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Groundwater Studies at National Institute of Hydrology, Roorkee, India

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Abstract — National Institute of Hydrology is a Government of India society under Ministry of Water Resources, River Development & Ganga Rejuvenation. It has been functioning as a research Institute in the area of hydrology and water resources in the country since December 1978 with headquarters at Roorkee (Uttarakhand, India) and six regional centres located in different physiographic regions of the country. This article presents salient details of groundwater studies undertaken by Ground Water Hydrology division of the Institute during last few years.

Keywords — Hydrology; Groundwater; Modelling; FEFLOW; NIH; Roorkee

I. INTRODUCTION

The National Institute of Hydrology (NIH) was established in December 1978 as an Autonomous Society (presently under Ministry of Water Resources, River Development & Ganga Rejuvenation, Government of India). Main objectives of the Institute are to undertake, support, promote and coordinate systematic and scientific research work in all aspects of Hydrology and Water Resources. The Institute has its headquarters at Roorkee (Uttarakhand, India), four Regional Centres at Belagavi, Jammu, Kakinada and Bhopal and two Centres for Flood Management Studies at Guwahati and Patna. The institute is well equipped to carry out computer, laboratory and field oriented studies.

The institute acts as a center of excellence for transfer of technology, human resources development and institutional development in specialized areas of hydrology and conducts user defined, demand-driven research through collaboration with relevant national and international organizations.

The institute vigorously pursues capacity development activities by organizing training programs for field engineers, scientists, researchers, NGOs etc. The institute is focusing studies and R&D in the thrust areas of impact of climate change on water resources; integrated water resources management; groundwater modelling and management; flood and drought management; regional hydrology; hydrology of extremes; reservoir/lake sedimentation; watershed hydrology; and water quality assessment in specific areas. The Institute was awarded the ISO 9001:2008 certificate on December 13, 2012.

II. OBJECTIVES OF NIH

NIH carries out basic, applied, and strategic research in hydrology and water resources. It aims to develop methodologies for optimum utilization of water resources, to develop methodologies for water and environmental sustainability, to propagate emerging technologies in water resources development, to protect the society from water related hazards, and to develop mass awareness for water conservation and optimum utilization. The specific objectives of NIH are as follows:

1. To undertake, promote, assist, and coordinate systematic research and work in all aspects of hydrological sciences and other water-related disciplines, and to publish the findings and results of research and investigations through appropriate offline and online media.

2. To carry out modelling and other advanced techniques to aid in the resolution of pressing societal issues concerning water quantity and quality, including floods, droughts, groundwater, sedimentation, salinization, pollution, and climate change.

3. To research and develop novel, cost-effective tools, techniques, methodologies, procedures, software, and field and laboratory instrumentation, to aid in the performance of its mission.

4. To establish and maintain a live, dynamic and committed resource base in terms of staff, laboratories, equipment, libraries, and specialized expertise in hydrological sciences and other water-related fields.

5. To propagate across society-at-large the application of emerging technologies in water resources development and management.

6. To develop, maintain, and continuously improve its online presence to ensure the widest dissemination of its research.

7. To collaborate with appropriate national and international organizations engaged in research in hydrological sciences.

8. To carry out other activities that are considered by the NIH Society to be necessary, incidental, or conducive to the attainment of its mission.

III. RESEARCH ACTIVITIES

At the headquarters (Roorkee), the R & D activities and consulting services are carried out through six divisions – Surface Water Hydrology, Ground Water Hydrology, Environmental Hydrology, Water Resources System, Hydrological Investigations, Research Management and Outreach. The comprehensive work program of the Institute covers: (i) In-house R & D studies on emerging areas, (ii) Sponsored R & D studies, (iii) Demand driven and referred problems, (iv) Consultancy and Technical services, and (v) Capacity building activities through regular training courses and technology transfer.

The Institute has more than 70 highly qualified and professionally skilled Scientists having expertise on various areas related to hydrology and water resources, ably supported by scientific and technical staff. The Institute has well equipped laboratories for Soil-Water analysis, Water Quality analysis, Isotope analysis, Remote Sensing and GIS, Hydrological Investigations, Centre of Excellence for Advanced Groundwater Research, Snow & Glacier, and Hydro-Meteorological Observatory. The scientific and technical credibility of the Institute in conducting hydrological and water resources research is well recognized both at the national and international level.

Ground Water Hydrology division, a key division of the Institute, has collaborated in many national and international projects. The division undertakes in-house R & D studies, sponsored studies and consultancy projects from the Central and State Government departments and other stakeholders of water. As part of the technology transfer program of the Institute, the division organizes various training courses/ workshops/ seminars/ symposia/ conferences from time to time. The division presently has a number of highly acclaimed scientists along with trained scientific and project staff. Two state-of-the-art units, viz., Centre of Excellence for Advanced Groundwater Research and Soil Water Laboratory, possessing advanced computational and analytical facilities are associated with the division.

IV. GROUNDWATER STUDIES AT NIH, ROORKEE

Providing efficient and effective methodologies and technologies for sustainable groundwater resources development and management are the vision of Ground Water Hydrology division of National Institute of Hydrology, Roorkee, Uttarakhand, India. Some of the emerging areas in the field of groundwater hydrology needing inputs to modern science include groundwater storage and resource estimation; groundwater modelling and management; coastal aquifer dynamics; surface water and groundwater interaction; hard-rock and karst hydrology; groundwater sustainability on supply and demand, groundwater protection against contaminants, and impact of environmental changes on groundwater resources. Keeping in view of these thrust areas, the Ground Water Hydrology division is pursuing the basic and applied research pertaining to various aspects of groundwater hydrology such as, aquifer parameter estimation; aquifer responses due to untoward stresses; groundwater assessment, modelling and management; coastal groundwater dynamics; contaminant transport modelling; managed aquifer recharge; bank filtration; and impact of climate change on groundwater resources. The following groundwater studies and projects have been completed by Ground Water Hydrology division of National Institute of Hydrology, Roorkee (India) during last ten years [1].

