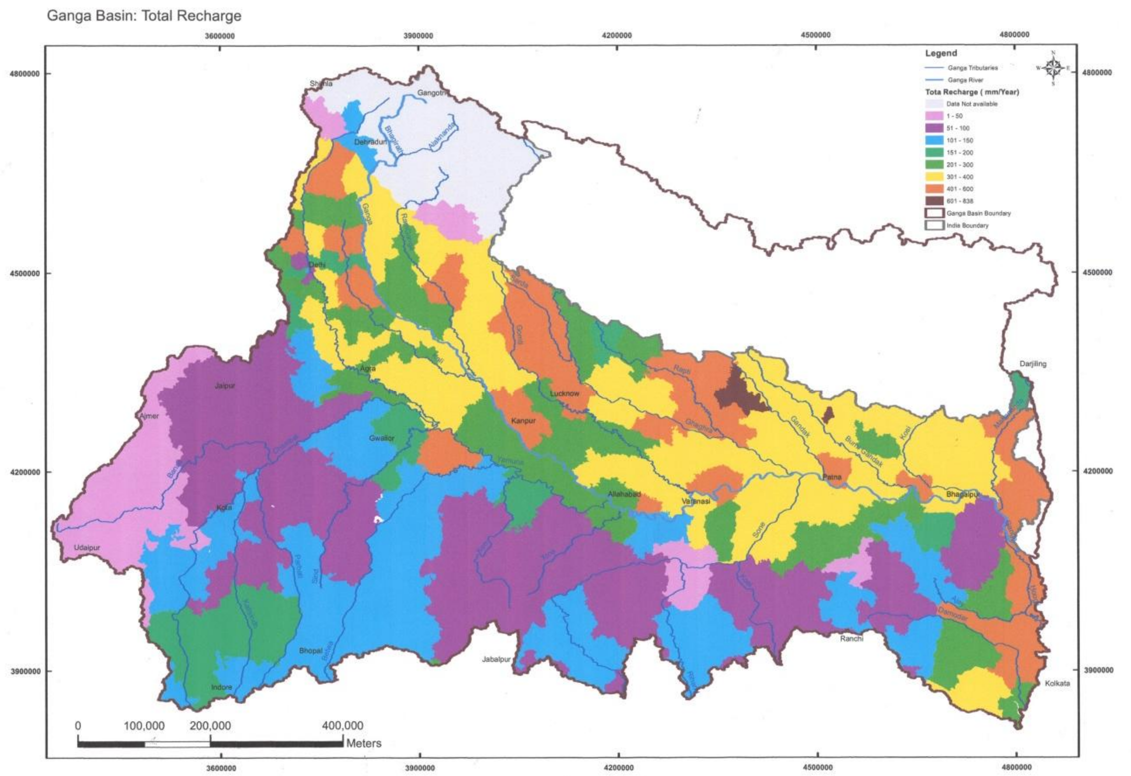

Figure 17-6: Calculated total recharge using monitoring data (CGWB, 2014).

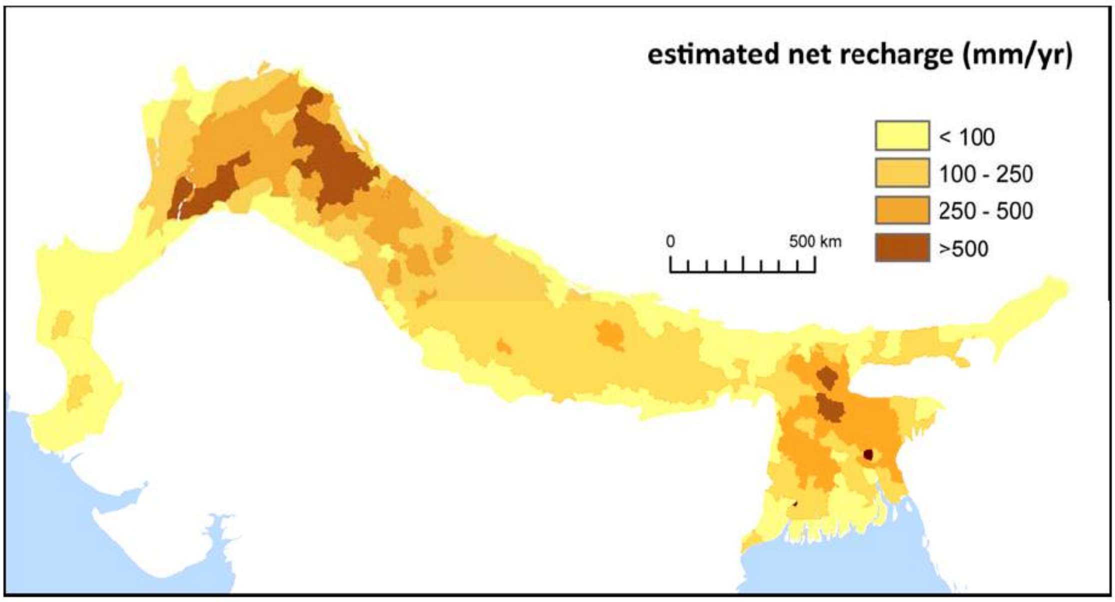

Figure 17-7: Net recharge, calculated by subtracting the calculated annual water storage change from abstraction. Net recharge will be equivalent to the groundwater recharge minus natural discharge to rivers (Bonsor et al., 2017).

17.3 Groundwater Recharge by Surface Water

Important groundwater recharge components are (1) irrigation canal water loss and (2) irrigation loss. The source of irrigation loss is not only surface water, but also pumped groundwater. Figure 17-8 presents the distribution of the main irrigation canals. These canals capture river water upstream and distribute this water over the relatively higher elevated, interfluves. The bottom of these canals is not entirely impermeable; the canals lose water during water transport and the recharging groundwater sometimes creates water logging problems in the neighborhood of the canals.

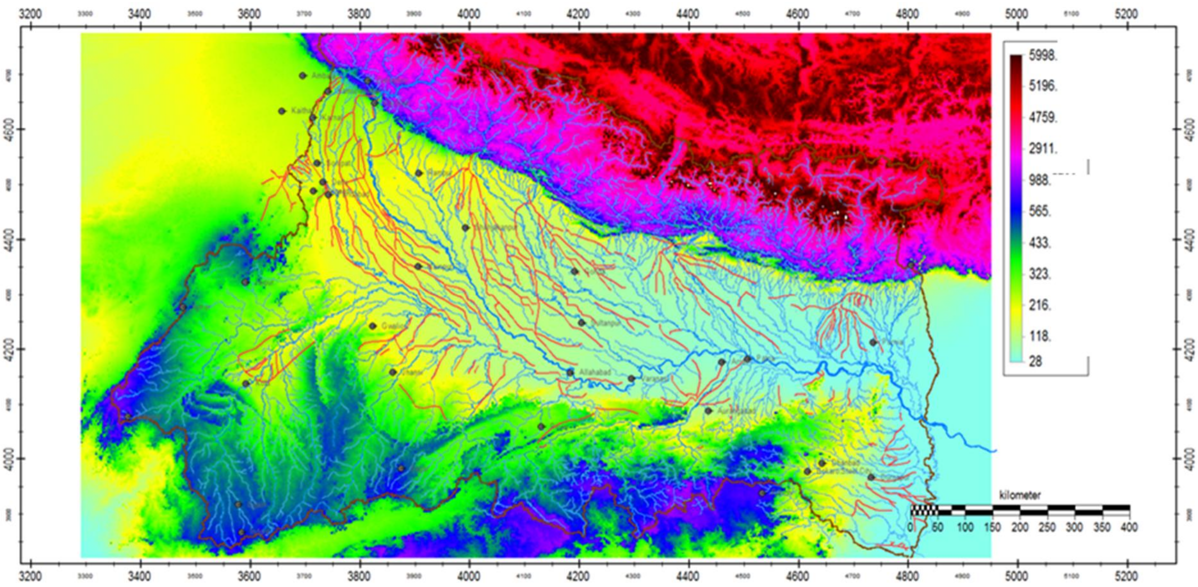

Figure 17-8: Ganga drainage network and distribution of irrigation canals (elevation in meters).

The Ministry of Water Resources of India (Table 17-1) estimated water loss in the transition from surface water to groundwater.

Table 17-1: Parameter ranges recommended for the assessment of recharge from surface water systems (ham = hectare meters).

Parameters	Sources of Recharge	Range of Parameters
Canal seepage factor	Unlined canals	15 to 30 ham/day/million sq.m. of wetted area
	Lined canals & canals in hard rock terrain	20% of above value suggested for unlined canals
Return flow factor	Surface water Irrigation	0.10 – 0.50
	Ground water Irrigation	0.05 – 0.45
Seepage from tanks and ponds	1.4 mm/day over the average water spread area	
Water conservation structures	50% of the Gross Storage. Out of this, 50% is during monsoon season and the remaining 50% during non-monsoon season	

(Source: Ministry of Water Resources, 1997)

The Ganga canal is a canal system that irrigates the Doab region between the Ganga river and the Yamuna river in India. The canal is primarily an irrigation canal, although parts of it have been used for navigation, primarily for transporting construction materials. Separate navigation channels with lock gates were provided to allow boats to negotiate falls. It was originally constructed from 1842 to 1854, with an original head discharge of 6000 cubic feet per second. The upper Ganga canal has since been enlarged gradually to the present head discharge of 10,500 cubic feet per second (295 cubic meters per second). The system consists of a main canal of 272 miles with about 4,000 miles of distribution channels. The canal system irrigates nearly 9,000 km² of fertile agricultural land in ten districts of Uttar Pradesh and Uttarakhand. Today the canal is the source of agricultural prosperity in these states; the state irrigation departments of these states actively maintain the canal with a user fee system.

Surface water irrigation is quantified with Ribasim and the results are presented in Figure 17-9. This surface water irrigation can be very high, similar to natural recharge in The Netherlands, approximately 300 mm/year. The Ribasim calculated patterns are somewhat similar with the patterns of the CGWB net recharge map (Figure 6.6); the very high BGS net recharge in the northwest remains an anomaly.

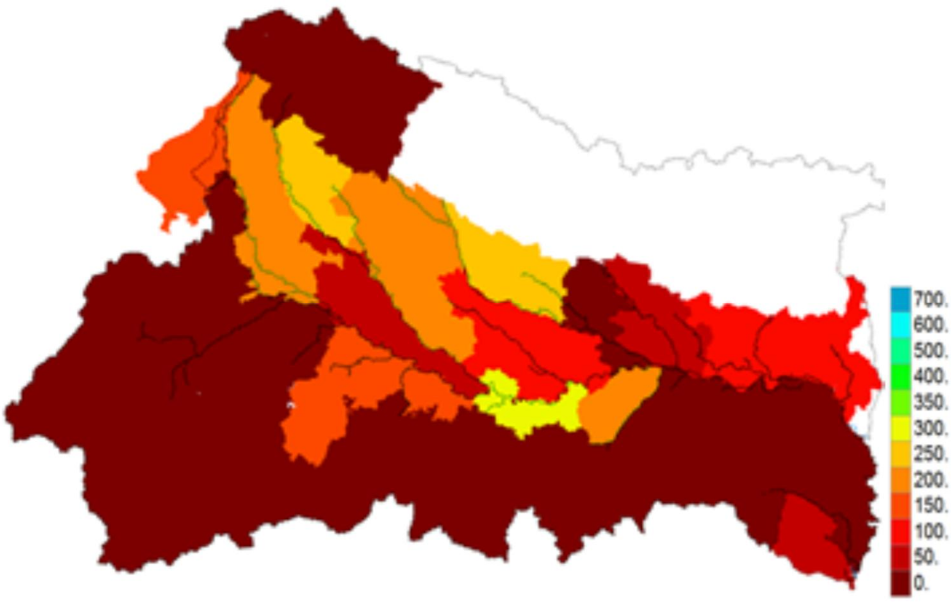

Figure 17-9: Calculated surface irrigation in mm/year.

