Analysis of Developmental Scenarios in Ganga River Basin using a Strategic River Basin Planning Tool (GangaWIS)

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ABSTRACT

The Ganga River basin is the most populated river basin in the world and almost half of the population of India is living in this basin. The Ganga basin outspreads in India, Tibet (China), Nepal and Bangladesh over the total area of 10,86,000 Sq.km. The major part of the geographical area of the Ganga basin lies in India and it is the biggest river basin in the country draining an area of 8,61,452 Sq.km. It covers states of Uttar Pradesh, Madhya Pradesh, Rajasthan, Bihar, West Bengal, Uttarakhand, Jharkhand, Haryana, Chhattisgarh, Himachal Pradesh and Delhi. As per the reports average water resources potential of Ganga basin is 525 BCM. The Ganga basin has a vast reservoir of groundwater, replenished every year at a very high rate. The mean annual replenishable groundwater in Ganga basin is about 202.5 billion cumec per annum.The health of the Ganga basin is deteoriating significantly due to increase in population, high level of water stress due to abstraction of water for increasing agricultural, industrial and domestic uses, and pollution in the river. The major water resources challenge in the Ganga basin is to judiciously manage the water resources to fulfil the ever-increasing agriculture, domestic, and industrial water demands without harming the eco-system. About 77% of the population in the basin is engaged in agriculture which is mostly dependent on irrigation, as almost 85% of rainfall in the basin takes places in four monsoon months from June to September. To deal with such a large and intricate river basin, a tool named GangaWIS (Ganga Water Information System), which is based on Deltares model FEWS (Flood Early Warning System) and developed recently, has been used in the present study to analyse the integrated impact of different possible management strategies on the basin water resources.

GangaWIS is a comprehensive tool that integrates various hydrological components of the Ganga River basin and supports the policy makers in analysing the impact of various future developmental and climate change scenarios and possible interventions. It describes the functioning of water system of the Ganga basin within India with respect to rainfall-runoff, surface water and groundwater flow, storage and diversion of water for various purposes, water quality and ecology. The model simulates the present situation with respect to water resources, infrastructure and water demand. The water information system serves to store and disseminate all relevant information for planning, i.e. maps, measurements and input and output of the river basin model. A dashboard depicts the various indicators to judge the impact of the different scenarios, such as state of groundwater development, lowest discharge, volume of water stored in reservoirs, agricultural crop production, deficit irrigation and drinking water, surface water quality index, volume of groundwater extracted and ecological, hydrological and socio-economic status. The interaction between surface and groundwater is included in the model concept. GangaWIS can be used to analyse and visualise various data (temporal/spatial) and model result and it can provide relevant measured and modelled information to various users such as data managers, modelers and policy makers.

Ganga river basin model is capable of assessing the impacts of future developmental/climate change scenarios and various interventions/measures at basin scale by comparison of simulation results. The scenarios are used to describe model input that approximates the expected situation so that the model output provides a simulation of the river flows, water quality aspects, and groundwater levels. The model inputs include land use, infrastructure development, population/industry/agriculture settings as well as the precipitation and temperature settings. In this study, the indicators of around 20 scenarios simulated by the Deltares in their study (Bons, 2018) were analysed and some of the interventions that can be immediately implemented in the field were identified. Some such interventions include a) implementing approved infrastructure plans, b) conjunctive use management in some irrigation commands, c) increasing irrigation efficiency by 10% etc. The model runs were taken to see the integrated impact of these interventions in achieving better utilization of water resources. The results obtained have been compared with the indicators analysed in the report and will be presented in detail in the paper. The results give a deep insight to the water resources issues in the basin and the impact analysis of various planned interventions. The findings of the study can be useful to the decision makers and different stakeholders in the basin. This analysis helps in visualizing the utility of GangaWIS tool to support strategic basin planning and can be continuously updated with improved data and better interventions.

1. INTRODUCTION

Water is the lifeblood of ecosystems, vital to human health and well-being and a precondition for economic prosperity, Terrestrial water storage is a vital resource for agricultural, industrial and domestic purposes and plays a crucial role in the overall development of a civilisation. Rapidly increasing population and exponential growth of industrialisation and urbanisation have exposed the water resources, to various forms of degradation and put on very alarming rate of depletion. The problem of decreasing water availability and how future climate change might impact existing serious situation is well-recognized for northern India. Monitoring total water storage on and beneath Earth's surface is essential for understanding the hydrological cycle in a changing climate, and for achieving sustainable water management for a continually increasing population.