4.1 Modelling of a Coastal Aquifer using FEFLOW (2007)

Coastal tracts of Goa are rapidly being transformed into settlement areas. The poor water supply facilities have encouraged people to have their own source of water by digging or boring a well. During the last decade, there have been large-scale withdrawals of groundwater by builders, hotels and other tourist establishments. Though the seawater intrusion has not yet assumed serious magnitude, but in the coming years it may turn to be a major problem if corrective measures are not initiated at this stage. It is necessary to understand how fresh and salt water move under various realistic pumping and recharge scenarios. Objectives of the present study include simulation of seawater intrusion in a part of the coastal area in Bardez taluk of North Goa, evaluation of the impact on seawater intrusion due to various groundwater pumping scenarios and sensitivity analysis to find the most sensitive parameters affecting the simulation.

The study area lies in Bardez taluka of North Goa within the watersheds of Baga river and Nerul creek (around 74 km^2) and covered by Survey of India toposheets number 48E/10, 48E/14 and 48E/15 on 1:50,000 scale. It is bound by rivers Chapora and Mandovi in north and south directions respectively, besides Arabian sea in the west and encompasses coastal tract from Fort Aguada in the south to Fort Chapora in the north (15 km). The soils are predominantly of lateritic nature. However, the coastal areas are made up of alluvial soils composed of loamy mixed sand and loamy sands. Around 30 km^2 area close to the coast (15 km along the coast and 2 km wide) is more prone to seawater intrusion. Layout maps of North Goa and the study area are given in Figures 1 and 2 respectively.

Twenty observation wells were identified in the study area. Monthly groundwater level data was measured in observation wells (September 2004 to August 2005) and groundwater samples were collected in September, November 2004, January, March, April, May 2005. Salinity for collected groundwater samples was measured in the laboratory. Based upon the bi-monthly measurements of salinity, groundwater quality in all the observation wells was found to be reasonably fresh, both in pre- and post-monsoon periods. It can be attributed to the fact that the transition zone of fresh water-saline water lies below the shallow open wells, as evidenced by vertical electrical soundings.

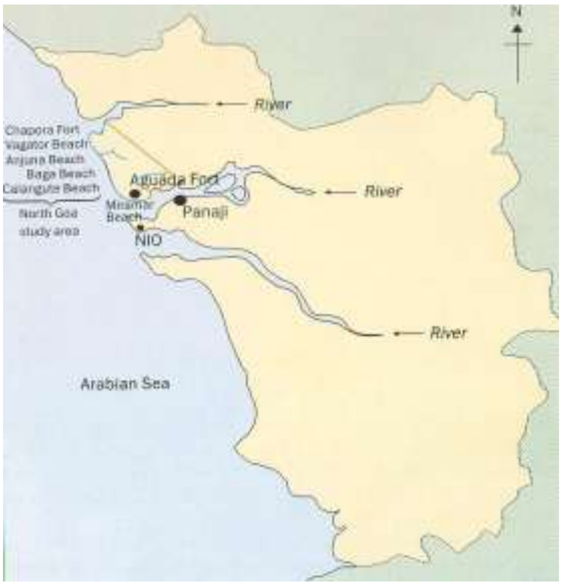

Figure 1. Location Map of Study Area in Goa

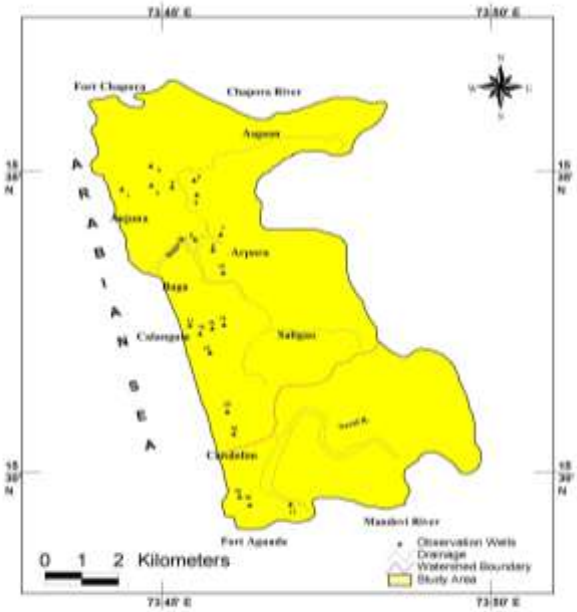

Figure 2. Layout Map of the Study Area

Apparent electrical resistivity (ohm-m) was measured in four profiles along the Bardez coast (Anjuna, Baga, Calangute, Candolim) at 18 locations upto 525 metres from the coast. The inter-electrode separation was kept at 10 meter, that is, the resistivity values measured are at 10 m depth plane. The seawater mixed zone is witnessed along Anjuna (12 to 45 ohm-m) and Baga beach (4 to 46 ohm-m) sections along the low lying sandy alluvial areas. However, along Calangute (75 to 900 ohm-m) and Candolim (142 to 700 ohm-m) beaches, there is no indication of seawater mixing at 10 m depth, as all values are higher.