17.4 Groundwater Use

The water demand will increase from 656 km³ in 2010 to 1069 km³ by 2050 (Tatte et al., 2009). Irrigation is the largest consumer of water, which accounted for 85 percent of the water demand in 2010, followed by domestic use (6 per cent), energy development (3 percent), and industries (6 percent). The demand for water from non-irrigation sectors will grow rapidly over the next 40 years.

In Figure 17-10 the present pumping rates as simulated by the iMOD and Ribasim models are presented for irrigation polygons in mm/year. In the western part of the basin pumping is high relative to recharge rates.

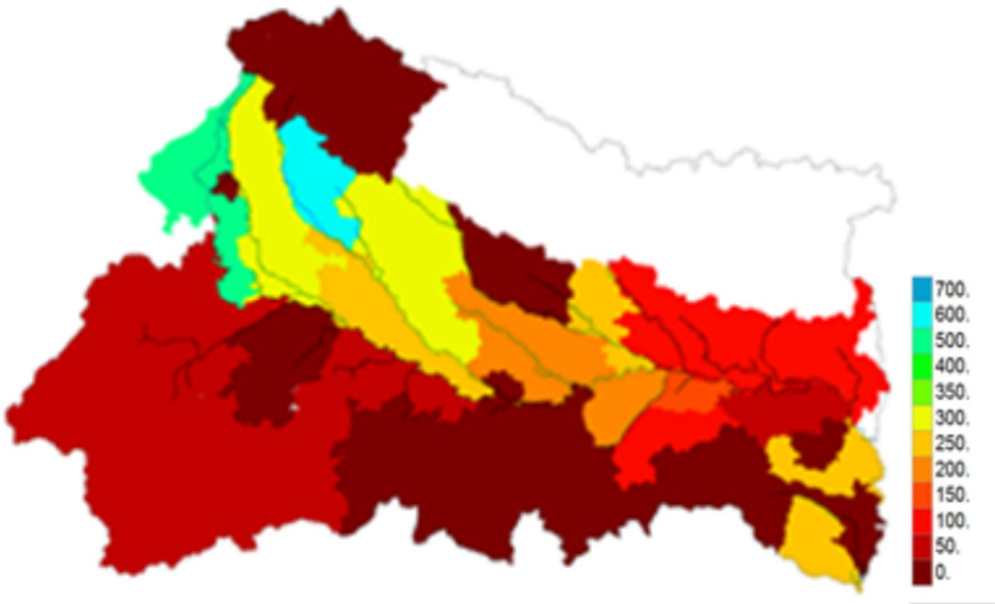

Figure 17-10: Groundwater pumping for irrigation use (mm/year).

17.5 Groundwater Stress Quantified

Based on the estimated water balance, calculated with our model instruments, the “stress factor” of the Ganga groundwater balance can be determined. According to the calculations actual groundwater recharge by rain, canal loss and irrigation loss is at an irrigation polygon scale higher than groundwater pumping (Figure 17-11).

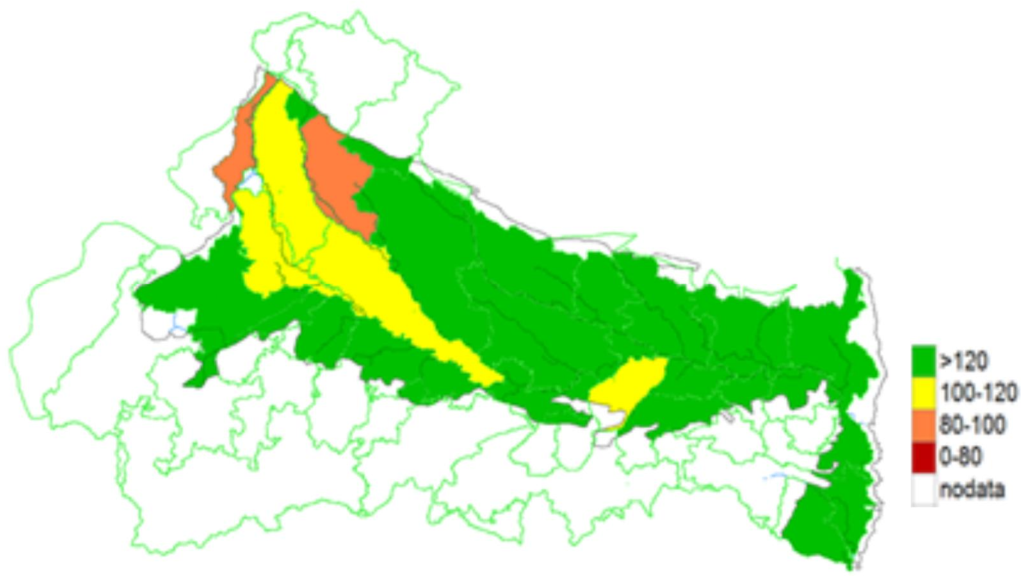

Figure 17-11: The difference between total recharge and groundwater pumping (mm/year) based on iMOD-Ribasim model instruments. Recharge is in general higher than pumping rates.

In Figure 17-12 this water balance is visualized for the entire Ganga river basin, indicating the importance of canal loss and irrigation loss; and that at a basin scale approximately half the amount of pumped groundwater still is drained into the river system to support base flow.

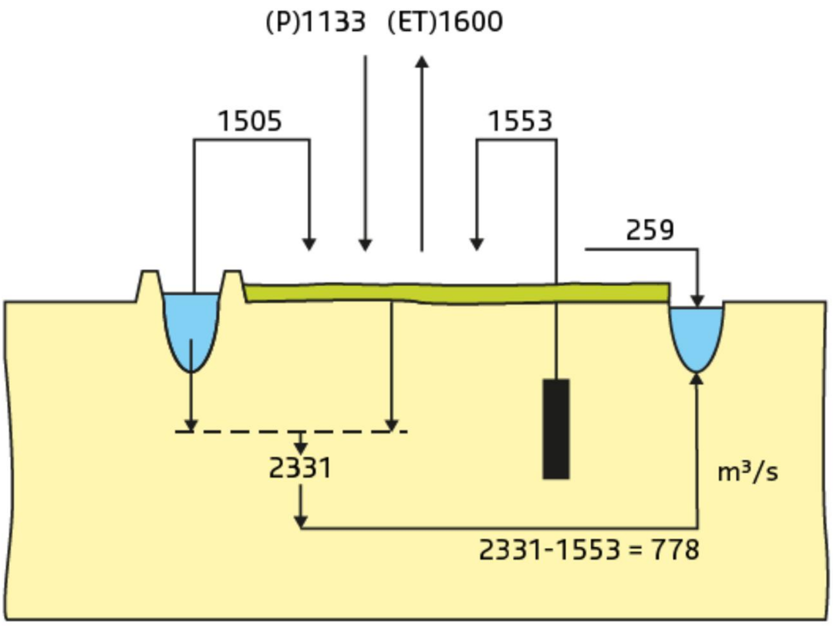

Figure 17-12: Total water balance at Ganga basin scale.

The future 2040 situation (Figure 17-13) demonstrates that the groundwater situation will change significantly.

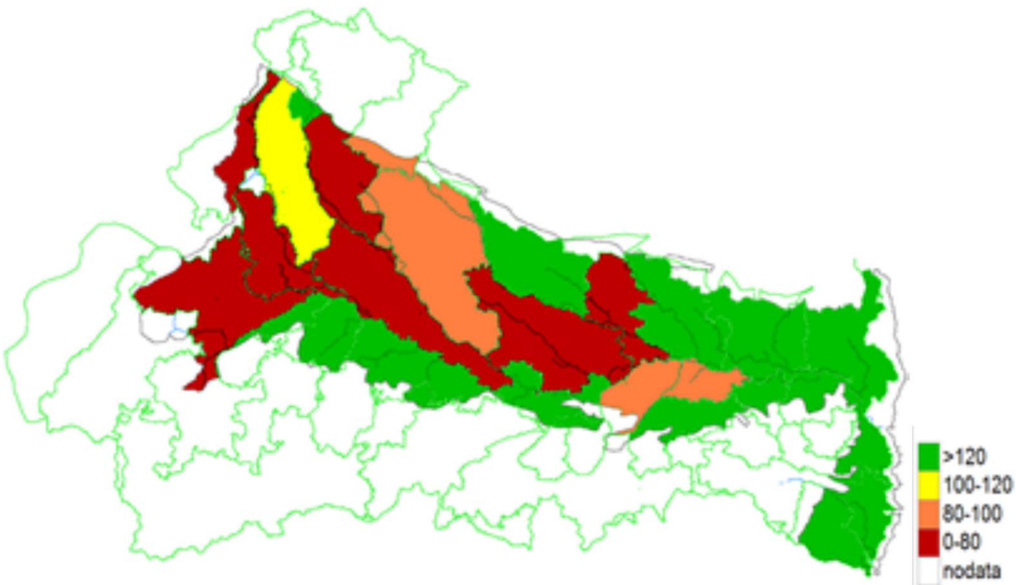

Figure 17-13: Calculated difference (based on Ribasim study) between groundwater recharge and groundwater pumping in 2040 scenario.

17.6 Groundwater Stress Discussion

There are still uncertainties about the groundwater status of the Ganga basin groundwater body. Several GRACE satellite studies estimated groundwater depletion in the northwest part of the basin i.e. Punjab, Haryana/Delhi and Rajasthan states, and assumed that the current abstraction is unsustainable (Rodell et al., 2009; Richey et al., 2015). GRACE measures gravity anomalies which are related to variations in weight of the sum of soil moisture, groundwater and surface water at a 400 x 400 km grid scale.

Several authors published the same results. However, the results were questioned by the CGWB and the British Geological Survey (BGS). The project calculations support the BGS opinion. The BGS argues that the GRACE large-scale interpretations lack the spatial-temporal resolution required to govern groundwater effectively (MacDonald et al., 2017). Based on a study of high-resolution in situ records of groundwater levels (3810 sites) BGS concludes that the GRACE results are overestimated (Figure 17-14). This overestimation question of GRACE studies was recently analyzed by Di Long et al. (2016). The conclusion: yes, there is an overestimation, approximately 30 mm/y instead of approximately 40 mm/y groundwater depletion; net result is depletion and is still a very serious issue.

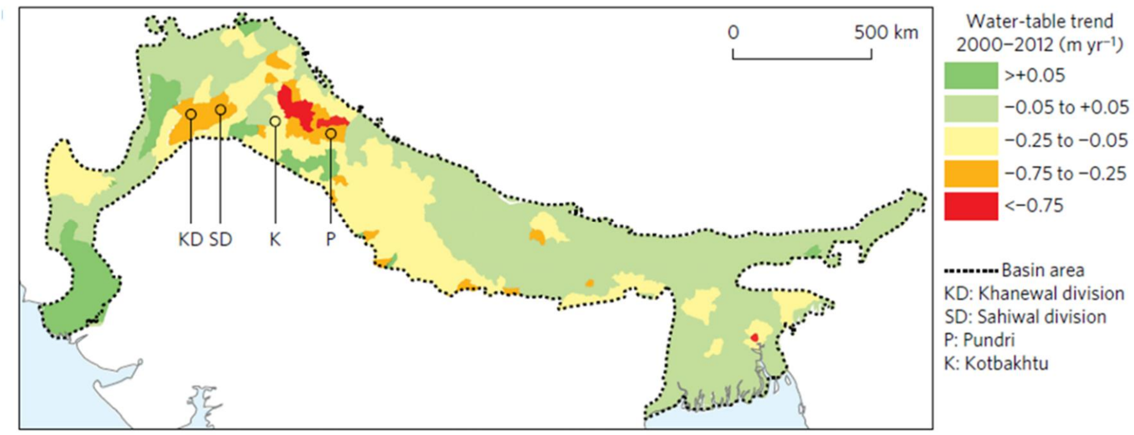

Figure 17-14: Water table trend (MacDonald, 2017)

The BGS study, based on monitoring, and the GRACE study agree about the most affected area, namely the northwest Ganga Basin. Model results in the present study support this view. This area is characterized by enormous groundwater extractions.

The BGS report suggested that local groundwater accumulation or depletion is determined by the interaction of rainfall, canal leakage and abstraction rates, while large abstraction are partially offset by induced recharge and reduced natural discharge, causing reduced base flow in rivers (MacDonald et al., 2017). We argued that rising water levels and water-logging started around 1875 as a consequence of major leakages from irrigation canals, and that the aquifer accumulated water at the expense of river flow.

