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IMPACT OF CLIMATE CHANGE ON DYNAMIC GROUNDWATER SYSTEM IN A DROUGHT PRONE AREA

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PREFACE

Groundwater is the most dependable source for drinking water supply in the rural as well as urban areas which serve around 80% of the rural population and 50% of the urban population. This resource is being exploited since long for groundwater development and management across the country in an unplanned manner. A new threat to the groundwater resources is being emerged due to the future projected climate change.

The Sonar basin, which falls in the Bundelkhand region of the Madhya Pradesh, is subjected to recurrent droughts. The groundwater recharge in the basin is less because of its topography and geological setup. Although the basin receives good rainfall though it faces acute shortage of water and there exists scope of rainwater harvesting and groundwater recharge for augmentation of water resources. The groundwater recharge is likely to be affected by the projected climate change through changes in the major long-term climate variables, while the relationship between the changing climate variables and the components, which shape groundwater resource, is more complicated and poorly understood. The greater variability in rainfall could mean more frequent and prolonged periods of high or low groundwater levels. The direct effect of climate change on groundwater resources depends upon the change in the volume and distribution of groundwater recharge which may be affected as a result of changes in the rainfall pattern.

The 30th Working Group of the National Institute of Hydrology, Roorkee has approved the present study entitled "*Impact of Climate Change on Dynamic Groundwater System in a Drought Prone Area*" for a period of three years duration, 2009-2012. The study is an attempt to quantify the impact of climate change on groundwater resource in the Sonar sub-basin of the Madhya Pradesh. The study primarily focuses on quantification of changes in groundwater recharge and levels in response to the projected climate change in the basin. The report deals with the databases and their analysis, generation of future rainfall and temperature, recharge estimation and groundwater simulation for proper management and augmentation of groundwater in the basin.

The report has been prepared by Dr. Surjeet Singh, Scientist-E1 as Principal Investigator along with Sh. C.P. Kumar, Scientist-F; Dr. Anupma Sharma, Scientist-E1 and Sh. Rajan Vatsa, Scientist-B.

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ABSTRACT

The Sonar basin lies in the Bundelkhand region of the Madhya Pradesh State and it is subjected to frequent droughts. The basin suffers with water scarcity problem and most of the agriculture is under rain-fed conditions. Climate change is unequivocal and is expected to affect the recharge to the groundwater because of high intensity and short duration rainfall. In order to quantify the impact of climate change on groundwater, the present study is being carried out to quantify the impacts of climate change on groundwater recharge in a part of Sonar basin of Madhya Pradesh and to simulate the groundwater levels and investigate the temporal response of the aquifer system to historic and future climate periods.

The present study entitled "*Impact of Climate Change on Dynamic Groundwater System in a Drought Prone Area*" deals with the databases and their analysis, generation of future rainfall and temperature, recharge estimation and groundwater simulation for proper management and augmentation of groundwater in the basin. All the thematic maps have been generated in ILWIS 3.2 and necessary data have been collected. Future rainfall has also been generated based on the SRES GCM projections for the South-Asia region for baseline, A1F1 and B1 scenarios for the time-slice 2004-2039. The site-specific soil, vegetation and climate database needed for the VHELP model is generated and site-specific groundwater recharge is estimated at twelve locations in the basin. The groundwater simulation is done using the water balance method by dividing the whole basin into twelve zones. Finally, the quantification of impact of climate change on the groundwater recharge and levels for the time-slice 2004-2039 has been done.

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1.0 INTRODUCTION

Climate change in IPCC usage refers to any change in climate over time, whether due to natural variability or as a result of human activity. Alternatively, as per article 1 of the UN Framework Convention on Climate Change (UNFCCC), climate change means a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods. The causes of rising temperatures are considered to be both natural and human. Groundwater is the major source of water across much of the world, particularly in rural areas in arid and semi-arid regions, but there has been very little research on the potential effects of climate change (IPCC 2001). There is a need to improve understanding and modelling of climate changes related to the hydrological cycle at scales relevant to decision making. Information about the water-related impacts of climate change is inadequate - especially with respect to water quality, aquatic ecosystems and groundwater - including their socioeconomic dimensions (IPCC 2008).

Evidence is mounting that we are in a period of climate change brought about by increasing atmospheric concentrations of greenhouse gases. Atmospheric carbon dioxide levels have continually increased since the 1950s. The continuation of this phenomenon may significantly alter global and local climate characteristics, including temperature and precipitation. Climate change can have profound effects on the hydrologic cycle through precipitation, evapotranspiration, and soil moisture with increasing temperatures. The hydrologic cycle will be intensified with more evaporation and more precipitation. However, the extra precipitation will be unequally distributed around the globe. Some parts of the world may see significant reductions in precipitation or major alterations in the timing of wet and dry seasons. Information on the local or regional impacts of climate change on hydrological processes and water resources is becoming more important. The effects of global warming and climatic change require multi-disciplinary research, especially when considering hydrology and global water resources.