Ganga basin has an extraordinary variation in altitude, climate, land use and cropping patterns. Ganga river has been a cradle of human civilization since the time immemorial. It is one of the most sacred rivers in the India and is deeply revered by the people of country. River Ganga consists of hilly terrains of the Himalaya with dense forest, sparsely forested Shiwalik hills and the fertile Ganga Plains. The ecological health of the Ganga river and some if its tributaries has deteriorated significantly as a result of high pollution loads through industrial waste; high levels of groundwater abstraction for various purposes like irrigation, domestic, industry; and development of water resources infrastructure like dams, barrages etc. have impacted flow regime of rivers.

One most difficult water resources management challenge in the Ganges Basin is the imbalance between water demand and seasonal availability. More than 80 % of the annual flow in the Ganges River occurs during the South-west monsoon, resulting in widespread flooding. During the rest of the year, irrigation, navigation, and ecosystems suffer because of water scarcity. Storage of monsoonal flow for utilization during the dry season is one approach to mitigate these problems. Keeping these issues in mind, an integrated model (GangaWIS) is used to implement some interventions for mitigating such issues and can see the impact of these intervention in the complete basin and how the system can be improved for future water resource management.

2. STUDY AREA

Ganga river basin is the largest river basin in India, extending over the states of Uttarakhand, Uttar Pradesh, Haryana, Himachal Pradesh, Delhi, Bihar, Jharkhand, Rajasthan, Madhya Pradesh, Chhattisgarh and West Bengal. It lies between East longitudes 73°30 and 89° 0 and North latitudes of 22°30 and 31°30, covering an area of 1,086,000 sq km, extending over India, Nepal and Bangladesh. It has a catchment area of 8,61,404 sq. km in India, constituting 26% of the country's land mass and supporting about 43% of population. The annual average rainfall in the basin varies between 39 cm to 200 cm, with an average of 110 cm. 80% of the rainfall occurs during the monsoon months i.e. between June and October. Because of large temporal variations in precipitation over the year, there is wide fluctuation in the flow characteristics of the river. Rainfall, subsurface flows and snow melt from glaciers are the main sources of water in river Ganga.

More than 60 percent of the water flowing into the Ganga basin comes from the Himalayan streams joining the Ganga from the north. The Peninsular streams combine to contribute only 40 percent of the water, despite the fact that the catchment area of the peninsular streams extends well over 60 percent of the entire Ganga basin. The reported average Water Resources Potential of Ganga basin is 525 BCM. According to the assessment, the total utilizable surface water resource in the Ganga is 250 BCM. The tributaries which contribute the largest amount of water per annum are, the Ghaghara including the Gomti (113.5 BCM), followed by Kosi-Mahananda (81.85 BCM), the Gandak- Burhi Gandak together (58.96 BCM), Yamuna (57.2 BCM), Sone-East of Sone (44.14 BCM), the Chambal (32.55 BCM) and Ramganga (17.79 BCM).

The Ganga basin consists of about 2,76,947 surface water bodies. The majority of water bodies that accounts 98.9 percent of total waterbodies having a size range of 0-25 ha. There are 23 major waterbodies which have size more than 2,500 ha. The Ganga has total 5,25,020 MCM as average water resource potential out of which 2,50,000 MCM is utilizable surface water potential. The total live storage capacity of the Ganga basin is 60,660 MCM where live storage capacity of completed projects is 42,060 MCM and that under construction is 18,600 MCM. The Ganga basin has a vast reservoir of groundwater, replenished every year at a very high rate. The mean annual replenishable groundwater in India as a whole has been assessed at 433 BCM per annum, of which about 202.5 billion cumec per annum (46.8%) lies in the states of the Ganga basin. The conjunctive use of groundwater for irrigation within the canal command areas not only ensures steady supply to the cultivated fields on time but also helps reduce water logging and salinization due to consequent downward movement of subsurface moisture. The most extensively used water sources for irrigation in the basin are the groundwater wells. The water quality monitoring of the River Ganga and its several tributaries are being done in the basin by the State Pollution Control Boards, Central Water Commission, Central Ground Water Board and Central Pollution Control Board. The river water quality in the Himalayan Segment and the Diluted Segment is comparatively good. However, due to heavy discharge of pollutants into the river system, the lower segments are very highly polluted.