Seven vertical electrical soundings were carried out at monitoring well sites 1, 3, 6, 7, 8, 15 and 17. These were restricted to a depth of 20 m to know any change in the quality of water vis-à-vis seawater intrusion (3 m to 20 m with 1 m interval). As seen from the apparent resistivity values, well numbers 6, 7 and 8 show low values of resistivity (2 to 33 ohm-m) below about 12 m depth, indicating the presence of seawater or mixed zone below this depth. However, at other sites, there is no indication of the seawater mixing upto 20 m depth. It is noted here that wells located in low lying sandy alluvial areas show seawater mixing than the wells located in laterites at higher altitudes. In both laterite and alluvial soils, the wells are built well above the salt water – fresh water interface and hence no change in water quality was found in summer also.

For the present study, a finite-element model (FEFLOW) was selected for model simulations. The FEFLOW is an interactive finite element simulation system (Version 5.1) for three-dimensional (3D) or two-dimensional (2D), i.e. horizontal (aquifer-averaged), vertical or axi-symmetric, transient or steady-state, fluid density- coupled or linear, flow and mass, flow and heat or completely coupled thermohaline transport processes in subsurface water resources (groundwater systems). The package is fully graphics-based and interactive. Pre-, main- and post-processing are integrated. There is a data interface to GIS (Geographic Information System) and a programming interface. The implemented numerical features allow the solution of large problems.

The aquifer domain of the study area (74 km^2) was discretized using 6 nodal triangular prism elements with 52,656 mesh elements and 32,053 mesh nodes. The transient state simulation of the solute transport was carried out using automatic time step control via predictor-corrector schemes, with initial time step length as 0.001 day and final time as 3650 days (10 years) to reach steady state conditions. Calibration objective for the mass transport was focused mainly at observation wells near Anjuna and Baga beaches and Baga river where resistivity survey has indicated the presence of brackish water.

Three-dimensional plot for mass distribution has been presented in Figure 3. It indicates 3 peaks where salinity near the coast exceeds 6000 mg/l. Along these three sections, the salinity of groundwater was found to be greater than 500 mg/l upto 300 m inland, the maximum (near the coast) being 9400 mg/l, 9600 mg/l and 6800 mg/l respectively. The computed salinity in the aquifer show a sharp decrease of salinity from the coast towards inland. As an example, for the middle section, the salinity varies from 9,600 mg/l to 500 mg/l from the coastal front to a distance 300 m. The model was not fully calibrated because of uncertainties in the hydrodynamic flow and mass transport data used. However, the results show that the density dependent 3D model is reasonable.

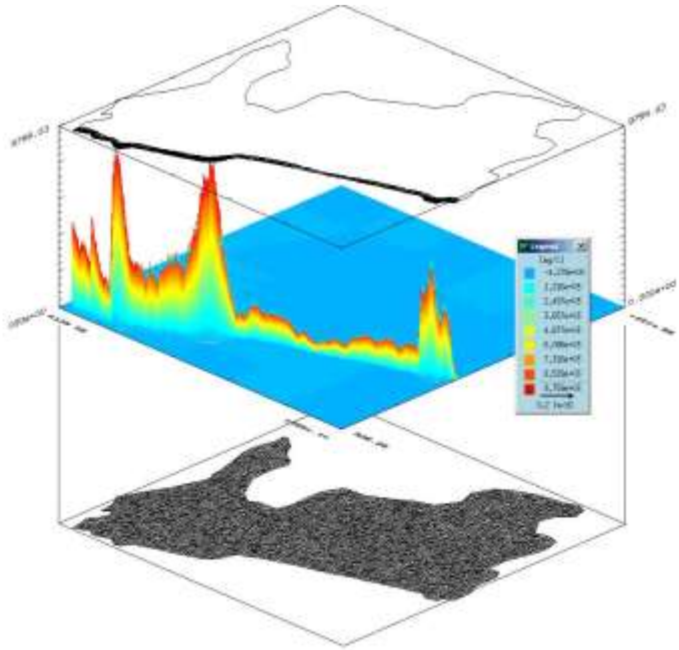

Figure 3. Three-Dimensional Plot for Mass Distribution

The above results indicate that presently, seawater intrusion is confined only upto 300 m from the coast under normal rainfall conditions and present draft pattern. It may be slightly more for low rainfall years. However, seawater intrusion may further advance inland if withdrawals of groundwater by builders, hotels and other tourist establishments continue to increase in the coming years. Therefore, corrective measures with proper planning and management of groundwater resources in the area need to be initiated at this stage so that it may not turn to be a major water quality problem in the coming times. This study will guide in making management decisions to monitor and control seawater intrusion and planning of groundwater development in the area.

4.2 Hydrological and Hydrogeological Investigations to assess Causes of Seepage from the Reservoir of Jaswant Sagar Dam in Jodhpur, Rajasthan (2008)

The Jaswant Sagar dam, locally known as Pichiyak dam, commissioned in the year 1899 by the then Maharaja Jaswant Singh across the ephemeral Luni River with its catchment area of 3367 sq. km. and designed storage capacity of 43.1 million-cubic-meter (mcm) over the water spread area of 18 sq. km. for storage of surface water runoff to supply irrigation water requirement at the downstream canal commands, has been facing the problem of withholding its storage water for a long time.

Reports of earlier investigations opined reasons of excessive losses from storage are due to construction and operation of number of wells inside the reservoir. In order to delineate the reasons in proper scientific terms and to resolve the issues, Water Resources Department, Jodhpur zone, Government of Rajasthan had referred the problem to the National Institute of Hydrology, Roorkee with objectives to find reasons as to why the reservoir of the Jaswant Sagar dam was not capable to retain water for a longer period as designed, and also to find reasons of excessive losses from storage of the reservoir.