The Intergovernmental Panel on Climate Change (IPCC) estimates that the global mean surface temperature has increased 0.6 ± 0.2 °C since 1861, and predicts an increase of 2 to 4 °C over the next 100 years. Global sea levels have risen between 10 and 25 cm since the late 19th century. As a direct consequence of warmer temperatures, the hydrologic cycle will undergo significant impact with accompanying changes in the rates of precipitation and evaporation. Predictions include higher incidences of severe weather events, a higher likelihood of flooding, and more droughts. The impact would be particularly severe in the tropical areas, which mainly consist of developing countries, including India.

Coupled atmosphere-ocean global climate models (GCMs) are used to estimate changes in climate. These physically-based numerical models simulate synoptic-scale climate and hydrological processes, and are forced with greenhouse gas and aerosol emission scenarios. A wide diversity of

GCMs developed by leading climate centres is available for other researchers to evaluate potential impacts of climate change. To ensure that the predictive elements from a GCM are realistic, a statistical downscaling technique should be employed to bridge the local- and synoptic-scale processes. Statistical downscaling uses a correlation between predictands (site measured variables, such as precipitation) and predictors (region-scale variables, such as GCM variables).

Changes in regional temperature and precipitation have important implications for all aspects of the hydrologic cycle. Variations in these parameters determine the amount of water that reaches the surface, evaporates or transpires back to the atmosphere, becomes stored as snow or ice, infiltrates into the groundwater system, runs off the land, and ultimately becomes base flow to streams and rivers.

Hydrological impact assessments of watersheds (and aquifers) require information on changes in evapotranspiration because it is a key component of the water balance. However, climate-change scenarios tend to be expressed in terms of changes in temperature and precipitation. Consequently, the effects of global warming on potential evaporation (or more inclusively, evapotranspiration) are not simple to estimate. Many global scenarios suggest an increase in potential evaporation, but these factors may be outweighed locally or regionally by other factors reducing evaporation. Various models may be used to calculate potential evaporation using data on net radiation, temperature, humidity, and wind speed, and sometimes plant physiological properties. The estimated effect of a change in climate on potential evaporation depends on the characteristics of the site.

Many rivers and streams that are fed by glacier runoff could be significantly impacted as a result of climate change. As glacier retreat accelerates, increased summer runoff could occur. However, when the glaciers have largely melted, the late summer and fall glacial input into streams and rivers may be lost, resulting in a significant reduction in flow in some cases.

India is one among the countries that had long-past history of facing hardships of droughts and famines from time to time. Nearly 39% of the total cultivated lands are affected frequently by drought events spread over 185 administrative districts. The occurrence of drought is normally linked with the amount, distribution, and time of onset and withdrawal of monsoon rainfall in India. Since, the monsoon rainfall is highly erratic and unevenly distributed, drought conditions prevail in almost any year in one or the other part of country. This leads to instability of agriculture system and economy in considerable sections of the society. In spite of the above fact, a comprehensive drought preparedness and mitigation policy for the country is lacking. Yet, we respond to a drought through ad hoc strategies and more like crisis management approach rather than through proactive, coordinated strategies designed to mitigate the impacts.

In view of above this research study is taken up with following objectives:

1. To quantify the impacts of climate change on groundwater recharge in a part of Sonar basin, Madhya Pradesh.
2. To simulate the groundwater levels and investigate the temporal response of the aquifer system to historic and future climate periods.

2.0 REVIEW AND LITERATURE

In order to find ways to mitigate the rising temperatures, it is necessary to examine the primary causes of global and regional warming. This phenomenon is linked to both natural and human causes. A natural cause - water vapor in the atmosphere - contributes the most to natural greenhouse warming (Figure 1). Water vapor and other "greenhouse gases" such as carbon dioxide, methane, and CFCs cause the greenhouse effect by trapping radiant heat emitted at infrared (long) wavelengths (as opposed to shorter, solar wavelengths which can pass through the atmospheric gases) from the earth's surface and reradiating it back to the earth's surface (Schneider 1989). This trapped energy effectively creates an enclosure around the earth's atmosphere similar to a greenhouse which not only traps heat, but also restricts air circulation that would otherwise cause cooling (Botkin and Keller 2000). Prior to the IPCC's report in 2001, there was still significant uncertainty about human beings' contribution to global warming. Many scientists believed that natural global cooling mechanisms worked to offset warming.