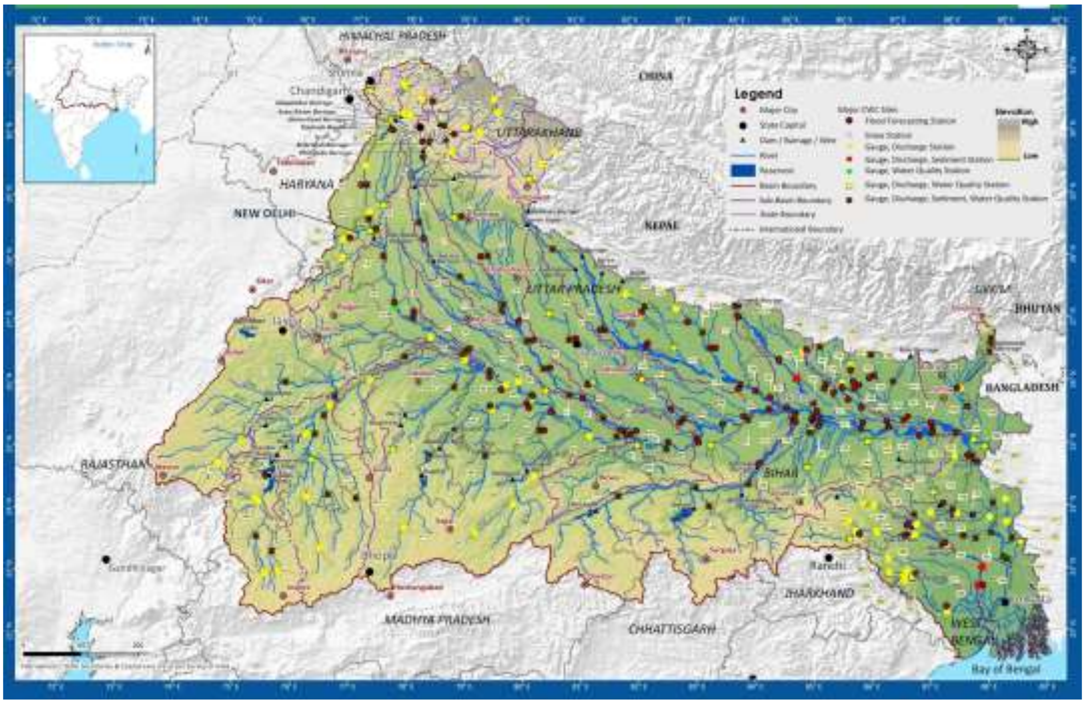

Figure - 1. Ganga basin with sub basin, drainage, and major water resources structure (Source: India-WRIS)

3. METHODOLOGY

In this study, a new integrated model set up GangaWIS (Ganga Water Information System) has been used to analyse the integrated impact assessment of different strategies implemented in model (Figure 2 User Interface of GangaWIS). GangaWIS is developed on the already existing framework known as FEWS (Flood early warning System) originally developed by Deltares, Netherlands. The various component of hydrological process have been incorporated in the GangaWIS, right starting from snow/glacier melt, surface runoff, ground water recharge, surface water quality and surface- groundwater interaction (**see Figure 3**) for a schematic presentation of the interactions between the models). The rainfall-runoff process has been divided into two different models: SPHY and WFlow. They are both fully distributed models working on a grid of square cells. SPHY is used for calculating rainfall-runoff process for mountainous part in the Himalaya region lies in the Ganga basin. It is specifically designed for glacier and snow hydrology. The rainfall-runoff processes for the non-mountainous part of the Ganga Basin are described by the WFlow model. This is a general purpose hydrological model. The river discharges calculated by the SPHY model for the Himalayas are used as upstream boundaries for the WFlow model.