The editor of Journal of Geological Society of India (2012) also believes that the GRACE projection does not match with ground reality. Based on the CGWB opinion he writes: “exploitation of groundwater in the region is on without any adverse effects”. The project analysis disagrees with this opinion. For example, it is very clear that decreased base flow conditions are related to changes in the groundwater system. To clarify, additional high-quality field information is required. How representative are the groundwater monitoring time series? Do the results reflect conditions from built-up situations or do the results accommodate the less structured conditions of regional and agriculture land use situations?

In addition, “perched” groundwater situations could be of importance. This situation is likely in the Ganga basin. In areas with shallow clay layers, or even clogged rice paddy soils, shallow “perched” water can become disconnected from deeper groundwater that dropped because of pumping (Figure 17-15). This “perched” situation can also explain the differences between GRACE results and groundwater monitoring data. Most monitoring observation wells are very shallow and could monitor perched water tables. GRACE is monitoring differences in total soil moisture and groundwater volumes. Thus, when perched water situations develop decreasing groundwater volumes are observed, while shallow groundwater monitoring data can at the same time indicate rising water tables as irrigation increases.

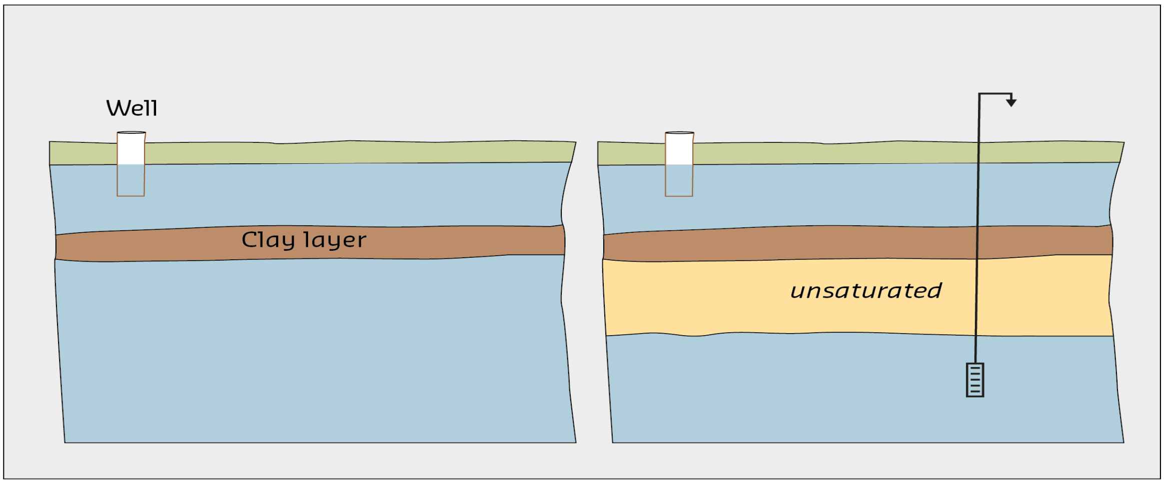

Figure 17-15: Examples of “normal” (left) and “perched” (right) groundwater situation (blue = groundwater)

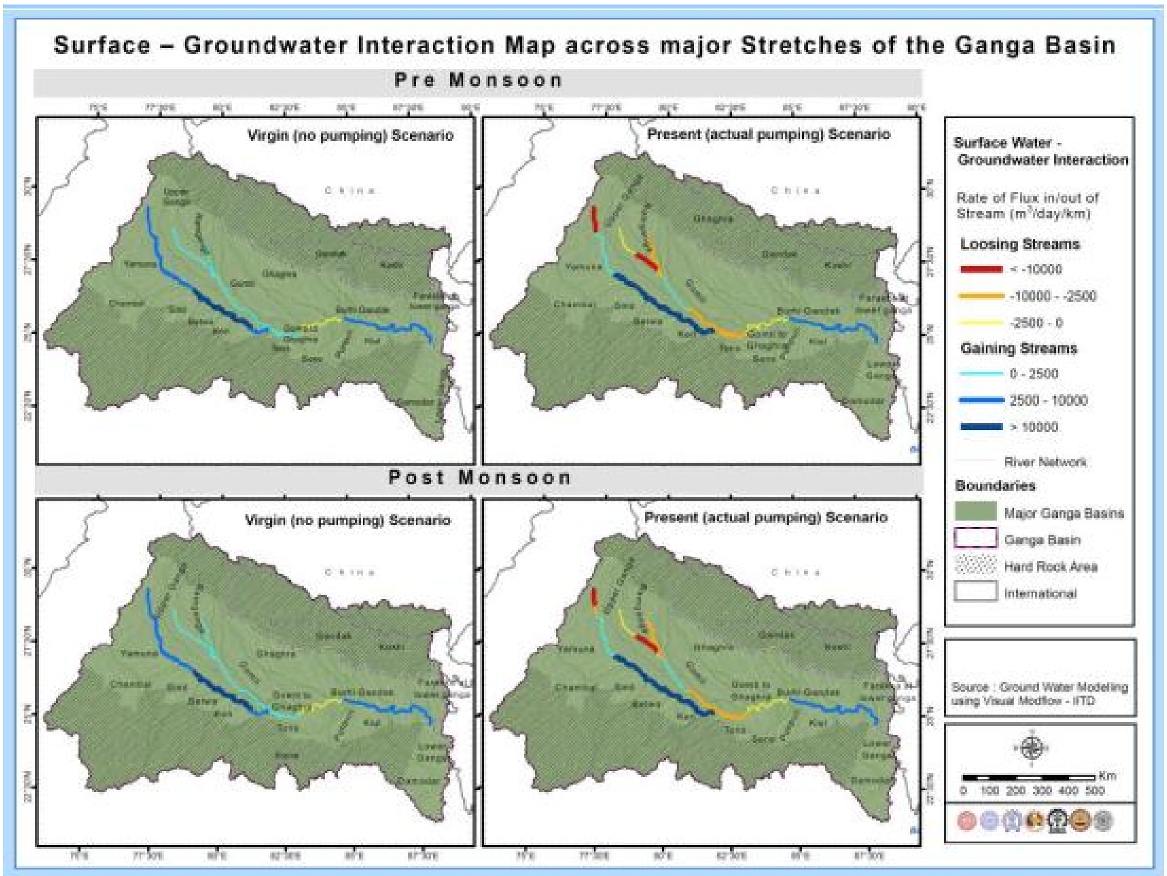

Figure 17-16: Surface water ground water interaction according to Maheswaran et al., 2016.

A recent regional scale groundwater modelling study for the Ganga river basin determined the groundwater-surface water interaction for the main river tributaries (Maheswaran et al., 2016). The losing and gaining stretches were demarcated (Figure 17-16). It was proved that long term groundwater extraction has induced a sharp decrease in critical dry weather base flow contributions. This study differs from those opinions that state groundwater depletion is less important in the middle part of the basin. Long stretches of the Ganga lose water according to this modelling study.

Groundwater pumping in Delhi and Lucknow results in serious subsidence. Minimal information is available on subsidence from pumping in other cities and in agriculture areas. Appendix L provides some more information on subsidence.

17.7 Conclusions and Recommendations

In agreement with the BGS monitoring based study and other model studies, the project concurs that estimated “recharge minus pumping” results are rather positive, in balance, for the present time, except for the over-pumped northwest area. However, this view may be too positive considering the groundwater–surface water interaction in the river system with mainly infiltrating rivers and only few draining river segments. The groundwater base flow component is an integral component of the groundwater system and according to the project groundwater model, this flow component is very low or nonexistent in large parts of the basin. The project modelling results indicate a very negative future groundwater picture (2040) if the present management practices continue.

Despite many studies of the water balance terms of the Ganga river basin, there is still considerable uncertainty. The reasons are:

- All subsurface hydrogeological schematizations are based on generalized schematizations. A clear and detailed hydrogeological, lithological, subsurface model from surface to the top of bedrock has yet to be developed;
- Modeling and monitoring results are based on a monitoring network that is unevenly distributed with design limitations. For example, what is the distribution of observation wells between urban and agriculture areas; or what is the distance from observation well to surface water;
- All GRACE studies agree on a continuous nearly basin-wide decreasing groundwater volume, while monitoring studies and groundwater model studies, calibrated by the monitoring data, present less negative results. The differences may be a result of the possible existence of “perched water”.

Considering the probability of the existence of perched groundwater tables, given the basin lithology, land-use (rice paddies), groundwater pumping and irrigation activities, this needs further research.

A basin-wide groundwater monitoring network needs to be updated. This network, with shallow and deep filters should incorporate existing observation wells where possible.

18 Local Scale Groundwater–Surface Water Interaction

18.1 Introduction

To optimize the integrated water system of the Ganga Basin, the interaction between surface water and groundwater must be analyzed. These interactions have spatial identities (Figure 18-1) and combined spatial-temporal aspects (Figure 18-2). The spatial groundwater–surface water interaction can be summarized as follows:

- Surface water (rivers, canals, ponds) draining groundwater;
- Surface water (rivers, canals, ponds) losing water into the groundwater system (groundwater recharge);
- Irrigated areas, either from surface water or from groundwater, lose irrigation water to the groundwater system, irrigation water may also drain into the surface water drainage system;
- Because of pumping and local geology, “perched” water tables can develop, including drainage of perched water towards the surface water system;
- In urban areas, drinking water pipes and sewer pipes often lose water and therefore recharge the groundwater system.

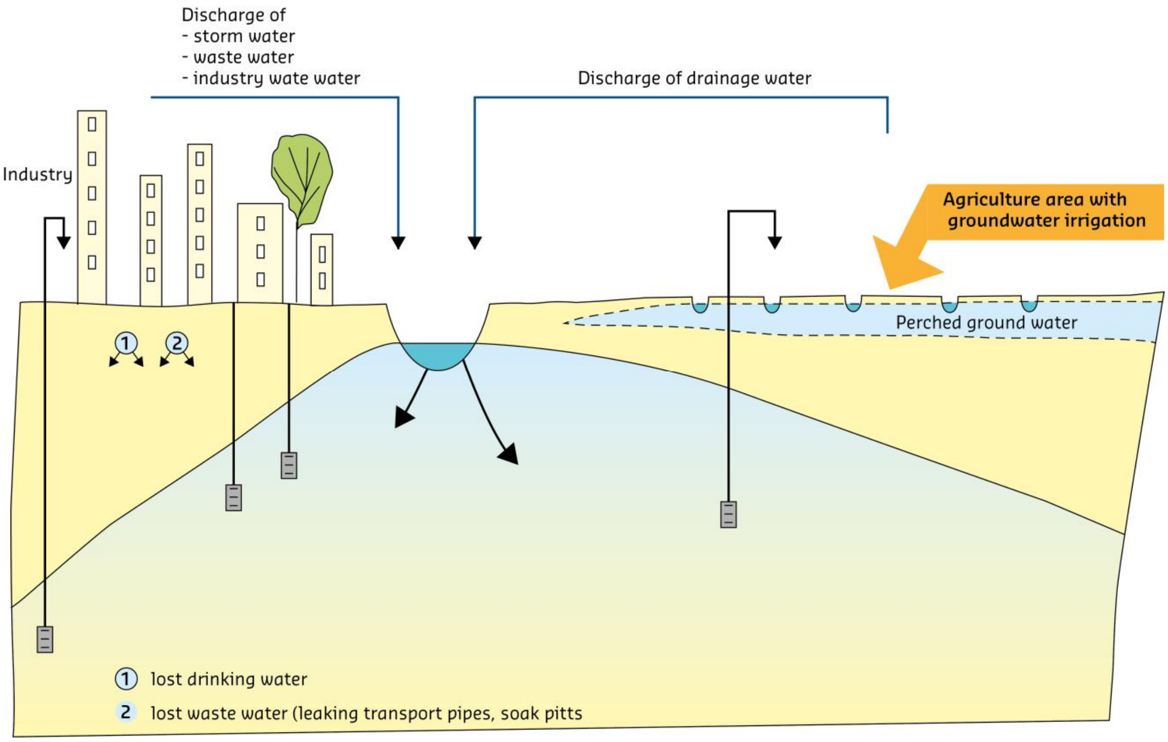

Figure 18-1: Different groundwater surface water interaction possibilities.