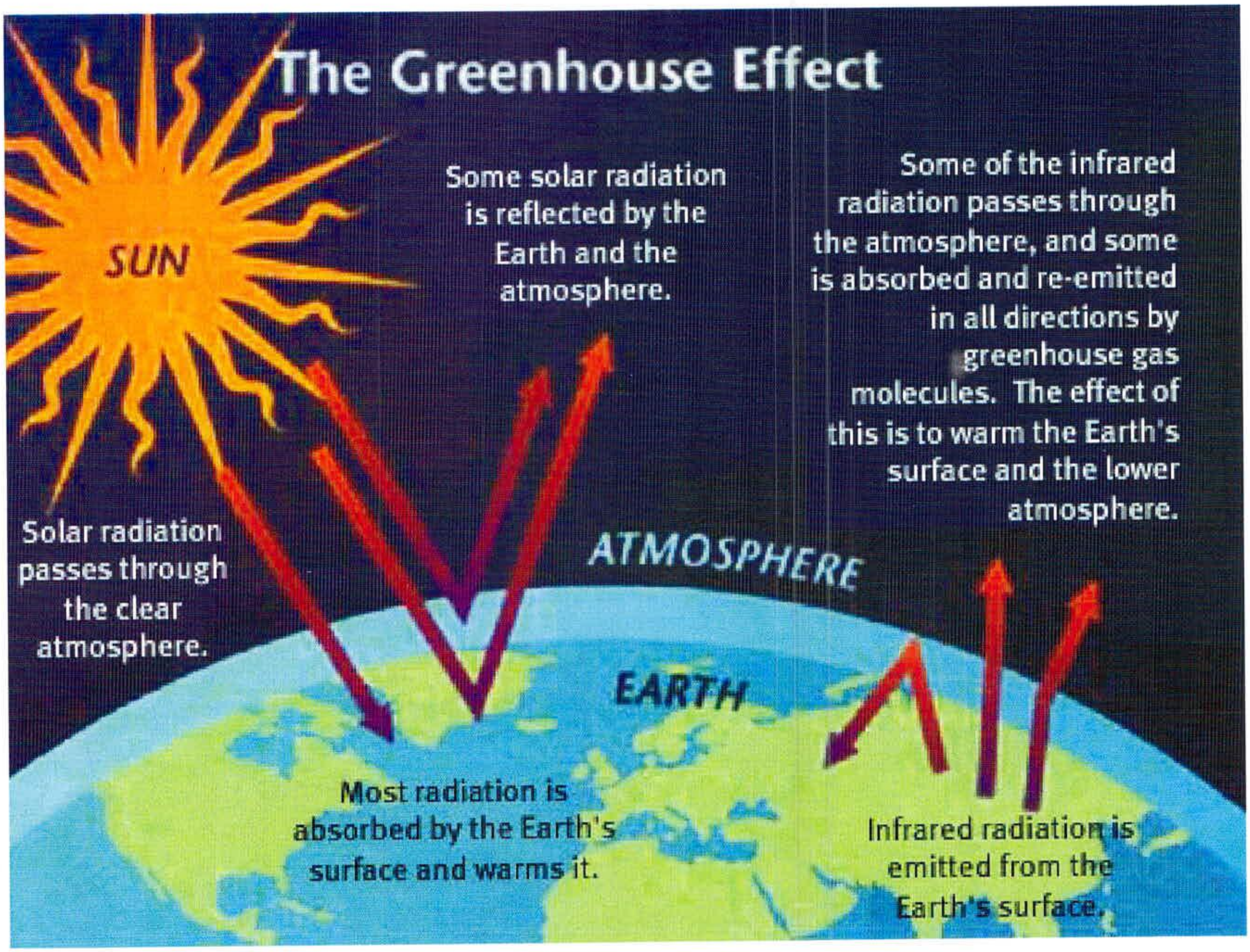


Fig. 1. Schematic of the green house effect and global warming

With the release of the IPCC's Third Assessment Report in 2001, however, came new evidence that climate change over the last 50 years was, indeed, attributable to humans, mostly from burning fossil fuels that emit more carbon dioxide into the atmosphere than it should contain to achieve climate equilibrium (5.4 billion metric tons annually). Two additional human causes of global warming include deforestation, which adds another 1.6 billion metric tons, and emission of other greenhouse gases (methane, CFCs, ozone, nitrous oxides) that also contribute to the greenhouse effect (Botkin and Keller 2000). Urban warming is driven by some of the same factors that create greenhouse gas warming: vegetation loss, increase in mineral-based construction materials, and waste heat emissions from combustion and electricity consumption. The loss of vegetation in urban areas, compared to that in rural areas, reduces in cities the natural cooling provided by evapotranspiration, "the process through which intercepted radiation is utilized by plants, soils, and water bodies to convert water to water vapor" (Stone and Rodgers 2001). Second, building materials such as asphalt, cement and roofing tile absorb more thermal energy than the vegetation that existed prior to urbanization. This energy is released into the air late in the day and into the evening, keeping the city warmer than it would normally be (Lawrence Berkeley Laboratories 2000). Finally, some portion of the urban heat island effect is attributable to the heat emissions from air conditioners, industry, automobiles and other sources of heat in urban centers (Stone and Rodgers 2001). The urban heat island effect is reinforced by increased demand for cooling, consequently raising the level of greenhouse gas emissions from power plants.