In order to find reasons, whether the upstream hydrological interventions or the hydro-geological interventions in the vicinity of the reservoir or there are other factors causing problem to the non-sustaining conditions of the Jaswant Sagar reservoir; a comprehensive hydrological and hydrogeological study and analysis was formulated and carried out envisaging extensive field investigations and experimentations on different aspects as deemed fit for the study. Besides analysis of the information and data supplied by the Water Resources Department and collected from other organizations and during the investigations, topographic survey of the reservoir, intensive infiltration tests, soil textures analysis in the laboratory, geophysical survey on a specific alignment inside the reservoir, and diagnosis survey of the water spread area of the reservoir have also been carried out for finding the more logical meaning of the problem. In scientific terms, the problem has largely been analyzed and resolved formulating the water balance of the Jaswant Sagar reservoir. Different hydrological and hydrogeological components, which are considered in the water balance, have been delineated and estimated from the systematic analysis of different components.

The existing conditions of the sub-surface formations and construction of large number of open wells explained that the reservoir is acting more as a groundwater recharge basin and a scheme of recharge structures than a storage reservoir. Out of the 18 sq. km. of water spread area of the reservoir, more than 2/3rd area represents limestone formation just below the top soil. Presence of fractures and cavities in the limestone formations underneath the reservoir and occurrence of sinkholes and potholes on the surface are the reasons to act more as groundwater recharge basin, while existence of large number of open wells, and tube wells in open wells in the bed of the reservoir explained a scheme more like created groundwater recharge structures. Although the occurrence of fractures, cavities, potholes and sinkholes are natural processes for limestone formation under saturated condition, but the installation and operation of the wells inside the reservoir had accelerated the natural processes to take place at faster rate.

The causes of excessive water losses from reservoir storage are, thus, established as sub-surface vulnerability exaggerated by the presence of wells inside the reservoir. The sub-surface formation representing limestone formation below the reservoir bed is, thus deemed to be unfit and unfavorable to retain stored water in the reservoir. Only about 1/3rd of the water spread area along the right side of the reservoir, underneath of which sandstone formation is laid down, is deemed fit and favorable to retain stored water for a longer time. Closure of the wells along with adequate sealing may partially reduce the loss of water from the reservoir, but the fractures, cavities and upcoming of sinkholes can not easily be restored, and effectively controlled. Any treatment as damage control measures to the underlain limestone formation may prove to be very complicated and expensive than the expected benefits to come.

The seepage rates estimated without the presence of sinkholes from the observed stages in the reservoir on different years have been found to be varied between 5.5 cm/day to 17 cm/day. The time duration for the reservoir to be emptied from its extended overflow level of 896.5 feet to its new zero level of 876 feet, for the estimated seepage rates along with the evaporation rate, has been worked out to be 57.27 days, if there were no sinkholes on the reservoir bed. The presence of sinkholes will reduce the time duration extensively.

4.3 A Vision Document on "Mitigation and Remediation of Ground Water Arsenic Menace in India (2009)

Occurrence of Arsenic in groundwater, in excess to the permissible limit of 50 μg/L in the Ganges-Brahmaputra fluvial plains in India covering seven states namely, West-Bengal, Jharkhand, Bihar, Uttar Pradesh (in flood plain of Ganga River); Assam and Manipur (in flood plain of Brahamaputra and Imphal rivers) and Chhattisgarh state (in Rajnandgaon village), has been described internationally as the World's biggest natural groundwater calamity to the mankind after Bangladesh.

Over the last 25 years, since the groundwater arsenic contamination first surfaced in the year 1983, a number of restorative and substituting measures coupled with action plans focusing mainly towards detailed investigations to understand the physio-chemical process and mechanism, alternate arrangement to supply arsenic free water to the affected populace have been initiated mainly in West Bengal. Efforts have also been made in the development of devices for arsenic removal and their implementation at the field. While in other states, they are meager. Despite number of corrective and precautionary measures, the spread over of arsenic contamination in groundwater continues to grow and more new areas have been added to the list of contaminated area. The problem resolving issues, thus, seem to be partial and inadequate, that need to be strengthened by strategic scientific backing.

The document focuses mainly on: (i) up to date status of arsenic menace in India, (ii) state-of-the-art of scientific knowledge base, understanding and technologies available from both national and international perspectives, (iii) technologies in place, (iv) preventive and corrective measures taken so far and results thereof, (v) shortcomings, and possibility of employing success stories of one place to another region, (vi) further work to be undertaken, (vii) roadmap to achieve the targeted milestones, (viii) framework of activities to be taken up, etc. For figuring these concerns and issues, a total of ten different Chapters linking one to another are deliberated. Of which, first six chapters illustrate the knowledge base, understanding, status , technologies available followed by a critical appraisal, while the other four chapters elaborate on further work required for achieving sustainable solution for arsenic menace, roadmap to achieve those along with an envisaged 'Plan of Actions' and financial requirement to achieve those targeted tasks.

A framework of activities with an estimated financial target of Rs. 200 crores for a period of five years has been envisaged to resolve arsenic menace exposed in seven states in India. It is believed that the outcome of these scientific tasks will help building the strategy to mitigate and remove groundwater arsenic menace in India.

4.4 Problem of Rising Ground Water Level in Jodhpur City (2011)

A sponsored project entitled "Problem of rising ground water level in Jodhpur City" was sponsored by Ground Water Department, Jodhpur in April 2009. The main objectives of the project are: (i) identification of cause(s) of rising groundwater levels in Jodhpur city (ii) development of an effective and sustainable management plan for maintaining the water table of area at a safe level to avoid any negative impact on the civil structures and population of the area.