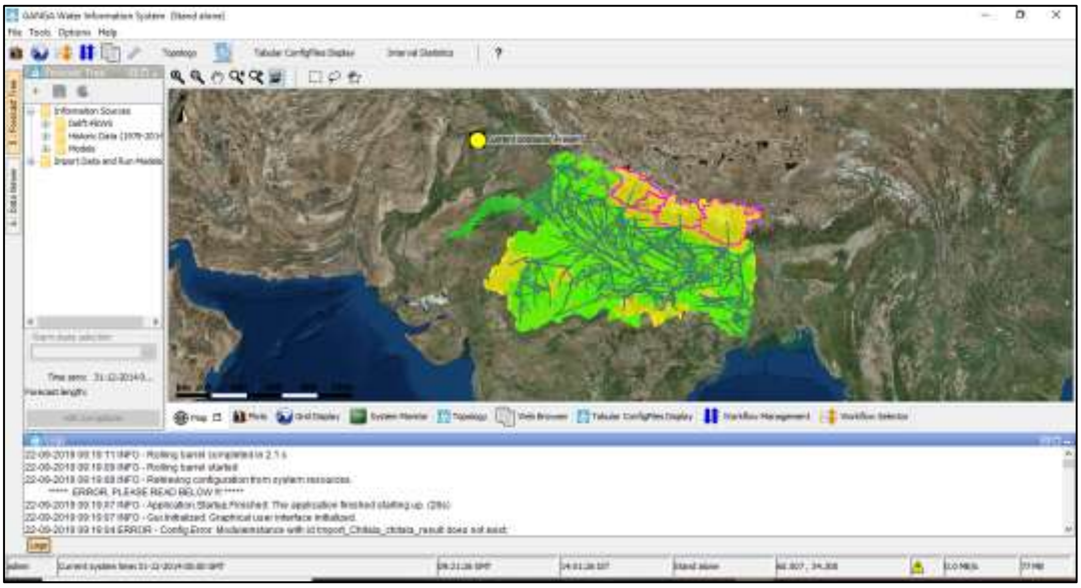

Figure - 2. User Interface of GangaWIS

The water resources planning model RIBASIM (River Basin Simulation Model) is used for allocation and management of water for fulfilling different demands like domestic, industrial, agriculture and e-flow assessment. Its hydrological input is derived from the river discharges calculated by WFlow. RIBASIM uses a schematization of links and nodes to describe the flow of water in the rivers, the storage in reservoirs, the diversion into canals and the use and return flow by different functions (see Figure 4 RIBASIM schematization with nodes and links network). Water can be used from rivers and canals or from groundwater. Furthermore, return flows can be divided over rivers, canals and groundwater. This is an important aspect for the description of the water system in the plains of the Ganga Basin, where extensive leakage from irrigation canals, feeds the groundwater aquifers, that are themselves used for irrigation water supply. Therefore, the RIBASIM model is also linked to the groundwater model by prescribing extraction and infiltration rates and by getting back the flux between the river and the groundwater. Water quality is assessed with the model DWAQ by combining Ribasim's discharges with a pollutant load estimation. Groundwater dynamics are described by the iMOD-MODFLOW model. The model uses the same calculation grid as the hydrological models, but is only applied to the alluvial part of the basin. The recharge into the groundwater is obtained from WFlow and Ribasim also provides the data on water abstractions and river discharges. Based on river discharge, river water levels are derived and used for the calculation of the flux between the river and the groundwater. The impact on the ecology and ecosystem services of the results of the models presented above with respect to discharges, water levels and water quality are evaluated using knowledge rules. All model inputs and all relevant outputs are stored in the GangaWIS.