Laboratory documented this effect in Los Angeles, and found a two percent increase in energy demand for every 1°F increase in temperature (Lawrence Berkeley Laboratories 2000). In fact, the lab estimated that as much as 15 percent of the electricity consumed for air conditioning was used just of offsetting the increased urban temperatures (Rosenfeld et al 1998).

Dragoni and Sukhija (2008) analyzed the main methods for studying the relationships between climate change and groundwater, and presented the main areas in which hydrogeological research should focus in order to mitigate the likely climate change impacts. Scibek and Allen (2006) developed a methodology for linking climate models and groundwater models to investigate future impacts of climate change on groundwater resources with the aid of HELP and MODFLOW using the climate change scenarios from the Canadian Global Coupled Model 1 (CGCM1) and downscaling using Statistical Downscaling Model (SDSM). Bouraoui et al. (1999) developed a general approach to evaluate the effect of potential climate changes on groundwater resources by application of CO_2-doubling scenario through the development of a local weather generator. Mujumdar and Ghosh (2007) have presented a broad overview of different approaches of downscaling and uncertainty modeling in assessing hydrological implications of global climate change with a case study of Orissa meteorological subdivision. Sherif and Singh (1999) investigated the effect of likely climate change on sea water intrusion and found the Nile Delta aquifer to be more vulnerable to climate change and sea level rise. Holman (2006) described an integrated approach to assess the regional impacts of climate and socio-economic change on groundwater recharge in East Angila, UK and discussed the important sources of uncertainty and shortcomings in recharge estimation. Eckhardt and Ulbrich (2003) investigated the impacts of climate change on groundwater recharge and stream flow in a central European low mountain range catchment using a conceptual eco-hydrologic model, a revised version of Soil and Water Assessment Tool (SWAT). Sathaye et al. (2006) described that the most effective way to address climate change is to adopt a sustainable development pathway by shifting to environmentally sustainable technologies and promotion of energy efficiency, renewable energy, forest conservation, reforestation, water conservation, etc. Toews et al. (2007) developed and implemented a methodology to estimate the impacts of global climate change on regional hydrological regimes using ArcGIS Geostatistical Analyst. They indicated that a 30% precipitation increase causes a 50% increase of stream flow when the temperature is normal compared to only a 20-30% increase in stream flow if the average annual air temperature is 1.5°C higher than normal. Conversely, a 20% precipitation decrease results in approximately 25-30% less stream flow when the temperature is normal but a 45% decrease in stream flow if the temperature is 1.5°C higher than normal.

3.0 STUDY AREA

The topographic and satellite view of the Sonar sub-basin is shown in Figure 2. Sonar basin falls in the Bundelkhand region of Madhya Pradesh.

Sonar river is a tributary of Ken river. Geographically the basin extends from 23°21′14″ to 23°50′05″N latitudes and 78°35′48″ to 79°10′50″E longitudes. The total area of the basin is 1538 sq.km up to the gauging site Garhakota. The Sonar river originates in the Raisen district and its major part 94% basin area falls in the Sagar district and balance 6% falls in the Raisen district.

Total basin perimeter is 284 km. Climatically the basin lies under semi-arid to sub-tropical region with a single rainy season (July-September) followed by dry winter and a very dry summer. The landscape of the region is rugged, undulated terrain with low rocky outcrops, narrow valleys and pains. Large portion of the basin falls under rain-fed agriculture. Forest type in the basin is dry deciduous. The