The Jodhpur city (also known as Sun City), that had spread in an area of about 14.5 sq.km. in the year 1972 (Survey of India map, 1972), is presently sprawled over 76 sq.km. between latitudes $26^0$15' N to $26^0$20' N and longitudes $73^0$0' E to $73^0$4' E in the Thar Dessert in Western Rajasthan. To support the water supply requirement of the city area for domestic, commercial and industrial purposes, since the year 1997 the Public Health Engineering department had switched over from the earlier mixed supply pattern of surface water and groundwater to the present completely canal water based supply system through storages in the Kailna-Takhatsagar reservoir. The Kailna-Takhatsagar reservoir are two cascading type naturally formed large depression storages located about 5 km. away from the city towards the western side. The monsoon runoffs that generate from the city's catchment partially flow out through the storm water drainage system and partially get accumulated in the water bodies located within the city.

Prior to the current arrangement of water supply from the transit storage in the Kailana lake, Takhatsagar reservoir and Umaid sagar reservoir, which are fed from the IGNP linked Rajiv Gandhi Lift canal, the domestic and municipal water supply including drinking water was met from hand-pumps, tube-wells, step-wells, baories, and from surface water storage in the city. After the existing arrangement of the water supply scheme to the city in the year 1996-97, i.e., feeding the Kailana Lake and Takhatsagar reservoir from the IGNP linked Rajiv Gandhi Lift canal and transferring the water from the Kailana and Takhatsagar reservoir largely by pumping and partially by gravity flow for treatment of water and then supplying to the city, almost all the previous provisions of water supply from the groundwater storages have been put into hold. The enhanced-urban-water-supply-return-flows and the seepage from the water bodies may cause rise in groundwater level. The existing hydrogeological condition and water usages transformation have consequently given rise to the problem of groundwater level increase. The resulting impact of rise in groundwater level over the years was such that a number of pockets and stretches in the city area have been experiencing waterlogged conditions. The rising trend of groundwater level was noticed since the year 1997, and over the years the situation had continued to be so aggravated that considerable area, mainly in the old city area had come under the grip of water logging conditions. Many depressed land surfaces along the built up groundwater flow direction had also experienced the surface water logging conditions.

To cope up with the situation of rising groundwater levels and water logging conditions, the State Groundwater Department has made several pumping stations to lower the groundwater levels in a number of affected areas. Even people having basement floors in the affected areas have also regularly drained out the accumulated groundwater in the basement floors. Pumping out of accumulated groundwater through network of bore wells, from baories (ponds) and from the basement floors in the affected areas is being carried out on daily basis. It has been reported that with the progression of time, the waterlogged areas are gradually spreading towards south-easterly along the direction of built up groundwater flow.

In order to achieve the above objectives, the scientific tasks carried out in the study are: diagnosis survey, field experiments, rigorous data analysis, hydrologic analysis of different components linked to the water balance of the area, and simulation of water table by groundwater modelling. Based on the analysis of groundwater data and other relevant information, the following important points are noted:

- The Kailana-Takhatsagar reservoir and Jodhpur city are located in two different geologic formations. The geological formation on which Kailana-Takhatsagar reservoir is located is of Malani group having low hydraulic conductivity. Therefore, the seepage loss from the lake will not be very significant.
- The source of water causing water logging is getting originated locally in the problematic area.
- The seepage from the Kailana-Takhatsagar reservoir does not enter to the waterlogged area.

4.5 Impact of Climate Change on Dynamic Groundwater Recharge in a Drought Prone Area (2012)

The objectives of this study were to quantify the impacts of climate change on groundwater in Sonar sub-basin, Madhya Pradesh and to simulate the groundwater levels and investigate the temporal response of the aquifer system to historic and future climate periods. The Sonar sub-basin falls in the Bundelkhand region of Madhya Pradesh. The Sonar river is a tributary of the Ken River. Geographically, the sub-basin extends from latitudes 23º21'14" to 23º50'05" N and longitudes 78º35'48" to 79º10'50" E. The total area of the sub-basin upto the gauging site at Garhakota is 1538 sq.km. The Sonar river originates in the Raisen district and its major part, 94% of the basin area, falls in the Sagar district and balance 6% falls in the Raisen district.

In this study, projected rainfall and temperature for the Sonar sub-basin for the years 2039, 2069 and 2099 have been generated based-upon IPCC SRES scenarios (A1FI and B1) [2] of GCM projections and site-specific groundwater recharge is estimated at 12 locations using Visual HELP model for historic and future climate periods. The simulation of groundwater levels has been done by dividing the whole study area into 12 zones. Historical rainfall showed a declining trend while temperature showed an increasing trend for the time period 1972-2003. Because of declining trend in historical rainfall, the future rainfall has been found to have declining trend for the baseline scenario. As compared to the baseline scenario, following changes for the time slice 2010-2039 have been obtained:

- change in temperature under A1FI and B1 scenarios is +1.27 and +1.22 respectively.
- change in rainfall under A1FI and B1 scenarios is +3.0 and +4.4% respectively.
- change in groundwater recharge under A1FI and B1 scenarios is +2.1 to +3.8% and +1.8 to +6.1% respectively.
- change in groundwater levels under A1FI and B1 scenarios is +8.0 and +14% respectively.

The additional quantity of water required as artificial recharge to maintain the sustainable groundwater levels comes out to be 4.3% of the average annual recharge. This amount is around 0.6% of the average annual rainfall. This study may also be used as decision support for developing scenarios of groundwater levels for various recharge conditions and artificial recharge volume required for groundwater sustainability. The output of this study will be helpful for the water resources management based on the long-term planning in response to the climate change. It is to be pointed out that the future impacts of climate change are associated with a number of uncertainty involving multiple driving forces and processes, therefore, the analyzed results can be considered as an indicative.