Figure 18-2 summarizes the most probable river–subsurface interactions. These situations can differ spatially as well as temporally:

1) A continuous groundwater draining situation;
2) Seasonal groundwater draining situation;
3) A continuous water losing situation, e.g., the coarse sediment Himalaya foothill area receiving mountain drainage water;
4) Flow through situation, i.e., at one side of the river, canal or pond the water body receives water while at the other side water is lost;
5) In extreme situations, e.g., extreme pumping or deep natural groundwater levels, surface water can also be completely disconnected from groundwater. An unsaturated zone below the river exists in this situation.

Understanding these river-subsurface interactions can be useful for water quality considerations. Extra groundwater pumping will cause extreme decreasing groundwater levels. This can seriously impact groundwater quality, e.g., in the unsaturated zone, Ammonium, waste water, can oxidize into Nitrates.

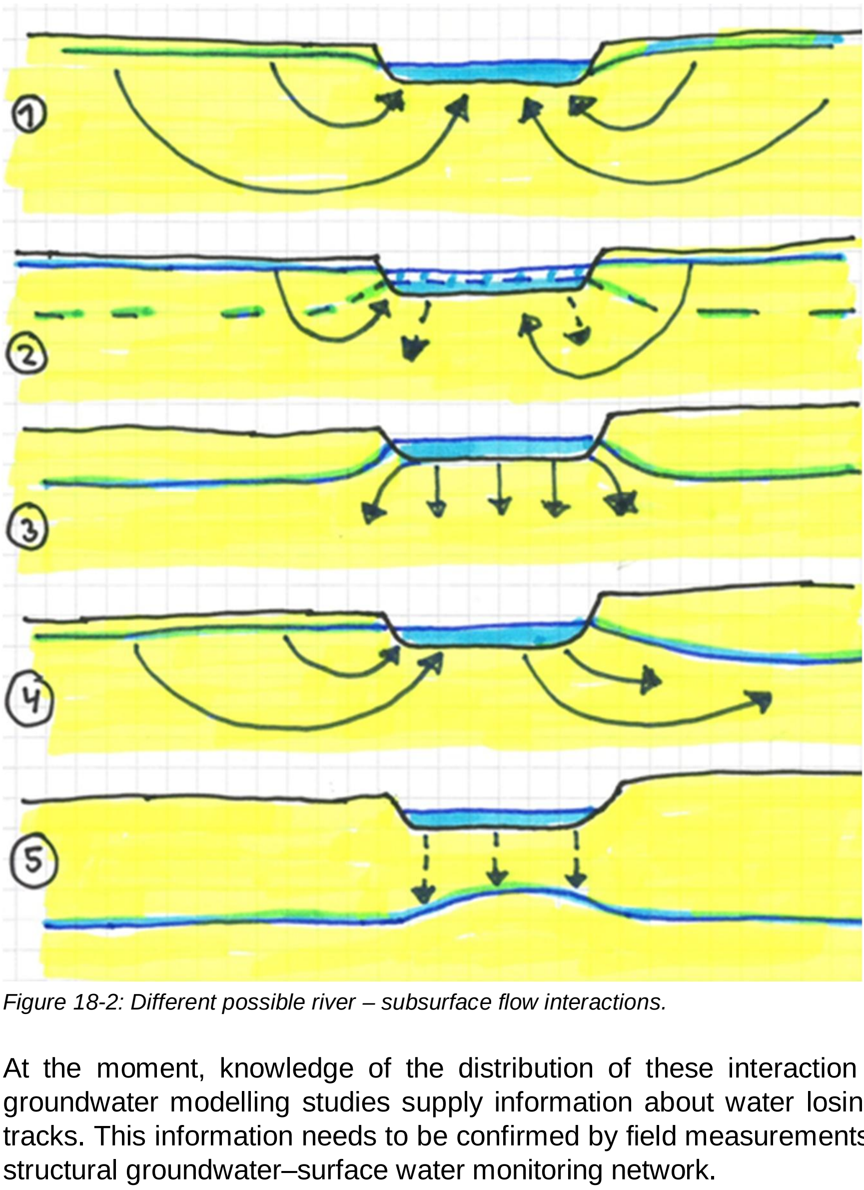

Figure 18-2: Different possible river – subsurface flow interactions.

At the moment, knowledge of the distribution of these interaction types is limited. Some groundwater modelling studies supply information about water losing or water gaining river tracks. This information needs to be confirmed by field measurements, to be used to design a structural groundwater–surface water monitoring network.

18.2 Estimated Groundwater-Surface Water Interaction

The iMOD groundwater model can calculate the interaction between river and groundwater during monsoon and non-monsoon periods to determine if the river is losing water into the groundwater system or if the river is gaining groundwater from seepage. These results are compared with the Maheswaran et al. (2016) study which produces similar calculations (Figure 18-3 and Figure 18-4). Contrary to Maheswaran et al. (2016), the iMOD results indicate a large difference between the monsoon and non-monsoon periods. Based on these calculations nearly the entire river system loses water during the monsoon period, while Maheswaran et al. (2016) presents only a draining Yamuna river.

The non-monsoon period results are more similar. These non-monsoon results, low surface water levels and high irrigation pumping, suggest unnatural low groundwater drainage, and therefore surface water base flow conditions.

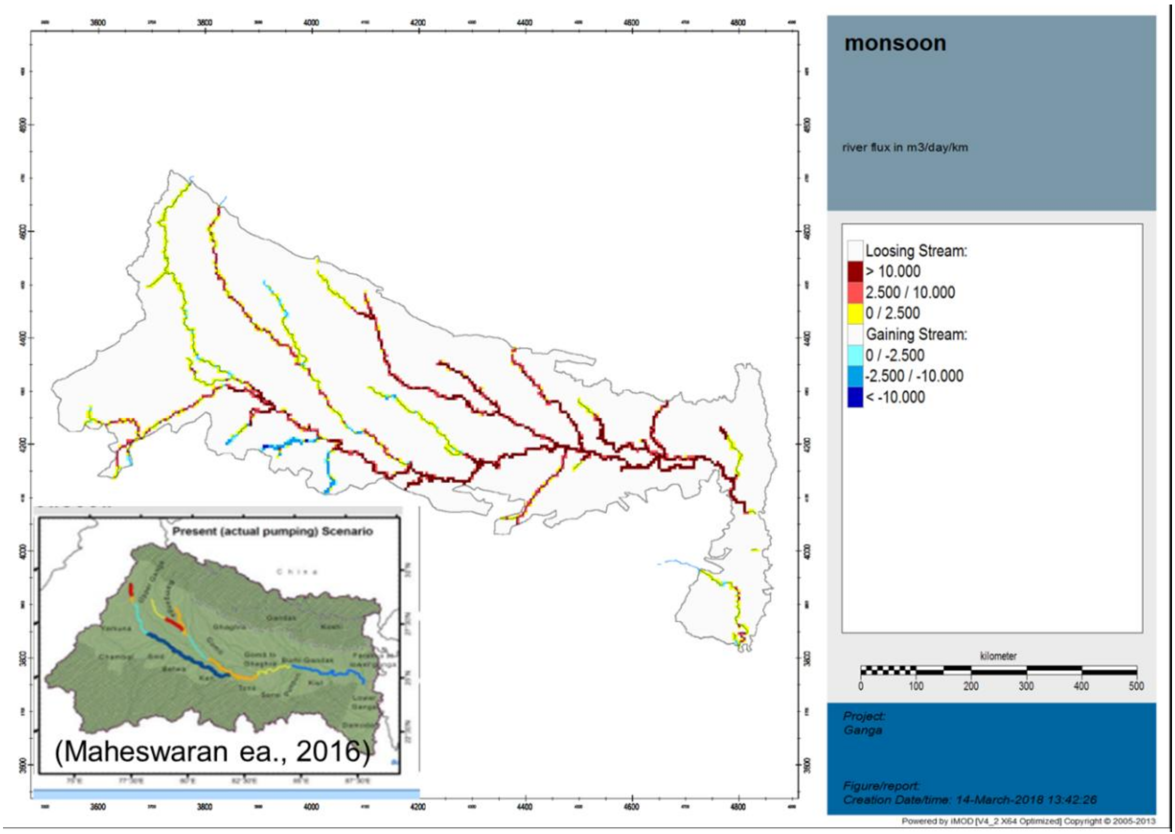

Figure 18-3: River – groundwater interaction during monsoon period.

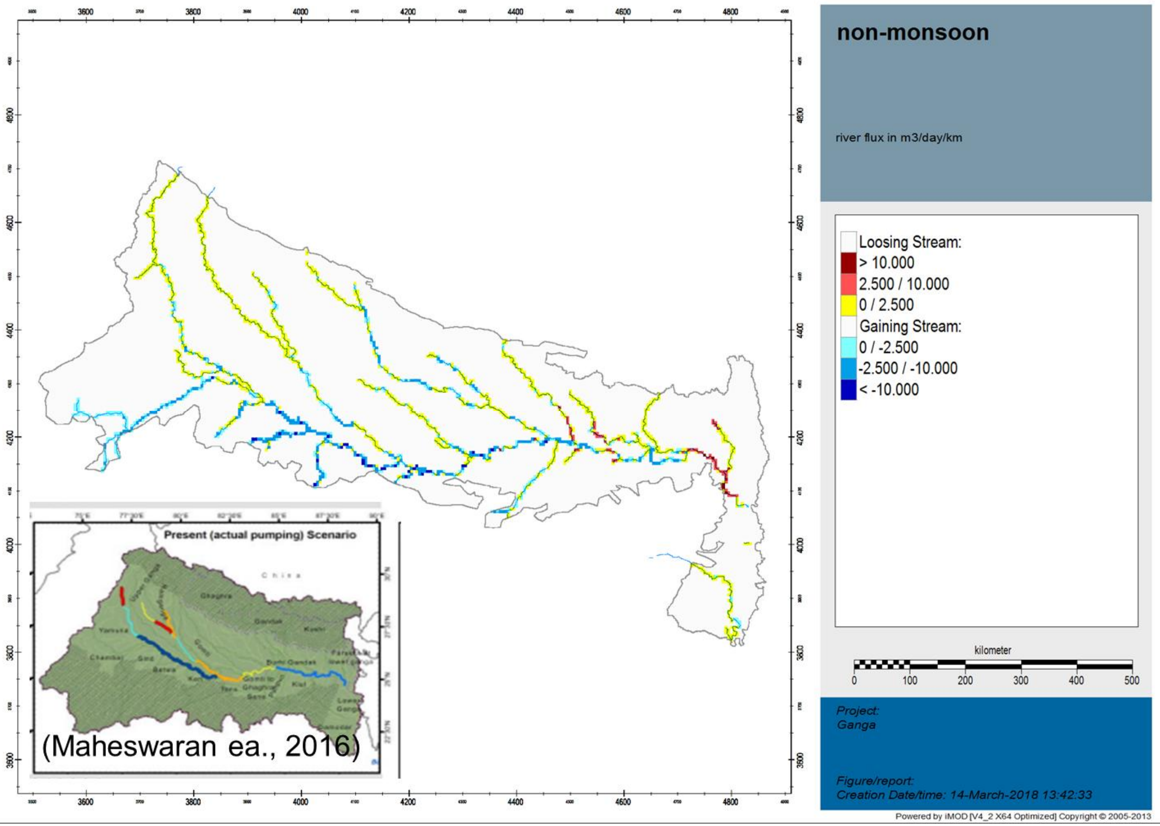

Figure 18-4: River- groundwater interaction during non-monsoon period.

18.3 Too Much Water: Flooding and Water Logging

Although water scarcity seems a problem in the basin, at the same time the basin also suffers from flooding and water logging. When India's monsoon season matures; the rivers keep rising, causing flooding in many parts of the country. Uttar Pradesh, Bihar and West Bengal are the major states affected by floods. Of course, high surface water levels impact the groundwater situation adjacent to the rivers. In areas with coarse sediments the groundwater levels will rise directly. It is possible that these short term high water levels also create extra groundwater recharge.