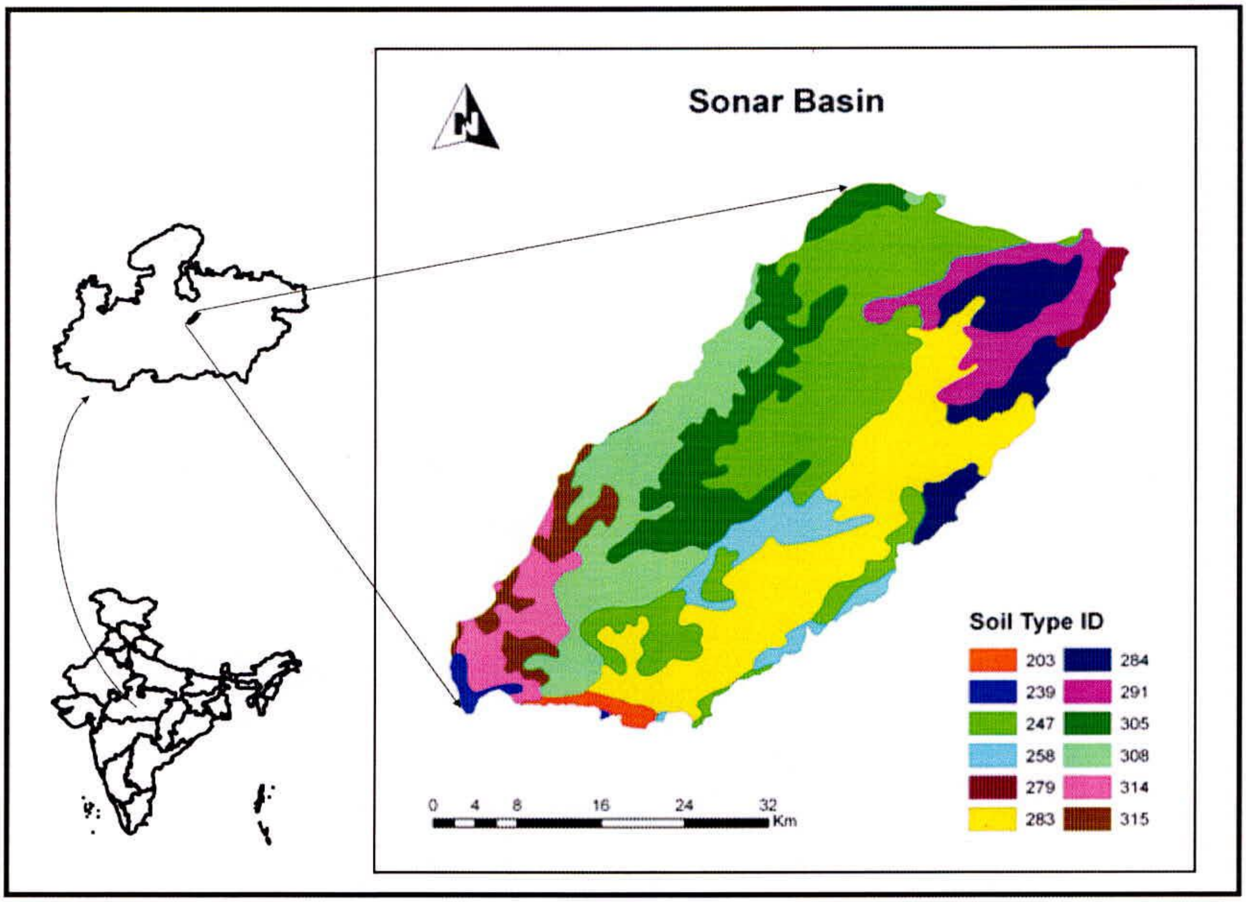
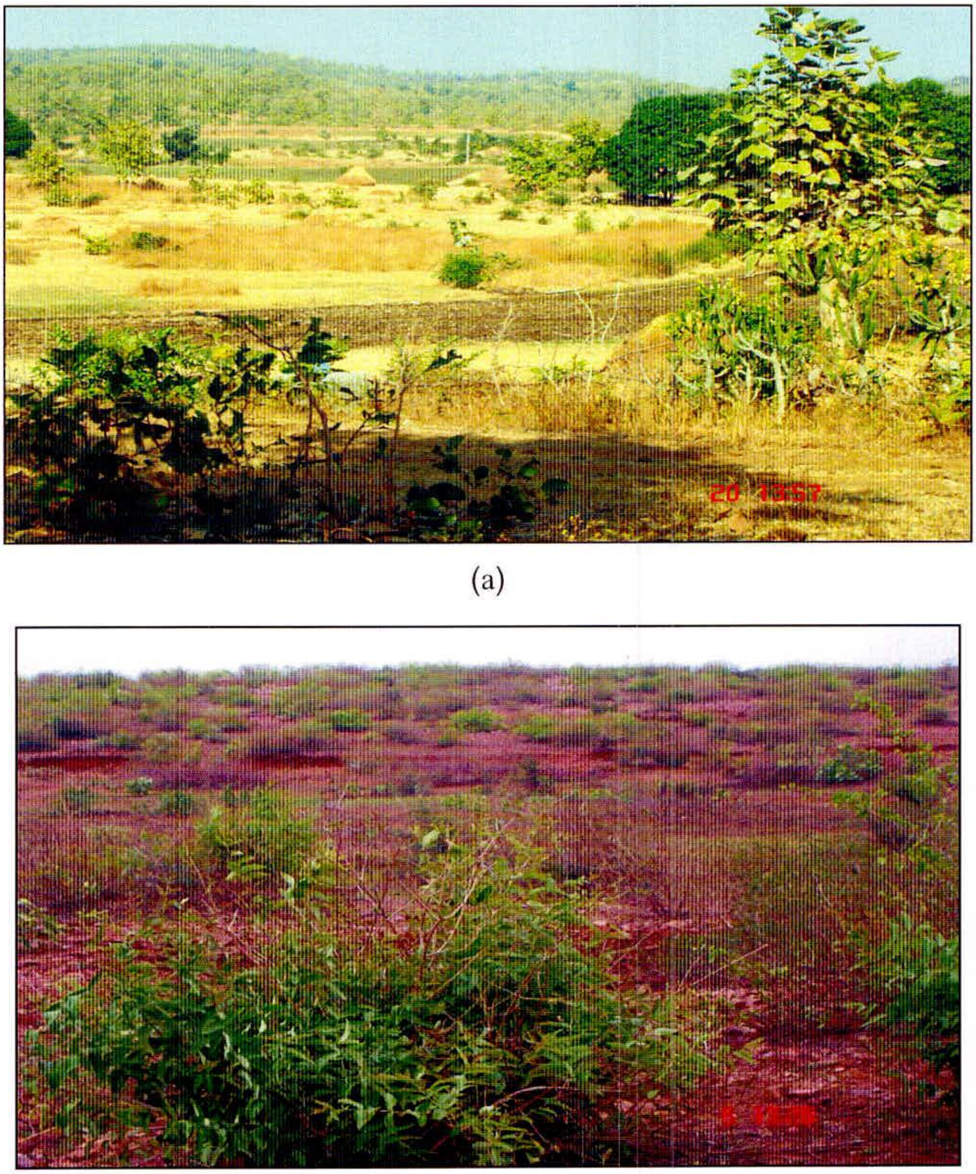