4.6 Quantification of Impact of Rainwater Harvesting on Groundwater Availability in Aravalli Hills (2013)

The main objective of the project was to study the enhanced groundwater recharge through rainwater harvesting structures in the region of Aravalli hills in Rajasthan. The study has been carried out in collaboration with Wells for India, a non-governmental organization in Udaipur, Rajasthan. The study area selected for investigation is located in Savna watershed of Jaisamand lake catchment which is a water scarce hilly hard rock terrain. The area is inhabited by poor tribal communities for whom groundwater is the major source of water supply. To augment groundwater recharge in the region, a number of rainwater harvesting structures such as anicuts and loose stone check dams besides other water conservation measures have been taken up in Savna watershed. To gauge the impact of these structures, mainly anicuts, on groundwater availability in the region, isotope based field investigations and mathematical analyses of the groundwater flow and recharge has been carried out. For this purpose, field surveys were performed and water samples for isotope analyses were collected from field. The soil samples were analysed at the Soil Water laboratory while the isotope samples were analyzed at the Nuclear Hydrology laboratory of the Institute. The study demonstrates that in a hilly hard rock region, rainwater harvesting structures help in augmenting the groundwater recharge and aid in cultivation of rabi crop through groundwater irrigation.

4.7 State-of-the-Art Report on Modelling of Coastal Aquifers Vulnerable to Sea Water Ingress (2013)

The study was undertaken with a view to characterize the water quality problems of coastal regions, compile recent advances in hydrochemical and solute transport investigations and modelling in areas vulnerable to seawater ingress and review studies on impact of climate change on water resources and water management of coastal regions. Freshwater stored in coastal aquifers is particularly susceptible to degradation due to its proximity to seawater, in combination with the intensive water demands that accompany higher population densities of coastal zones. The primary detrimental effects of seawater ingress are reduction in the available freshwater storage volume and contamination of production wells, whereby less than 2 percent of seawater renders freshwater unfit for drinking. Based on the above study, a base paper titled 'Coastal Aquifer Management Including Use of Hydraulic Barriers for Control of Seawater Ingress' was prepared and submitted to Ministry of Water Resources, Government of India. The paper addresses the issue of sea water ingress in the context of the growing need for freshwater in coastal regions and a changing climate. It further highlights the coastal aquifer management strategies and adaptation options in terms of (i) scientific monitoring, assessment and modelling, (ii) behavioural and institutional approaches, and (iii) engineering measures.

4.8 Coastal Groundwater Dynamics and Management in the Saurashtra Region, Gujarat (2014)

This Purpose Driven Study under the World Bank funded Hydrology Project (Phase-II) has been conducted in collaboration with Gujarat Water Resources Development Corporation (GWRDC) Ltd., Gandhinagar. The Minsar river basin in Saurashtra region of Gujarat was selected for conducting investigations under the project. The river basin extends between the latitudes 21°30'13.9" to 21°58'17" N and the longitudes 69°25'13.1" to 70°1'49.2" E, and covers an area of about 1751 km^2, with a coastline about 43 km long along the Arabian Sea. River Minsar which originates from the hills in the upland area is ephemeral carrying water mainly during the monsoon season. Groundwater is the major source of water supply for irrigation and domestic purposes. Miliolitic limestone forms the potential aquifer system along the coastal belt; however, the aquifer system on the entire stretch of the coast is affected by salinity. The major objectives of the study were to characterize the various hydrologic components, establish the physico-chemical mechanism of mixing of freshwater-saltwater, identify causes of groundwater salinity, numerical modelling of coastal aquifer system, and evaluate the effect of water availability and quality on the socio-economic growth.

To achieve the objectives, detailed hydrogeological and geochemical surveys were carried out in the Minsar river basin. Sixteen additional piezometers were also drilled to monitor water level and quality at selected locations and at different depths. Depth to groundwater levels and TDS profiles in the wells were monitored regularly over the observation network established in the study area. Water samples were also collected at regular intervals for chemical and isotope analysis. These samples were analyzed at Water Quality and Nuclear Hydrology laboratories at NIH, Roorkee. Using available litholog data from GWRDC and CGWB, a fence diagram of the area was constructed for aquifer characterization and numerical modelling of the aquifer system. Further, to evaluate the impact of the water quality and prevailing water management policies on the environment and socio-economics of the villages along the coastal belt, a parallel study was undertaken that involved the integration of remote sensing techniques and socio-economic surveys within a GIS framework. The major findings from the study are given below.

The region near the foothills of Barda hills exhibits significant thickness of limestone and comprises a major groundwater recharge zone. Several factors contribute to groundwater salinity in the Minsar basin. Gaj beds of Miocene age that were formed in marine environment, have contributed to groundwater salinity both close and away from the coast in inland areas. Upconing of underlying saltwater due to groundwater pumpage for crop irrigation enhances the groundwater salinity for limited time periods. Close to the sea coast, it is the seawater ingress in some pockets that has given rise to elevated levels of salinity. In addition, on the sea coast, sea water in the form of spray, gets deposited on the coastal land surface and plants and adds to soil salinity. Chemical analyses of water samples have indicated the presence of ion exchange phenomena in the transition zone of the freshwater-saltwater interface. Stable isotope investigations have revealed that in the Ghed region (Kerly creek), the zone of transition exists at 15 m ± 3 m (approx.) altitude. Numerical modelling of the coastal aquifer system in Minsar river basin has shown that the seaward hydraulic gradient suffices to control the landward movement of the freshwater-saltwater transition zone. As an outcome of the water conservation measures taken over the last two decades and above average rainfall in most of the years, relatively more freshwater is available for crop cultivation, compared to previous decades. A gradual change in cropping pattern is witnessed with more farmers opting for cash crops instead of the coarse cereals grown earlier. As part of the Technology Transfer under the project, three training courses were organized in Gujarat for officers of State Groundwater Departments of coastal states under HP-II.