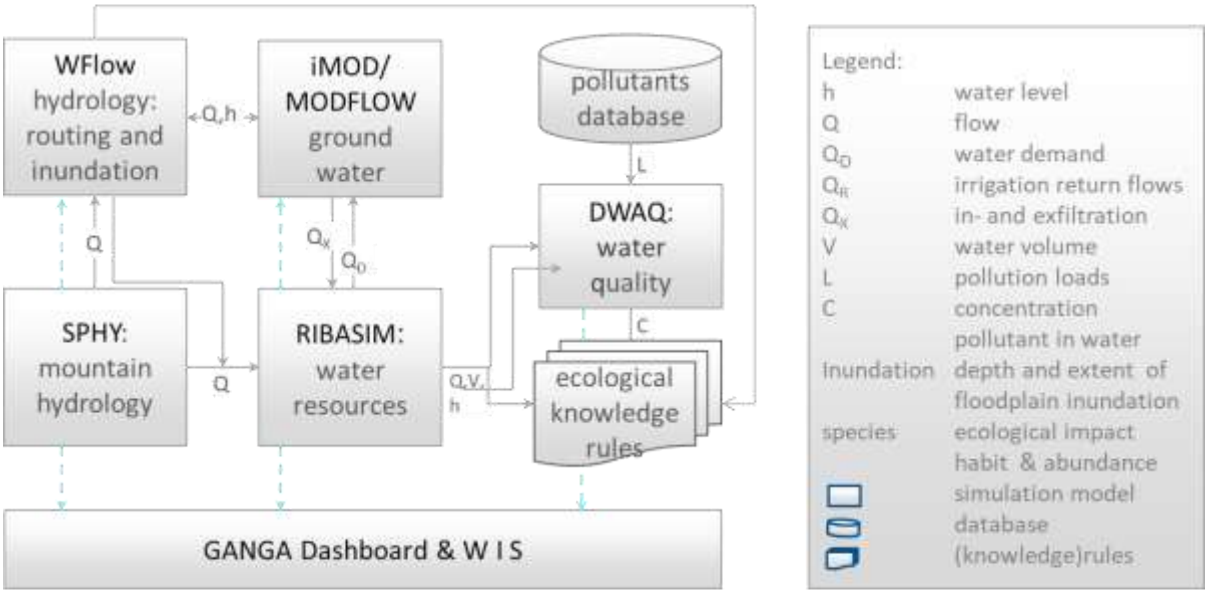

Figure - 3. Schematic presentation of the interactions between the models

The Ganga Water Information System (GangaWIS) is designed to support the understanding of the natural and social system of the Ganga Basin. It provides a central place with relevant measured and modeled information and data for various users, e.g. data managers, modelers, policy makers and decision-makers from different organizations in the Ganga Basin. Ganga WIS is used to analyse and visualise various data (temporal/spatial) and model result, it also facilitates the user to import new input data and run one model or more models in sequence. The exchange of information between the components of the River Basin Model is also taking place through the GangaWIS. The management of different versions of model input and output, to represent different scenarios and strategies, is included in the GangaWIS. Furthermore, the model results stored in the GangaWIS provide the input for the presentation of results in the form of summary in the dashboard.

Most of the components of the River Basin Model are open source. This applies to SPHY, WFlow, iMOD, MODFLOW and DWAQ. This means that both the source code and the executable form of the software are publicly available on internet. The RIBASIM software is licensed software under transition to become open source.