Fig. 2. Study area of the Sonar sub-basin in Madhya Pradesh

basin has limited soil depth and high soil erosion. The region is drought prone with average drought frequency of 01 in every 05 years. Average annual rainfall in the basin is 1100mm with average no. of 45 rainy days. Average annual potential evapotranspiration (PET) is 1852 mm. Mean temperature varies from 18°C to 33°C. Mean relative humidity varies from 27% to 85% and mean wind speed varies from 4.13 km/h in November to 8.45 km in July. Black cotton soil is dominantly found in the basin. A view of average topography in the basin is shown in Figure 3. The crops largely grown in the basin are wheat, soyabean, maize, arhar, ground nut, etc.



(a)

(b)

Fig. 3. Photographic view of general topography of the basin

4.0 MATERIALS AND METHODS

4.1 Methodology for Estimation of Groundwater Recharge and Flow Simulation for Climate Change Scenarios

The potential impacts of climate change on water resources have long been recognized although there has been comparatively little research relating to groundwater. The principle focus of climate change research with regard to groundwater has been on quantifying the likely direct impacts of changing precipitation and temperature patterns. Such studies have used a range of modeling techniques such as soil water balance models, empirical models, conceptual models and more complex distributed models, but all have derived changes in groundwater recharge assuming parameters other than precipitation and temperature remaining constant.

There are two main parameters that could have a significant impact on groundwater levels: recharge and river stage/discharge. To assess the impact on the groundwater system to changes in these two parameters, it is necessary to have a calibrated flow model and to conduct a sensitivity analysis by varying these two parameters and calculating changes to the water balance (e.g., differences in water levels).

The methodology consists of three main steps. First the climate change scenarios need to be formulated for the future years such as 2050 and 2100. This is done by assigning percentage or actual changes of climatic variables based on GCM predictions on a seasonal and/or annual basis for the future years relative to the present year. Secondly, based on these scenarios and present situation, seasonal and annual recharge, evapotranspiration and runoff are simulated with the WHI UnSat Suite (HELP module for recharge) and/or WetSpass model. Finally, the annual recharge outputs from WHI UnSat Suite or WetSpass model are used to simulate groundwater system conditions for the present condition and for the future years.

The main tasks that are involved in such a study are:

1. Describe hydrogeology of the study area.
2. Undertake a statistical analysis to separate climate into regional and local events and determine the role of each in contributing to groundwater recharge.
3. Analyze climate data from weather stations and modeled GCM, and build future predicted climate change datasets with temperature, precipitation and solar radiation variables.
4. Define methodology for estimating changes to recharge in the model under both current climate conditions and for the range of climate-change scenarios for the study area.
5. Use of a computer code (such as WHI UnSat Suite or WetSpass) to estimate recharge based on available precipitation and temperature records and anticipated changes to these parameters.

Recharge estimation by WHI UnSat Suite

UnSat Suite contains the subprogram, Visual HELP (Hydrologic Evaluation of Landfill Performance), which contains a more user-friendly interface for the program HELP that is approved by the United States Environmental Protection Agency (US EPA) for designing landfills. Visual HELP enables the modeler to generate estimates of recharge using a weather generator and the properties of the aquifer column.