4.9 Estimation of Specific Yield and Storage Coefficient of Aquifers (2014)

This study includes a critical appraisal of various methods and techniques for estimation of specific yield and storage coefficient including their merits and demerits, and also the data requirement of each method. The objectives of the study are: (1) compilation and critical appraisal on various methods developed and widely used for estimation of specific yield and storage coefficient, and (2) preparation of a state-of-the-art report on estimation of specific yield and storage coefficient.

On the basis of comprehensive literature survey on specific yield and storage coefficient, various methods have been categorized and an assessment on prioritization of suitability of various methods under different field conditions has been done. Windows based software has also been developed for the selection of suitable methods and computation of specific yield and storage coefficient under different field conditions. In addition to estimation of specific yield or storage coefficient, the developed software can also be used either for selection of methods based on data availability or assessing the data requirements based on selected method. The outputs of the study would be helpful to researchers and groundwater professionals as an option in deciding the appropriate method for the specific yield estimation for groundwater modelling and management.

4.10 Saph Pani - Enhancement of Natural Water Systems and Treatment Methods for Safe and Sustainable Water Supply in India (2014)

This collaborative R & D project with 20 partners from 8 Countries (Switzerland, France, Germany, Austria, Netherlands, India, Sri Lanka, and Australia) was funded by the European Union (EU) under its 7 Framework Program (Grant Agreement # 282911) with a total EU's contribution of 3,499,620 € for the period October 2011 to September 2014. The project was aimed to study and improve natural water treatment systems such as river bank filtration (RBF), managed aquifer recharge (MAR) and wetlands in India building local and European expertise in this field. The project also aimed to enhance water resources and water supply particularly in water stressed urban and peri-urban areas in different parts of the Indian subcontinent. The project focused on a set of specific case studies in India. These included a range of natural water systems and engineered treatment technologies investigated by different work packages including RBF, MAR and constructed wetlands.

The field site investigations included hydrogeological, hydrological and geochemical characterization and depending on the degree of site development, water quality monitoring or pre-feasibility studies for new treatment schemes. In addition to the natural treatment systems, the investigation recommended appropriate pre- and post- treatment steps to optimize production of potable water quality and to avoid operational issues such as clogging of aquifers. The experimental and conceptual studies were supported by modelling to improve the conceptual understanding of the sites and enhance the transferability of results across India and to Europe.

NIH, as one of the 20 consortium partners, worked on two specific technologies; RBF and MAR. In RBF, NIH was actively involved in Haridwar RBF study which contained analysis and modelling of RBF system including baseline data collection from different states of India on identification of feasible RBF sites. In MAR technology, NIH has carried out a comprehensive study on feasibility of MAR and ASR in Raipur area. In addition to these case study activities, NIH, as leader of the Training & Dissemination activity, organized a number of training courses jointly with the respective work package partner. The major achievements of the Saph Pani project are:

1. Knowledge on optimal hydrologic and hydrogeologic settings and methodologies for extending RBF to other areas in India.
2. A set of Indian MAR guidelines for aquifer recharge and storage schemes covering different hydrogeologic settings to cope with changing supply and demand of groundwater.
3. Strategies to make use of natural and constructed wetlands for conserving eco-balance of sprawling urban areas and recycling of wastewater for peri-urban agricultural production.

These achievements were complemented by optimized post-treatment for effective re-use of treated water, mathematical modelling and an integrated sustainability assessment. The knowledge base and technologies have been extended, shared and translated to the implementing agencies and the private sector, especially SME (small and medium-sized enterprises), through technical reports, training and an International Conference.

4.11 Managed Aquifer Recharge (MAR) and Aquifer Storage Recovery (ASR) (2014)

This study was undertaken as part of the 'Saph Pani' project sponsored by European Union and aimed to examine feasibility of Managed Aquifer Recharge (MAR) through a lake (Teliabandha lake) in Raipur city, Chhattisgarh by conserving monsoon surface runoff and its water quality constituents. Raipur municipal boundary, which lies between 21°10' and 21°21' N latitudes and 81°32' to 81°44' E longitudes, forms the study area. The Raipur city once had 154 small and large water bodies, out of which 85 talabs are now existing. The Teliabandha lake has a water spread area of 0.12 km^2 and a catchment area of 1.14 km^2. The objectives of the study are: (i) identification of potential recharge sites for groundwater resources augmentation; (ii) modelling and analyzing aquifer responses due to recharge from the identified potential recharge sites, and management of augmented groundwater resources for subsequent potential uses.

The components of water balance equation have been estimated by comprehensive analysis of hydrological and hydrogeological aspects of the selected lake, which include analysis of rainfall-runoff, evaporation rate, lake water quality, lake geometry, aquifer characterization, parameters estimate, ambient groundwater levels and quality. Based on the analysis, a semi-analytical mathematical model to estimate unsteady groundwater recharge resulting from variable depth of water in the lake, influenced by time variant inflows and outflows has been developed. Results reveal that the recharge rates from the lake is very less, which ranges between 3.75 mm/day to 4.82 mm/day. The lake water quality indicates contamination by bacteriological parameters (viz. Faecal coliform and Total coliform), turbidity and COD, exceeding the permissible limit for drinking water standards [3]. Lake catchment possesses favourable hydrological and hydrogeological features except the geological stratum of massive limestone configuration. However, despite this, MAR-ASR by additional engineering hydrological interventions has not been found viable because of the restraining purification capacity of limestone formations.