Figure 18-5 highlights those areas with regular flooding issues. The northeastern part of the basin and the lower Ganga-Yamuna area are especially vulnerable to flooding. Retention and groundwater storage areas could be explored in the source areas of the flooding.

Water logging is a serious issue in many locations. Figure 18-6 depicts those areas which suffer water logging. In general, water logging is related to high river and canal water levels causing nearby groundwater levels to rise. The construction of levees often causes higher water levels. In many cases, high surface water levels are related to rising channel-bottom levels due to sedimentation (Figure 18-7).

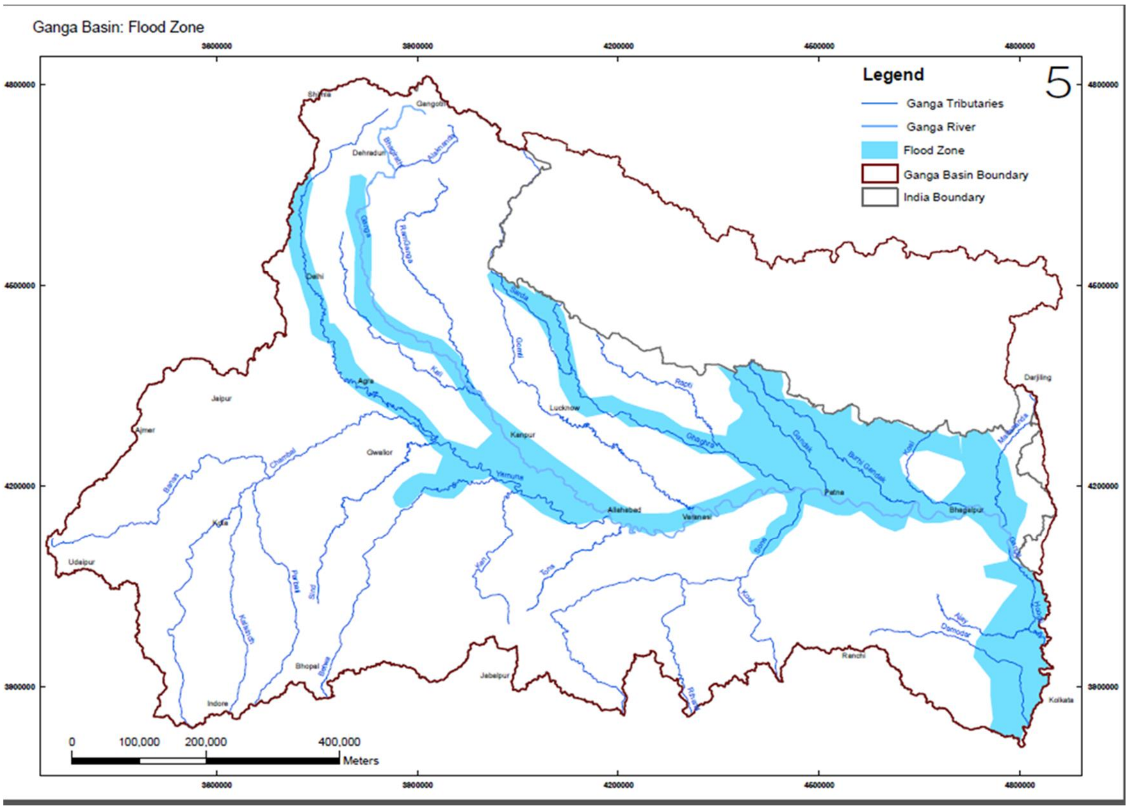

Figure 18-5: Flood zones in the Ganga basin (CGWB, 2014).

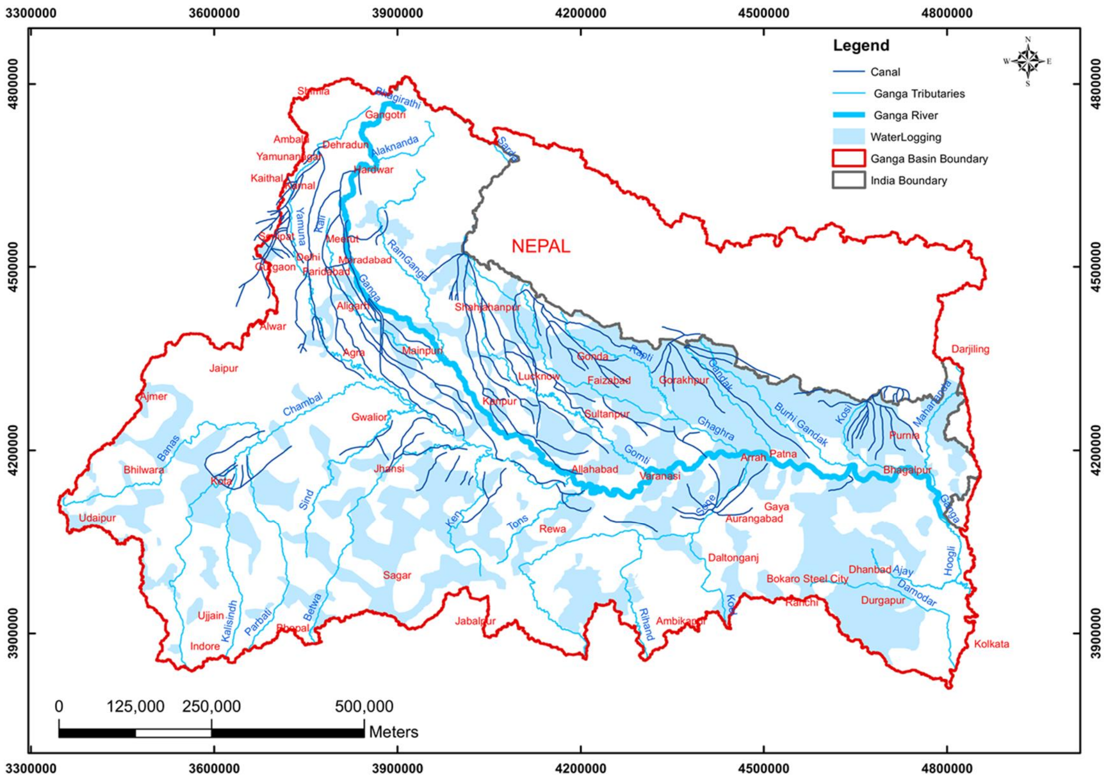

Figure 18-6: Areas suffering water logging (CGWB, 2014)

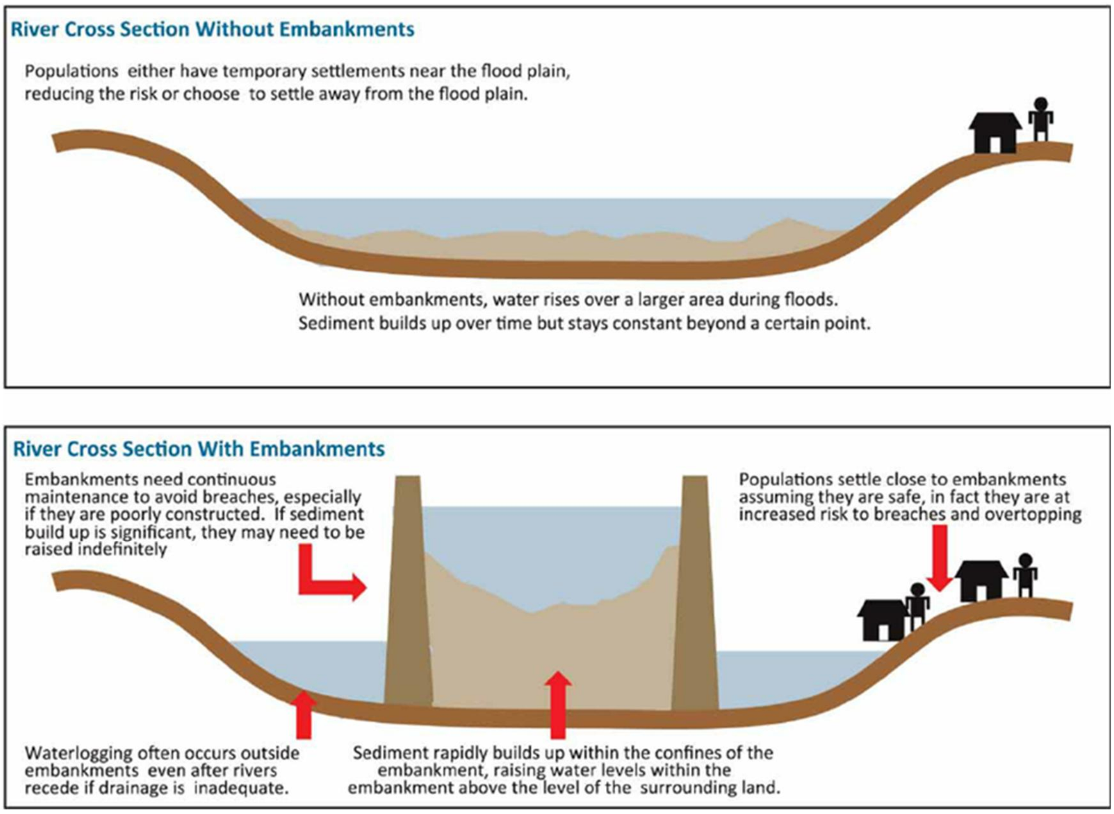

Figure 18-7: Rising surface water levels in relation to water logging in the neighboring areas (Bonsor et al., 2016).

18.4 Too Little Water: Drought

The arid southern hard rock craton area is suffering drought (Figure 18-8). Because this area lacks rainfall there is little opportunity for subsurface groundwater storage. Under these circumstances irrigation is exceedingly difficult.

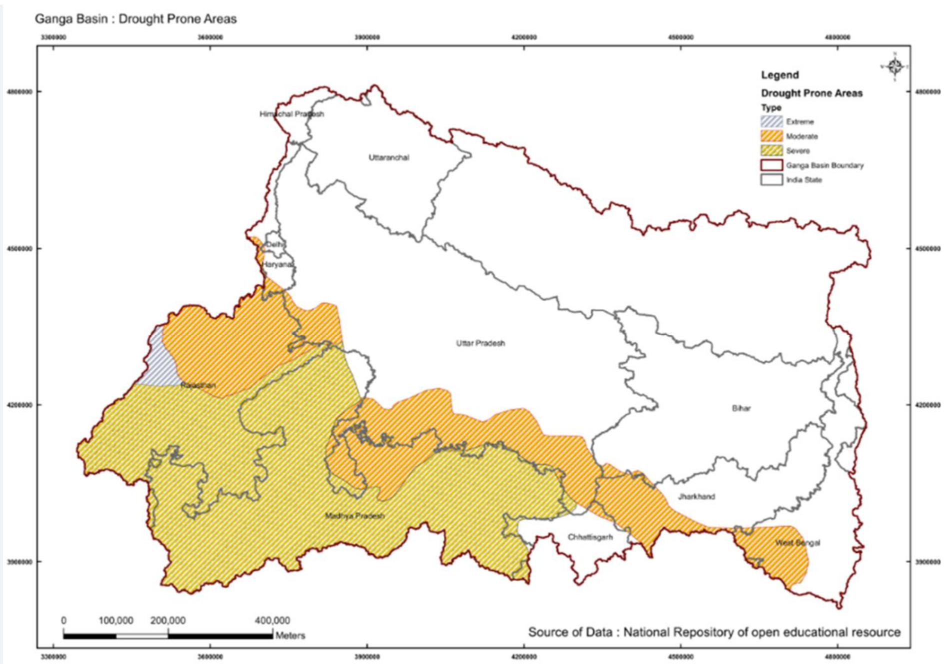

Figure 18-8: The drought prone areas (data source: National Repository of open educational resource).

18.5 Conclusions and Recommendations

The interaction between groundwater and surface water for the main rivers can be described only at a regional scale and only based on modelling. During the monsoon season nearly the entire river system is losing water to the groundwater system. Model studies show similar situations even during the dry period when low river water levels indicate that base flow conditions are weak. High surface water levels can cause water logging in the areas outside the levees. Geophysical studies can help to understand the possibility and/or distribution of perched groundwater situations.