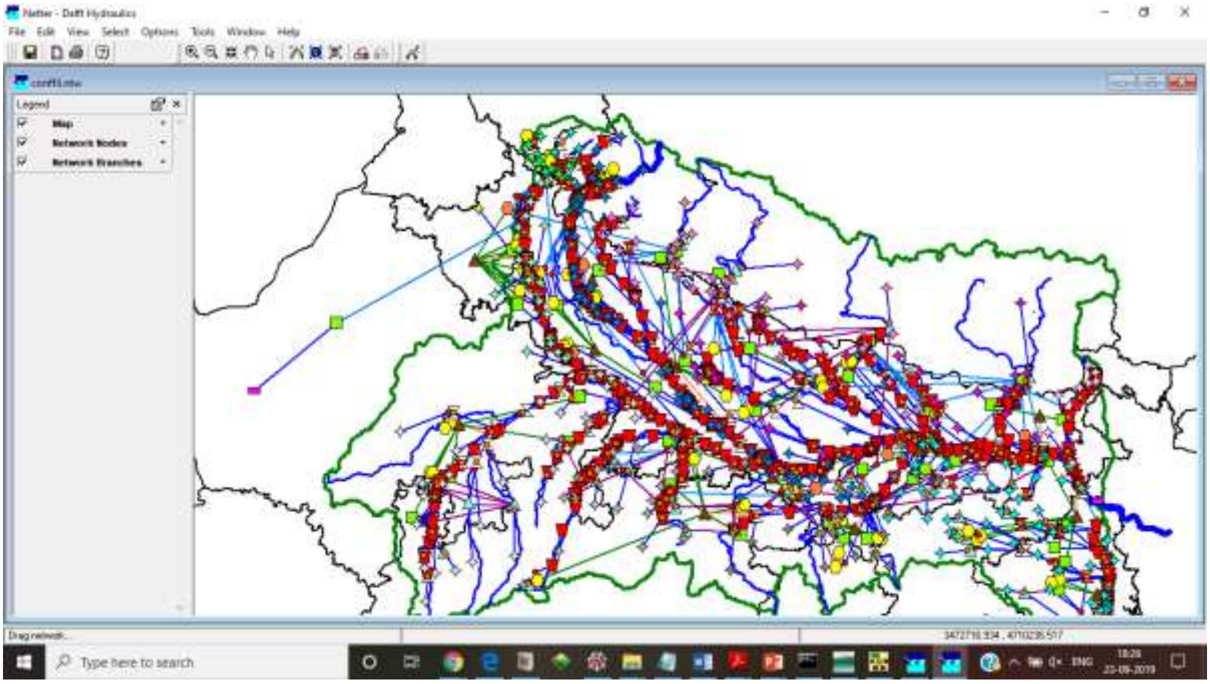

Figure - 4. RIBASIM schematization with nodes and link network

In the existing model based on inputs from various state departments requirements some of the strategies were developed that can be implemented in the model in combination or separately.

i) **Do nothing**: In this strategy it is assumed that in this situation there are no significant improvements in the water resources is implemented.
ii) **Approved Infrastructure**: In this strategy a number of infrastructure projects that are already approved by the government which will be implemented soon are modelled in the model.
iii) **Inter Basin Transfer Links**: In this strategy the main Inter Basin Transfer Link projects approved by the government in the Ganga Basin are implemented in the model.
iv) **NMCG planned treatment**: This strategy includes the additional treatment as planned by NMCG so that its impact can be evaluated.
v) **Improved treatment**: To evaluate the impact of additional investments in waste water treatment this strategy was implemented in which all presently planned WWTP are considered operational.
vi) **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.
vii) **Conjunctive use**: In this strategy the groundwater abstraction capacity is reduced by half for all over-extracted nodes.

The seven 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 any of the two selected run cases with a scale level of basin or state.

3.1 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.

3.2 Lowest Discharge :

River discharge is another important indicator which play a vital role in water resource management. 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.

3.3 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 at the end of the monsoon period for a 1/10 dry year is expressed in billion cubic meters.

3.4 Agricultural Production

The indicator provides agricultural production expressed in ratio between the actual and potential harvested area at basin level. The ratio for 1/10 lowest production is presented.

3.5 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.

3.6 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.

3.7 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. This 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.

3.8 Surface Water Quality Index

The "surface water quality index" is the 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. The classification is such that the water quality requirement becomes progressively lower from A (drinking water source) to E (irrigation and industrial cooling).

3.9 E-flow Status

To assess the impact of pollution 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.

Table - 1. Basin-wide scores for the selected indicators

Indicators	Present Case	2040 Do Nothing	2040 RCP4.5 Do nothing	2040 RCP8.5 Do nothing	Weights
State of GW development (%)	41(5)	89(1)	88(1)	88(1)	100
Lowest discharge (m3/s)	2683(9)	2170(9)	1502(9)	617(7)	100
Volume of water stored in reservoirs (Billion cubic meters)	56(5)	54(5)	52(5)	52(5)	100
Agriculture production (% of area harvested)	96(6)	88(8)	87(8)	87(8)	
Deficit irrigation water (%)	23(7)	31(6)	31(6)	32(6)	100

Indicators	Present Case	2040 Do Nothing	2040 RCP4.5 Do nothing	2040 RCP8.5 Do nothing	Weights
Deficit drinking water (%)	10(8)	34(6)	34(6)	35(6)	100
Surface water quality index	4(2)	4(2)	4(2)	5(0)	100
Volume of groundwater extracted (billion cubic meter)	99(3)	216(0)	217(0)	218(0)	100
Ecological Status	74(7)	73(7)	65(6)	60(5)	100
Hydrological status	62(6)	60(5)	47(4)	38(3)	100
Socio-economic	74(7)	72(7)	66(6)	64(6)	100
Total	68	56	54	48	

The scenarios described above have impacts on the water resources situation in the basin, especially when no additional interventions are implemented. Table - 1 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. A second reason is that water quality is scaled relative to the 'good or pristine' situation. The scenario assessments indicate a significant decrease in future water availability, water quality in the event no additional interventions are made. 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. The next 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.