6. Quantify the spatially distributed recharge rates using the climate data and spatial soil survey data.
7. Simulate groundwater flow using each recharge data set and evaluate the changes in groundwater flow and levels through time.

A typical flow chart for various aspects of such a study is shown in Figure 4. The figure shows the connection from the climate analysis, to recharge simulation, and finally to a groundwater model. Recharge is applied to a three-dimensional groundwater flow model, which is calibrated to historical water levels. Transient simulations are undertaken to investigate the temporal response of the aquifer system to historic and future climate periods.

Tasks in the upper part of the chart assemble several climate data sets for current and future predicted conditions, which are used to simulate recharge using HELP module of WHI UnSat Suite. The soil layers are parameterized using a pedo-transfer function program, which utilizes detailed soil survey measurements. Mapped monthly recharge from HELP is then used to simulate transient saturated groundwater flow.

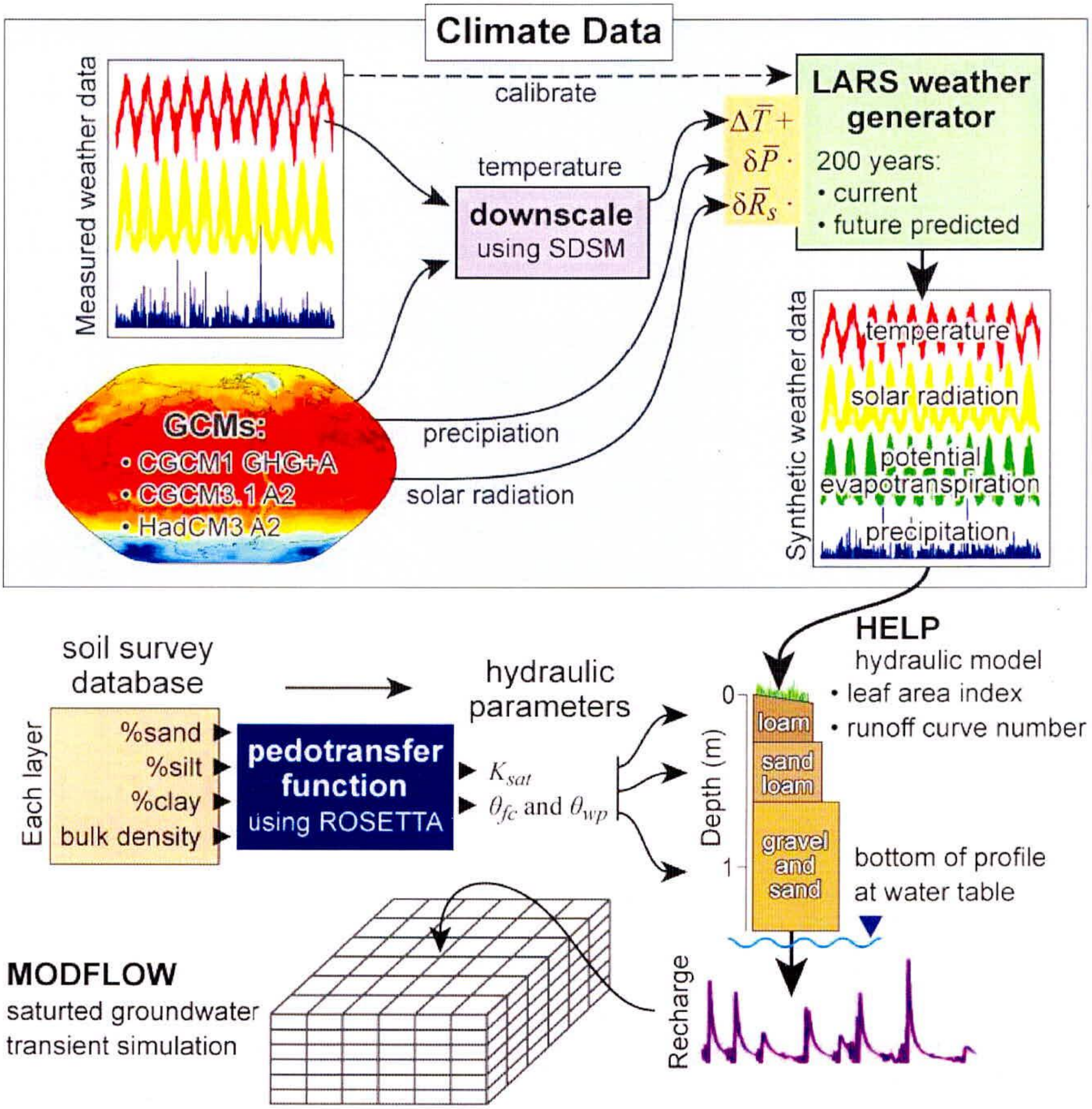


Fig. 4. Flow Chart of groundwater flow simulation in response to climate change (Toews et al., 2007)

5.0 RESULTS AND DISCUSSION

Survey of India toposheets are used to delineate the basin boundary as shown above in Figure 1. Sonar is the main river with total length of 95.21 km and the basin order is 5. Stream frequency and bifurcation ratio are estimated as 0.26 and 3.64, respectively. Drainage density of the basin is 0.61 and drainage map of the basin is shown below in the Figure 5. There is only one gauging site at Garhakota (owned by Central Water Commission, CWC) which is the outflow point of the basin.