4.12 Flow and Contaminant Transport Modelling of Riverbank Filtration (RBF) (2015)

The objectives of this study are to: (i) analyze and model the flow paths and travel times of the existing bank filtration sites along the bank of the Ganga river in Haridwar, and (ii) model and evaluate removal performance of organic pollutants, coliform bacteria and other pathogens by bank filtration. The study area encompasses the flow domain of 22 RBF (River Bank Filtration) wells in operation at Haridwar for drinking water supply in the city. These RBF wells, locally called 'Infiltration Wells', are situated in the vicinity of the river Ganga and Upper Ganga Canal (UGC) network. More than 50% (> 64,000 m^3/day) of drinking water requirement of the city is met from these 22 RBF wells. Each RBF well is equipped with a pump set above the ground surface and extracts water by a suction pipe of 15 cm diameter. Methodology adopted include (i) data collection and base data computerization, (ii) conceptualization of the problem, model setup, model data preparation and (iii) model calibration, validation and analysis. To assess the improvement in water quality of riverbank filtrate, samples of groundwater, surface water and RBF wells' water were collected once a month continuously for two years.

Compared results of water quality parameters for surface water, groundwater, and infiltration wells showed considerable improvement in the quality of riverbank filtrate water as it moves through the subsurface. Analyses of major ions such as, Na^{2+}, K^{+}, Ca^{2+}, Mg^{2+}, SO_4^{2-}, and NO_3^{-} enabled to understand the mineralization process of water during the subsurface passage. Ferrous (Fe^{2+}) and Manganese (Mn^{2+}) are essential dietary elements present in water with recommended values of 2 mg/L and 0.4 mg/L, respectively by WHO [4]. In the present case, the concentration of Fe^{2+} and Mn^{2+} in river water and in nearby RBF wells at Bhupatwala, Pantdweep and Bairagi camp indicated that river water has higher concentration of Fe^{2+} and Mn^{2+} ranging from 2.1 to 5.5 mg/L and 1.9 to 6.7 mg/L, respectively, during monsoon. Turbidity of the Ganga river (upstream and downstream of Bhimgoda barrage) during monsoon has been observed to be 2 to 15 times more than in the non-monsoon season due to high flow velocities, high runoff and erosion of soil and riverbed materials. However, the turbidity of the abstracted water has been observed to be below the Indian Standard limit of 5 NTU [5] during monsoon and non-monsoon. Using the data of aquifer hydraulic properties, pumping schedule of 22 RBF wells and characterized form of the aquifer in visual MODFLOW, a steady state groundwater flow has been developed to ascertain flow path of the groundwater system consequent from operation of RBF wells.

4.13 Web Enabled - Groundwater Recharge Estimation Model (WE-GREM) (2016)

Artificial groundwater recharge is promoted in India in large scale as a technique to replenish and re-pressurize depleted aquifers, controlling saline intrusion or land subsidence and improving water quality through filtration and chemical and biological processes. There are number of techniques for artificial recharge. Their uses depend on the hydrogeology and field conditions. Recharge basin is one of the popular techniques normally preferred in alluvium formations. Groundwater recharge from a recharge basin is time variant, and the rate of recharge depends on potential head difference between water in the recharge basin and underneath groundwater table. Water surface evaporation and recharge basin geometry also govern the recharge rate. Correct estimation of recharge component and other hydrological components is essential for judicious management of both surface water and groundwater. This 'Groundwater Recharge Estimation Model' is aimed to help groundwater professionals and researchers to use it as a tool for correct estimation of groundwater recharge and other hydrological components associated with a recharge basin. Thus, the objectives of the task were framed as:

• To develop a comprehensive user friendly web-enabled time-varying "Groundwater Recharge Estimation Model".
• To provide a platform to users and professionals for calculating time-varying depth of water in, and groundwater recharge from, a surface water body without using any third party software.
• To facilitate users and professionals in estimation of groundwater recharge from a large surface water body and depth of water in it and to visualize the output in graphical as well as tabular format.
• To host the module in the public domain for its large uses by stakeholders and groundwater professionals.

The above objectives were achieved by developing a process based web application model written in HTML, CSS and JavaScript using the semi-analytical mathematical model developed by Ghosh et al. [6] based on water balance equation of a recharge basin to estimate unsteady groundwater recharge resulting from variable depths of water in a large water body, influenced by time variant inflows and outflows. The water balance components include estimate of: inflows from the basin catchment by SCS-CN model, water surface evaporation by widely used methods depending upon availability of databases, and recharge by Hantush's basic equation for water table rise due to recharge from a rectangular spreading basin in absence of pumping well. The application offers the facility to assign measured values of inflows and evaporation rate and calculate the same on the fly. The output of the application is in the form of interactive charts and tables. The user friendly interface is designed intuitively along with the help at every step. The WE-GREM has scope to add more modules related to groundwater because of its structure and flexibility. The application can be accessed freely through NIH website at http://www.nihroorkee.gov.in/WEGREM/WEGREM.html and can be used for both research and field application.

V. CONCLUDING REMARKS

The Ground Water Hydrology division of NIH, in the recent past, has contributed to a number of frontier R & D studies, preparation of country's policy documents, collaborative demand driven studies, capacity building and technical services programs, etc. The outcomes of contributions appeared in peer reviewed journals, as symposia/conferences papers, technical reports and documents, as implementable technologies, etc. Future outlook for the division include:

- Develop as a "Centre of Excellence" for groundwater research to maintain balance between R & D pursuits and service expectations.

- Undertake collaborative R&D projects on frontier areas along with National and International Organizations.

- Expand the domain of technical programs to work in frontier areas of groundwater hydrology by further enhancing laboratory and computational capabilities.

- Foster the growth of division as a hub of advanced groundwater research, create environment to nurture young talent, and develop exchange programs with national and international academic and research organizations.

- Upgrade standards of excellence in providing consultancy and technical services.

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