“Depletion or not depletion” is still unclear. Modelling results and monitoring results tend to be inconsistent. Existing monitoring wells may not be representative for calibrating models. It is still uncertain whether areas with a perched water table exist. More field pilots should be undertaken to increase the water system knowledge base.

To better understand groundwater-surface water interactions dedicated monitoring networks could be designed and installed. For example, a cross-section of groundwater observation wells perpendicular to irrigation canals and rivers should be more than 100 meters deep and have multiple filters with depth. Water samples could then determine origin through the use of isotopes or other traces. Simple groundwater temperature measurements can provide basic information on the complex relationships. The locations of these transects can be based on existing modelling results. The design of clever piezometer observation wells can be useful to understand flow characteristics.

Base flow appears to be the most vulnerable water balance term, more so than groundwater use or groundwater depletion. Base flow can be better defined through sophisticated measurements, using hydro-chemical analysis. Groundwater monitoring networks should be integrated with surface water monitoring to better understand surface water-groundwater interaction.

The shallow groundwater quality in the Alluvial basin area could be studied to better understand the consequences of cycling groundwater, the pumping-irrigation-infiltration-pumping cycle. Negative concentration processes could be inadvertently increased.

Groundwater quality types (polluted, anthropogenic, pristine, brackish, salt) need to be mapped and boundaries monitored to better understand changes in the groundwater system. At the same time the spatial distribution (also with depth) of arsenic, fluoride and other geogenic constituents (like uranium) need to be improved. The relation irrigation water type (surface water, shallow or deep groundwater), soil situation and arsenic uptake of rice and vegetables need to be better understood to take appropriate water management actions.

19 Groundwater Management Units

19.1 Introduction

The Ganga river basin can be divided into Groundwater Management Units based on: (a) physical typologies: hydrogeology and geomorphology, including water flow processes and (b) Groundwater stress issues and water management opportunities.

The points of departure are the six main hydrogeological typologies, as defined by British Geological Survey (Figure 19-1). The BGS produced a typology classification (Bonsor et al., 2017), which fits well with standard geology and geomorphology descriptions. Our project added a sixth type, namely the nearly unknown deep alluvial aquifer, because of the presence of large volumes of fresh groundwater. The following hydrogeological typologies can be distinguished:

- The Alluvial Valley, covering the largest part of the basin and characterized by a heterogeneous build-up of fine sand and lenses of coarser sediments or clay lenses;
- The (northern) Piedmont Fan, a shallow Himalaya foothill zone. The deposits are mostly coarse material, interfingering into the alluvial valley deposits at different depths, and therefore a very important recharge zone;
- The Mega Fans, sandy deposits covering the alluvial valley and Piedmont Fan zone and important for groundwater recharge;
- The Southern Marginal Alluvial Plain, with similar conditions as the Piedmont Fan area but less important because this area receives less rain;
- The northern and southern hard rock areas: related to groundwater the hard rock areas can be subdivided into two subunits, (a) sedimentary stone, sandstone and limestone, with limited groundwater potential and (b) metamorphic stone with extremely low groundwater potential;
- The deep (> 200–300 meters) Alluvial aquifer. This nearly unknown part of the basin contains large volumes of fresh groundwater.

19.2 Groundwater Stress Issues

Based on literature research and the results of this study the following groundwater stress factors are identified:

- Drought: Climate related shortage of moisture and groundwater;
- Dropping groundwater levels: Man-made declining water tables in over-exploited areas:
    a. Creating shortage of capillary water for agriculture;
    b. Increasing costs from well renovation and construction;
    c. Causing extra water quality deterioration, e.g. reduced nitrate reduction;
    d. Causing subsidence and related damage;
    e. Damaging infrastructure (stability, collapse, corrosion);
    f. Damaging foundations e.g., dry wooden piles of Tai Mahal;
    g. Water shortages for water dependent nature (reduced base flow, dry tributaries, dry terrestrial wetlands);

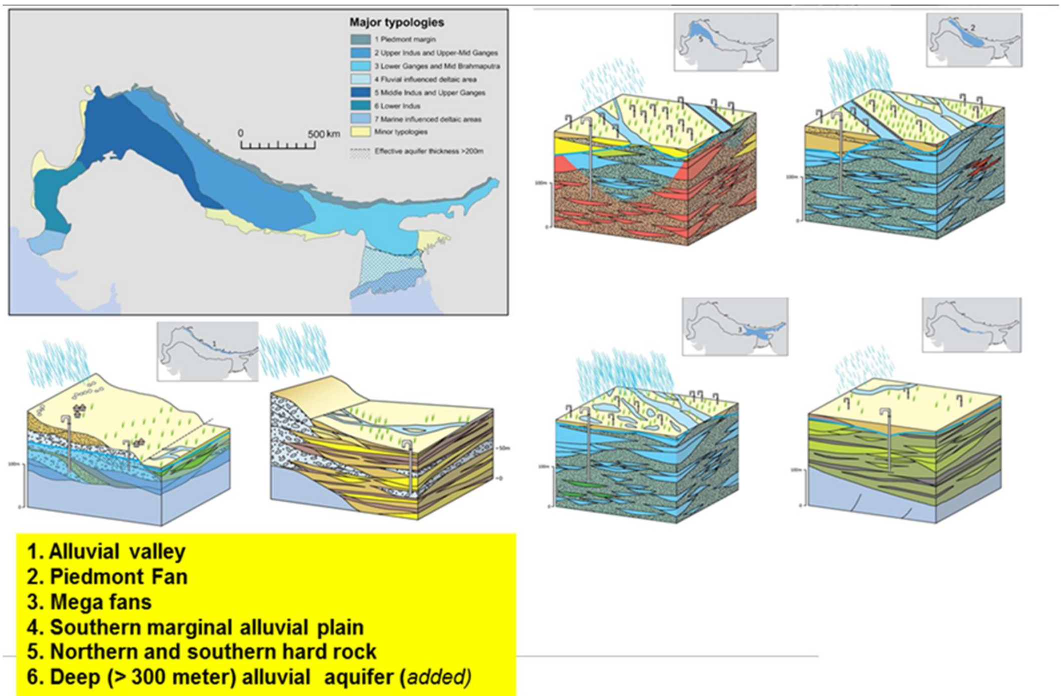

Figure 19-1: Major Ganga river basin topologies (3D-schematizations) according to BGS (Bonsor et al., 2015). The BGS map also includes the Indus basin.

- Rising groundwater levels: man-made because of (a) sedimentation of river and canal beds, (b) high river water levels during wet periods due to reduced space (water storage) and concentration of sedimentation between the constructed levees, (c) uncontrolled irrigation, (d) leaking drinking water and sewer water pipelines in urban areas and (e) leaking cesspits, volume increases with population growth. The following problems can arise:
  a. Water logging in areas near rivers and canals;
  b. Groundwater flooding of urban infrastructure, also creating urban health issues;
  c. Damaging heritage;
  d. Soil salinization;
- Groundwater pollution: groundwater pollution by agriculture, urban land-use and industry;
- Geogenic “pollution”, Arsenic, Fluoride, Uranium;
- Salinization: saline groundwater mobilization.

19.3 Risk Framework

A risk framework (Table 19-1) was developed based on water use, future demand, connectivity to surface water and water quality threats to identify groundwater management units.

Table 19-1: Risk framework used to develop groundwater management units.

Category	Sub-category	Issue	Aquifer	Demand		SW-GW connectivity		Quality
				Present demand>recharge	Future demand>>recharge	GW status will adversely affect SW	SW status will adversely affect GW	GW quality is threathened
Quality	Geogenic	Inland salinity	deeper					natural
		Arsenic	upper					
		Fluoride	upper					natural
	Antropogenic	Nitrate	upper					
Quantity	Natural	hard rock areas	any					
		drought areas	all					
	Antropogenic	over extraction	upper					
		waterlogging	upper					

safe	moderate	serious	very serious	other

In figures N-1 to N4 of Appendix N the design of Groundwater Management Units is elaborated in a systematical approach. Figure N-1 shows the contours of the geomorphological based schematization in main topologies, Figure N-2 presents the combination of these geomorphological units with the spatial distribution of several quantitative stress issues, and Figure N-3 with qualitative stress issues. Based on these 3 maps a palette of groundwater management units can be determined (Figure 19-2). Figure 19-3 presents the results in a 3D view.

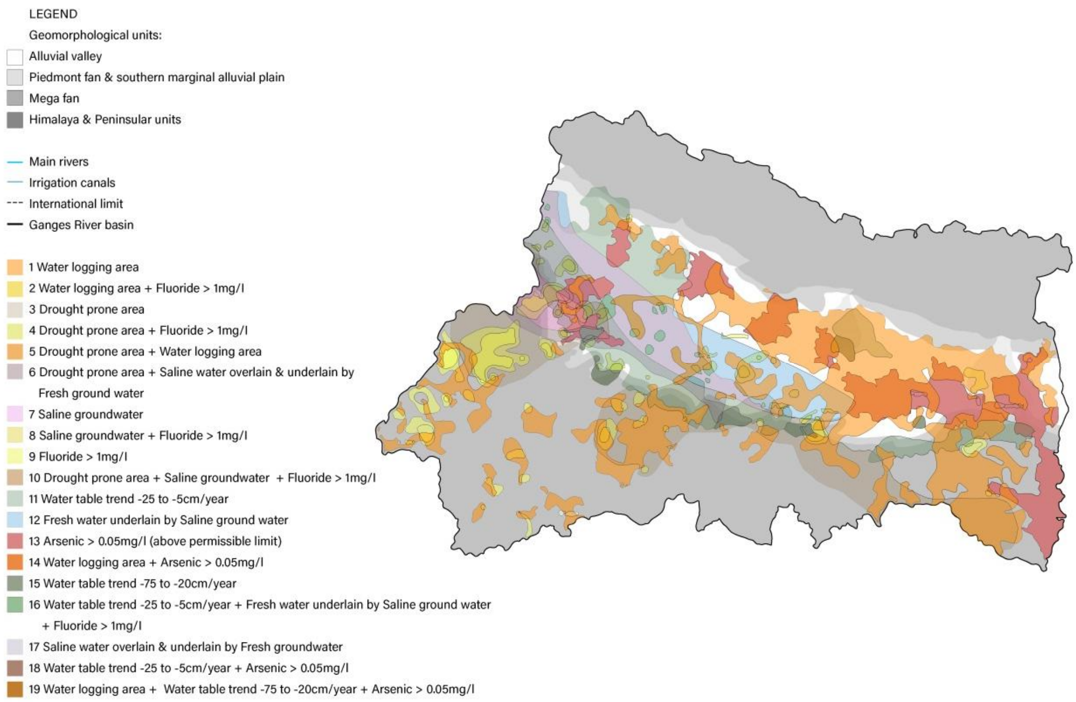

Figure 19-2: Combination map of detailed water management units.

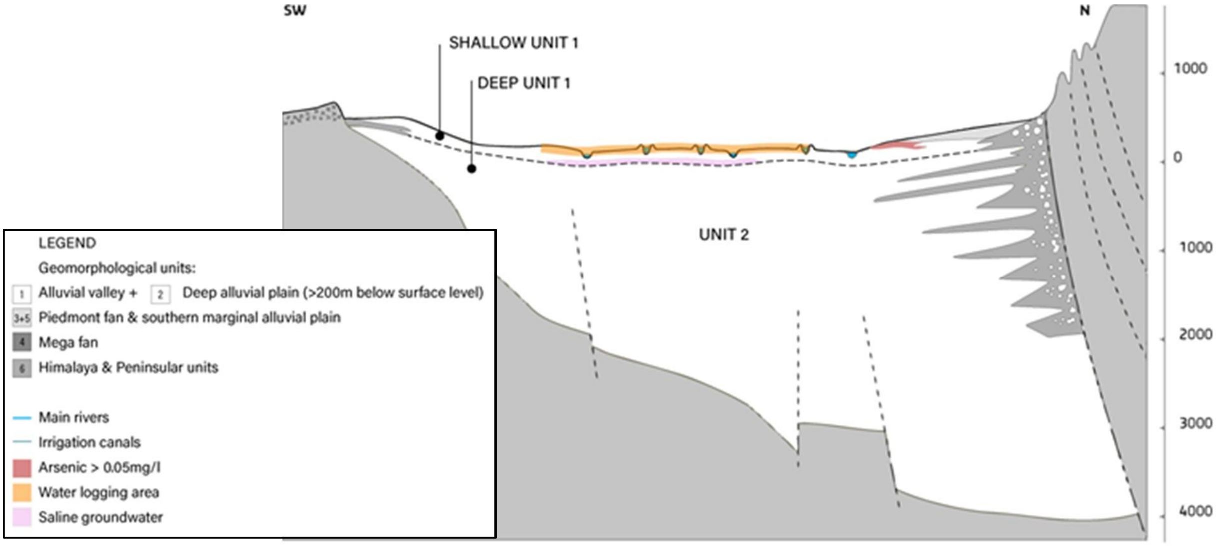

Figure 19-3:: Schematic cross section showing the units 1 & 2, including sub-management units.