4. Results and Discussion:

In this study, the indicators of around 20 scenarios simulated by the Deltares in their study (Bons, 2018) were analysed and some of the interventions that can be immediately implemented in the field were identified. Some such interventions include a) implementing approved infrastructure plans, b) conjunctive use management in some irrigation commands, c) increasing irrigation efficiency by 10% etc. To implement these strategies various settings have been modified in the model, all these interventions are combined in one strategy and implemented in the model. The model run has been taken for two years and compared. These results are indicative and same can be run for more years.

i) **Approved infrastructure**: In this intervention all new infrastructure projects that have been approved prior to 2018 have been included, this approved infrastructure plans includes the newly approved dam and reservoirs structures in the selected study area.

ii) **Conjunctive use:** In this intervention the water logged areas and the area where ground water level is rising is identified using the results generated by Ganga WIS. So in water logged areas, water source priority of irrigation node is changed to groundwater from surface water and reduced groundwater abstractions limit in currently over-abstracted locations.

iii) **Increased efficiency**: One of the practical solution is to increase irrigation conveyance efficiency, which can be implemented in near future. So in this intervention is to increase it by 10 percent so for all irrigation nodes the irrigation efficiency is increase by 10 % from existing 57 % to 67 %.

iv) **Improved treatment**: In this intervention all NMCG planned treatment are included and additional surface water treatment capacity in both rural and urban area are added.

Table - 2. Basin wide scores for the selected strategy with all interventions

Indicators	Run Case 1 (Present case)	Run Case 2 (Strategy with multiple interventions)	Weigths
State of groundwater development (%)	34(6)	31(6)	100
Lowest discharge (m3/s)	2811(9)	2789(9)	100
Volume of water stored in reservoirs (BCM)	61(6)	69(6)	100
Agriculture production (% of area harvested)	96(9)	96(9)	100
Deficit irrigation water (%)	20(7)	18(7)	100
Deficit drinking water (%)	11(8)	11(8)	100
Surface water quality index	4(2)	4(2)	100
Volume of groundwater extracted (BCM)	115(2)	112(2)	100
Ecological Status	51(5)	52(5)	100
Hydrological status	29(3)	28(3)	100
Socio-economic	59(5)	59(5)	100
Total	62	63	

This strategy with these intervention have impacted the water resources situation of the basin,. Table 2 shows the basin-wide scores for the selected indicators of the considered strategy. The run case 1(present case) and run case 2 (Strategy with multiple interventions) are compared to evaluate the results and analyse the changes in the scores of indicators. The results shows that there are some improvements in the condition if it is planned well and there are indicators which have adverse effect of the implemented intervention, which is quiet possible.

The results shows that with newly implemented strategy, there is positive impact on state of groundwater development, it has improved. There is decrease in the lowest discharge. Since the water source priority is changed so the results show increase in volume of water stored in reservoirs. Since there are no changes have been made in agriculture crop so there is no change found in agriculture crop production. The intervention has positive impact on deficit irrigation water which has decreased. There is not much impact on the surface water quality index. The implemented interventions have adverse effect on volume of groundwater abstraction, it has increased and there is no change found in deficit of drinking water. The factors related to e-flow assessment, the ecological status has improved, and the socio-economic status has no impact and hydrological status is decreased. The overall impact and score of the intervention is increased.

Conclusion

Ganga basin being the lifeline of millions of people, flora and fauna, aquatic life in Indian Subcontinent is very important to conserve and safeguard the water resources available in it weather it is surface water or under the beneath of ground. For the present study, GangaWIS has emerged as an integrated planning tool for water resource management and analyse the impact of various interventions, implementing conjunctive use model with set of different interventions is very useful tool to ensure long term planning and management of basin. But we have to keep in mind there is no single intervention that can solve all problems for basin planning. Combinations of different interventions is required to achieve optimal result.

The interventions considered in this paper can fetch useful and important results with a long term effect provided the remedies and solutions prescribed by model output implemented in field. However, there will few challenges for reaching the intervention like it will require huge investments and technical challenges. If we will able to overcome to these challenges we can deal with future challenges regarding water availability, water quality and ecology with restoration of the basin system.

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