19.4 Description of Groundwater Management Units

Table 19-2 presents the resulting groundwater management units. For every sub-unit the groundwater aspects are summarized and recommendations for groundwater use are presented.

The (shallow) Alluvial plain unit (1) dates from 1854 with the advent of irrigation canals; numerous groundwater wells became part of the unit beginning in the second half of the twentieth century. This is a completely artificial groundwater system, therefore very vulnerable. The Alluvial plain is characterized by recharge from precipitation and irrigation loss (including canals), nearly completely abstracted again by numerous irrigation wells. A 100–200 m deep, water-circulation system has been created.

This groundwater system is vulnerable to pollution from the heavy use of agro-chemicals (fertilizers, pesticides) and to polluted (infiltrating) surface water (waste water, agro-chemicals). Multiple harvests prompted a dramatic increase in fertilizer and pesticide usage; that usage is now one of the highest on a world scale. Because the basin models show low or no (groundwater) base flow during dry periods, it is reasonable to assume that pollutants will concentrate in groundwater systems over time. Managing fresh groundwater in the Alluvial Palin unit needs to include, and therefore better understand, the fresh – saline groundwater interactions and the three-dimensional distribution of Arsenic and other “natural’ pollutants (Fluoride, Uranium etc.).

The Piedmont Fan unit (3), Mega Fans (4) and Southern Marginal Alluvial Plain seem to be important for semi-horizontal recharge of the deeper groundwater of the Alluvial plain. This interfingering flow connection with the Alluvial Plain units should be documented before any optimization strategies are implemented. Optimization simply means increase recharge and protects the water quality of recharge water, in a manner similar to the EU Water directive measures currently operative in the Po Basin. Recharge can be increased by many local or sub-regional actions (see Chapter 10). In the Mega Fans unit, river bank groundwater pumping has great potential, especially in areas suffering from water logging. In the hard rock unit, groundwater must be conserved and groundwater quality must be diligently monitored.

Table 19-2: Groundwater management units and recommended groundwater use.

	Unit	Sub -units	Aquifer characteristics	Groundwater aspects	Groundwater use
1	Alluvial Plain (shallow aquifer)	1.1 general	Silty-sandy	Recharge by rain and irrigation (canals). Risk of soil salinization. No or low base flow. Pollution risks. A circulating (ground) water system.	• Not more than local recharge and, • Considering ecological (base-) flow
		1.2 Saline zone	Like 1.1, but with regional shallow appearance of salt water	A vertical sequence of shallow fresh water – salt water – deep fresh water. Risks for salinization fresh water resources.	• Shallow: limited quantity because of risk salt water "up-coning" • Deep: limited by "down-coning" and pumping costs • Perhaps mixing solutions (to explore, benefit from, salt water)
		1.3 Arsenic zone	Like 1.1: Organic rich layer between 1-3 and 40 meter below surface.	Recharge by rain and irrigation. Deep groundwater has little As contents.	• Only use of open wells, hand pumps to minimize oxidation of organic material by lowered groundwater levels; • Or from very deep confined aquifers;
2	Alluvial Plain (deep aquifer, > 200 m below surface level)		Sandy. Regionally unconfined, locally confined	a) Recharge in Piedmont Fan area important but now lacking (paleo water body?) b) Enormous reservoir, but; c) Very little knowledge about origin, flow, recharge, quality, thickness of fresh water body, extractable amount etc.	Unknown opportunity
3	Piedmont Fan		Very course sediments, boulders, gravel	a) Relative deep groundwater levels; b) Very important (regional) groundwater recharge area c) Need high priority protection (reduce polluting activities, increase recharge)	Stimulated recharge, reduce use
4	Mega Fans		Sandy to course, relative high permeability	Relative high groundwater levels, sub-regional infiltration area. Groundwater is very vulnerable to fertilizer and pesticide pollution. Groundwater risk area needs special attention.	• Great potential for river bank groundwater pumping, in combination with control water logging along rivers.
5	(southern) marginal alluvial plain		Very thin aquifer, drought prone.	Little water. Groundwater very vulnerable for pollution.	Not for irrigation.
6	Hard rock area	6.1 clastic stone	Sandstone, limestone	Limited groundwater availability	• Not for irrigation; • For hand pumps drinking water only
		6.2 crystalline, metamorphic stone		Very limited groundwater availability (shallow weathered zone, cracks)	• Only local open wells and hand pumps

19.5 Conclusions and Recommendations

Himalayan foothill, Piedmont Margin, zones are extremely important for groundwater recharge and require protection. Recharge stimulation should always be considered as a possible option. Italy's Po Basin has similar hydrogeological conditions as those found in the Ganga river basin (Fontana, 2014). The foothill area there became a groundwater protection zone in accordance with the EU Water Frame Work Directive (E-R Ambiente, 2013). A similar approach for groundwater protection zones could be undertaken in the Ganga Basin;

Monsoon period peak flows provide opportunities for groundwater recharge. River water discharge could be delayed; storm water could be stored, preferably below ground to support groundwater demand during dry periods. Water logging may be reduced by management of the river and canal system to realize lower surface water levels during monsoon periods, e.g., by dredging (deepening profile) or by widening, creating additional (surface water) storage ("room for rivers or canals"). A basin wide "storage opportunity" map would be an important first step;

Main alluvial areas can be used for groundwater extraction as long as abstraction does not exceed recharge, taking the recharge from inefficient agriculture into account. However, in saline zones upconing or downconing of saline water should be avoided. Special care should be taken in Arsenic zones. Shallow groundwater should not be used for drinking or rice cultivation.

The hard-rock area and southern shallow alluvial cannot sustainably supply groundwater for use in irrigation.

20 Planning Principles and Recommended Follow-up

20.1 Apply Water Planning Guiding Principles

To restore the Ganga river basin and achieve a sustainable groundwater system the following principles (Stuurman, 2018) can serve as a guide (Table 20-1).

Table 20-1: Planning principles.

	Principles	***Description***
1	Safety first	
2	You can't manage what you don't know	a. "demystify" groundwater and subsidence for non-hydrogeologists (factsheets etc.), b. Monitor and report regularly all water flows, c. Create and distribute (open) data, atlases, conceptual and numerical models, d. Create awareness. Design using drawings. Involve schools etc.
3	Conserve → store → discharge	a. Harvest rain where it falls, b. Store (urban) runoff where possible, c. Don't waste water by over-drainage, d. Stimulate artificial recharge at any scale and location. e. Helping to reduce drought and restoration of environmental flow.
4	Land use follows soil type and groundwater situation	a. Protect (natural) recharge areas (quantity and quality), b. Reduce drainage of soft soils and soft layers: soft soils areas need solid management
5	"Working with nature"	a. Don't fight nature. Let nature work for you, b. Choose for "soft" solutions if possible, only "hard" solutions if nothing else is possible, c. Examples: room for the river, water quality treatment by wetlands
6	All scales matter	a. From private houses, rice paddies, catchments, transboundary, b. Organize optimization at the same time
7	Never shift problems, neither in time as in space	a. Not to your neighbors or downstream, b. Create water neutral development or better (increase recharge, decrease drainage),
8	Re-use and re-cycle: integrate water system and water chain	a. Don't waste waste water, b. Re-use industrial cooling water, c. Harvest winter of monsoon water
9	Effective water management includes all stakeholders	a. From international level to private house owners, b. Determine water targets (e.g. sectorial groundwater levels, groundwater quality targets), c. Reduce groundwater spillage (financial incentives), d. Design shared solutions (e.g. water recreation park and artificial recharge)
10	Learn from your mistakes	Millions are spilled because of low transparency. Evaluate projects and programs, publish and learn.
11	Remember: water is fun!	a. Water and recreation, b. Source for mineral water and beer, c. Living facing water (in EU houses facing water are more expensive)

20.2 Develop an Integrated Groundwater Recharge Plan

The most difficult water resources management challenge is the imbalance between water demand and seasonal availability. More than 80 percent of the annual flow occurs during the 4-month monsoon (June–September), and the highest demands occur during the 8-9 months (October-May) of the non-monsoon period. Because an expansion of surface water storage is problematic in the Ganga basin, extra groundwater availability should be realized by increasing recharge at any scale. Many studies were executed to find structural regional solutions (Khan et al., 2014).

The recharge situation in the Piedmont fan area and the Mega Fans should be improved or be better managed. Figure 20-2 and Appendix M summarize many possible methods to improve and increase groundwater recharge.

20.2.1 At a Regional Scale

Khan et al. (2014) summarized and evaluated the 4 most promising strategies (Figure 10.5):

1. The current irrigation system: a system of partly water losing/infiltrating irrigation canals, groundwater pumping and irrigation loss.
2. The Ganga Water Machine strategy: Intensive dry season pumping in narrow bands along rivers to lower the water table. Infiltrating water should raise the water table again during the following monsoon season. The induced storage is pumped out during the following dry season.
3. The Pumping along Canals strategy: This strategy resembles the Ganga water machine but the pumps are now located along the unlined diversion canals.
4. The distributed Pumping and Recharge strategy: this strategy resembles the actual situation but the intention is to lower the water table more uniformly throughout the basin, thus creating more storage for extra recharge.

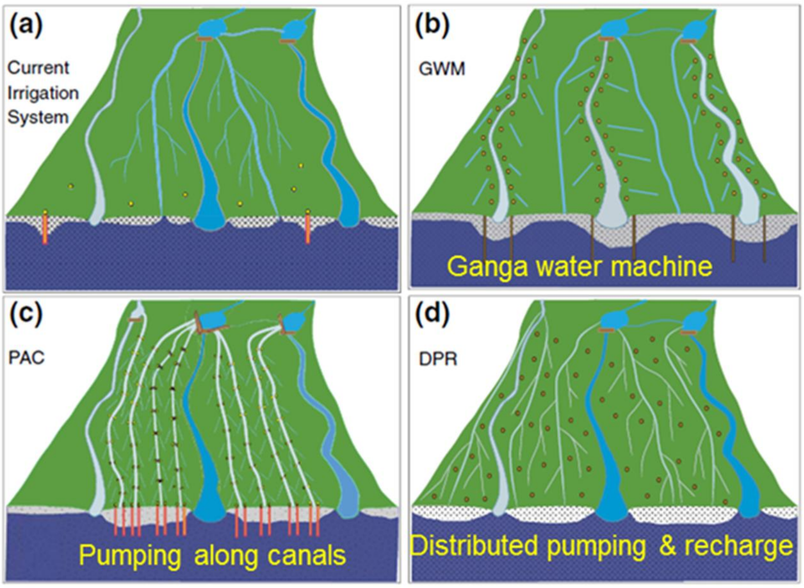

Figure 20-1: Regional strategies for improved groundwater recharge (Khan et al., 2014).

Figure 20-2 presents the results of these strategies, based on the Modflow model results of Khan et al. (2014). The results conclude that these strategies could be useful. Additional pilots are needed to better understand surface water–groundwater interaction around rivers and canals. Solid field studies are lacking.

Strategy comparison. Ranges are for low to high storage scenarios. For GWM, the range encompasses three design drawdown scenarios, for PAC the range is for two different canal spacing, and for DPR the range is for silty to clayey near-surface sediment permeability values

Relative benefits/Drawbacks	Ganges Water Machine (GWM)	Pumping Along Canals (PAC)	Distributed Pumping and Recharge (DPR)
Storage (% of average monsoonal flow in Ganges exiting UP)[a]	~ 7–19 %	~ 8–16 %	~ 6–37 %
Ratio of storage volume to annual volume pumped	0.29–0.42	0.31–0.47	0.25–0.68
Annual cost per m^3 water storage [USD]	0.09–0.17	0.04–0.03	0.03–0.01
Proportion of the pumped water available for irrigation	0.57–0.77	0.78–0.84	0.91–0.96
Annual irrigation water cost per ha land irrigation [USD]	230–450	80–70	40–35
Increase of dry season flow (% of current dry season flow in Ganges exiting UP)	>25 %	>25 %	>25 %
Risk of land subsidence near well-fields	High	Low	None
Disruption of domestic water supply	Yes	Possible	No
Requires ephemeral rivers	Yes	No	No
Complexity/intensity of planning, management and maintenance	High	High	Low

[a] (Based on the estimated 240 BCM monsoon season flow at UP-Bihar boundary; source: World Bank, Ganges Strategic Basin Assessment: A Regional Perspective on Risks and Opportunities, unpublished)

Figure 20-2: Results of 4 most mentioned strategies summarized and evaluated by Khan et al. (2014).

20.2.2 At a Local or Sub-regional Scale

Many opportunities exist to collect and store storm drainage water. Ten ideas are summarized in Table 20-2.

Table 20-2: Methods to improve groundwater recharge.

1	Collect & infiltrate local rainfall from buildings, streets & rice paddy's	a. Dry wells, b. Recharge basins, c. Rice system
2	Improved rainfall harvesting ponds	a. improved design b. Adding infiltration wells
3	Water reservoir optimalization	a. Increasing water level b. Adding infiltration wells
4	Retain intermittent stream water	a. Adding small dams or weirs b. Divert into infiltration depressions c. Increase stream bottom elevation
5	Harvest monsoon river water	a. Divert into infiltration basins b. Add IT-drains
6	Reduce groundwater drainage	a. Increase bottom elevation b. Install vertical underground dams
7	Collect Piedmont area drainage water & infiltrate in alluvium area	a. Divert water into infiltration basins along the Piedmont – alluvium border
8	Reduce evaporation Infiltration areas	a. Improve land use (planning)
9	Infiltration by IT-drains	a. Rain water b. Pond, Reservoir or River water
10	Re-use waste water	

These methods are further visualized in Appendix M (Stuurman, 2018).

20.3 Start Waste Water Treatment and Re-use Initiative

Waste water treatment and reuse will have multiple benefits:

a. It will reduce groundwater use;
b. It will improve the river water quality;
c. Treated waste water will become an important resource;
d. If used for irrigation: treatment can be cheaper and agriculture friendly by not removing Phosphorus and Nitrogen;
e. When future de-centralized treatment plants are planned away from water, especially rivers, but elevated, water can be distributed by gravity (Figure 20-3).

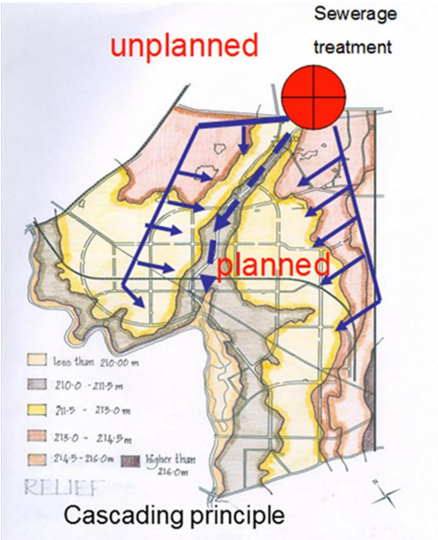

Figure 20-3: Example of a design for a possible re-use system for green areas (parks etc.) in Dwarka (New Delhi) based on elevation data.

20.4 Provide Sufficient Water Supply

Urban subsidence is related to an insufficient drinking water distribution system and non-rigorous water management control. Individuals and companies are therefore drilling their private wells and together over exploiting the aquifers. Improving drinking water distribution will decrease subsidence and also reduce salinization by upconing.

20.5 Recommended Monitoring Actions

1. Construct an easy accessible geological subsurface database:
   a. Dutch example: www.dinoloket.nl (Figure 20-4);
   b. All subsurface data including groundwater monitoring data;
   c. Subsurface models based on geo-statistical methods.
2. Assess deeper groundwater system
   a. Design 2-3 regional assessment transects from Piedmont Fan – South hard rock area (Figure 20-5).
      i. Using existing deeper wells,
      ii. Using existing deep geological drilling results
   b. For each transect: Install 6 very deep (1,000-2,500 m) groundwater observation wells with multiple filters.
      i. Geophysical borehole logging (EM, Temp, Resistivity, gamma to determine aquifer and salt characteristics)

ii. Sample and determine all chemical parameters (to determine quality state and depth of polluted or anthropogenic water);
iii. Sample and analyze all relevant natural isotopes (to determine age and origin of water).

c. Sample, store and analyze drilling cores (lithology, geochemistry).
d. Apply aquifer tests if possible (pumping test).
e. Apply helicopter Electric-Magnetic survey to more accurately map the spatial distribution of saline groundwater.

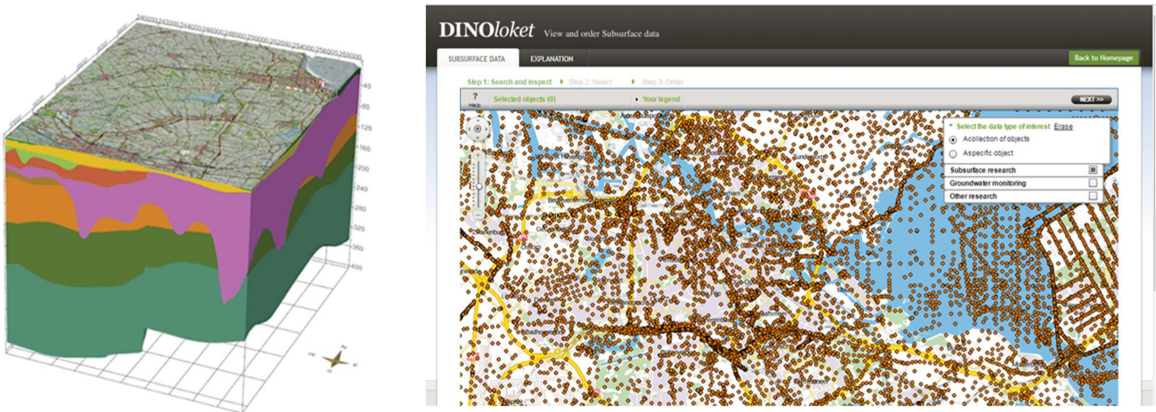

Figure 20-4: Examples of the Dinoloket data base (www.dinoloket.nl).

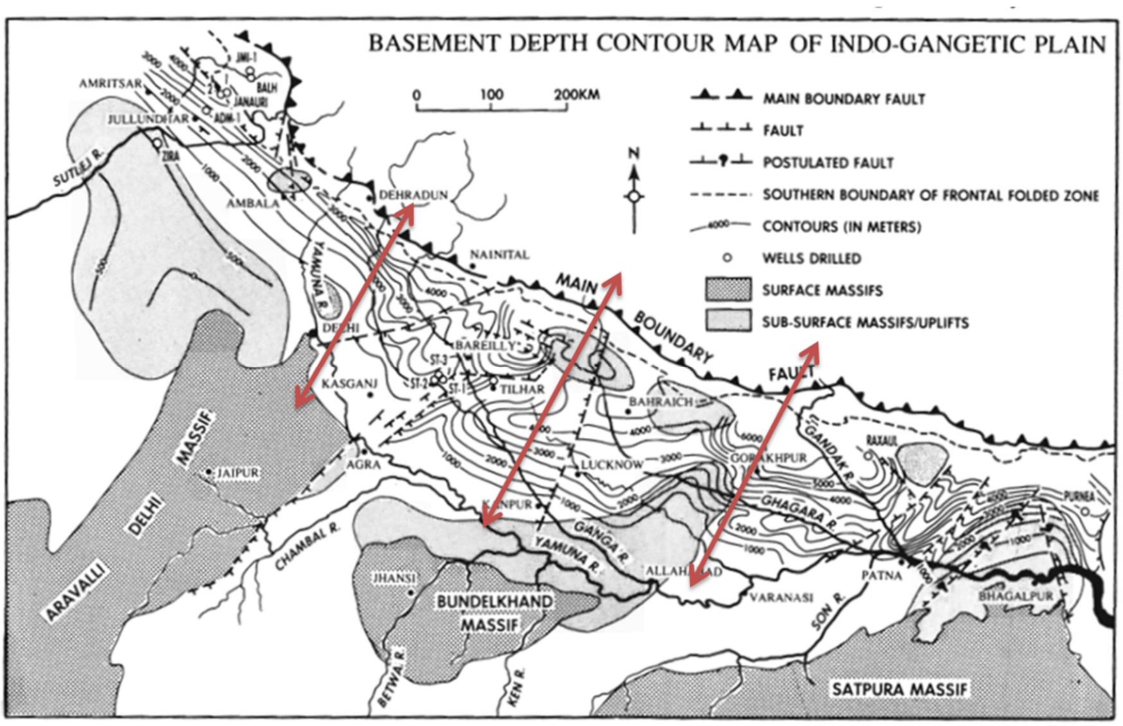

Figure 20-5: Possible locations of north-south (deep/shallow) groundwater monitoring cross sections (map from Singh, 1996).

3. Design and develop a canal and river typology map, making use of the “river styles” assessment (Chapter 2) and groundwater model results, including hydrogeology, groundwater–surface water interaction and water quality.
4. Start Basin wide subsidence assessment:
    a. By satellite InSar study (not possible in agriculture areas. Need solid land cover);
    b. By installation of extensometers:
    c. By analyzing the relation of foundation depths and subsidence rates. The “thousands extensimeter method” will be applied in New Orleans in 2018/2019 (Figure 20-6).

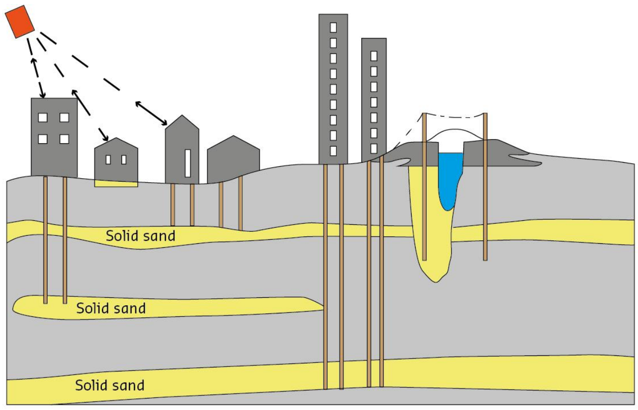

Figure 20-6: Example of thousand extensometer method making use of existing foundations: collect foundation depth data (roads without foundation, bridges and high rise buildings with deep foundations etc.) and analyze subsidence velocity using processed satellite data.

5. To understand and manage Ganga river basin groundwater, the existing groundwater observation network, quality and quantity, needs optimization:
    a. To better understand the canals and river–groundwater relations. Make use of monitoring transects;
    b. To better understand phreatic water: perched, or connected to the deeper groundwater?
    c. Integrate surface water monitoring, water use monitoring and subsidence monitoring.
6. Start with a solid analysis of the existing monitoring results, including all monitoring well characteristics.
7. Start a program to study and protect the Piedmont Fan area. To protect and improve groundwater recharge.
8. Create a basin wide “subsurface (water) storage opportunity” map.
9. Organize a 2-3 day workshop with all Ganga basin groundwater experts (CGWB, BGS, Universities, GRACE experts, Ganga basin groundwater model experts, subsidence experts, Ganga basin geology experts) to identify knowledge gaps

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