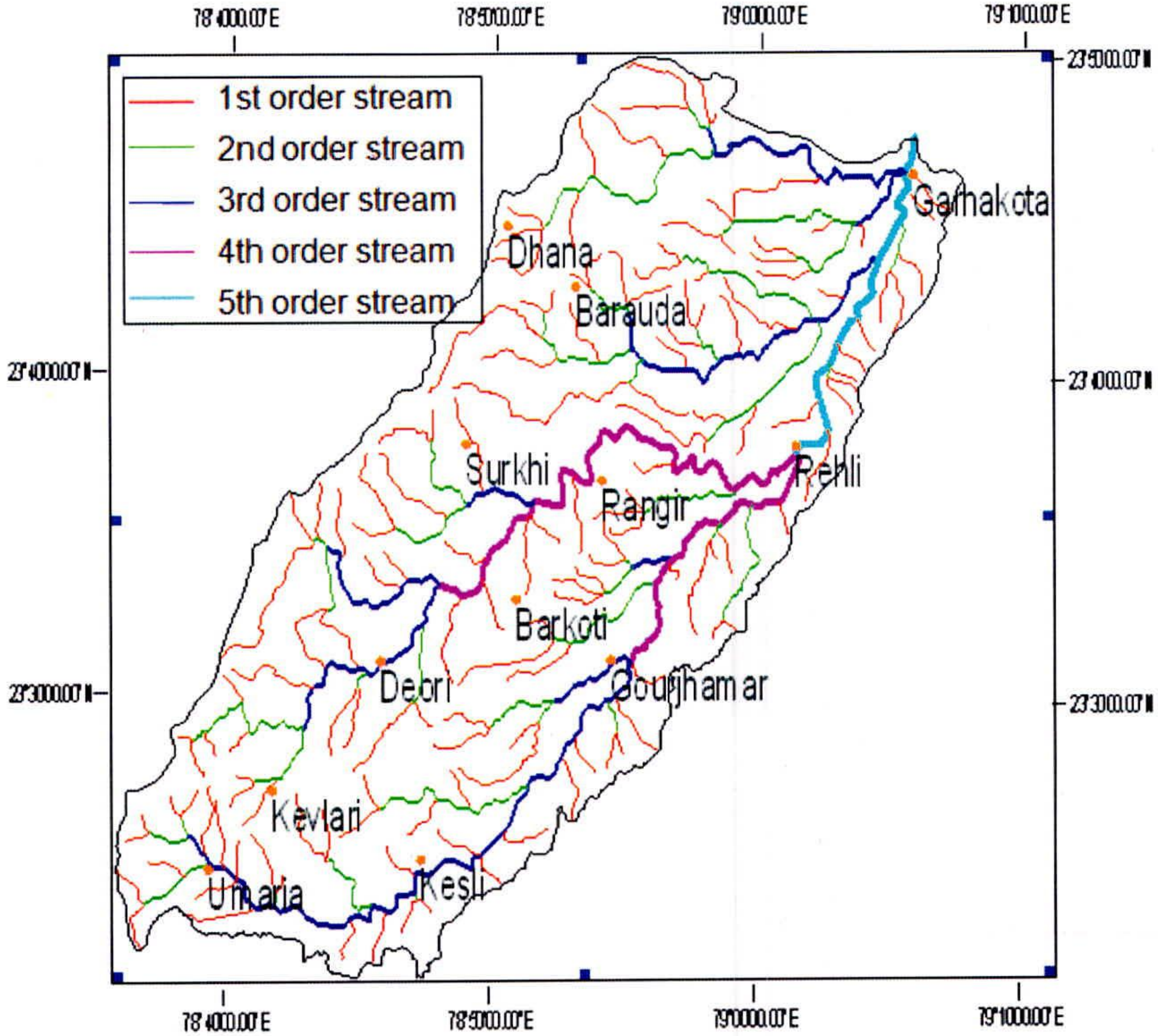


Fig. 5. Drainage map of the Sonar sub-basin

The soil map of the basin is prepared from the National Bureau of Soil Survey and Land Use Planning (NBSSLUP) map and is shown in Figure 6. There are total 12 soil groups and the description of each group is given in the figure.

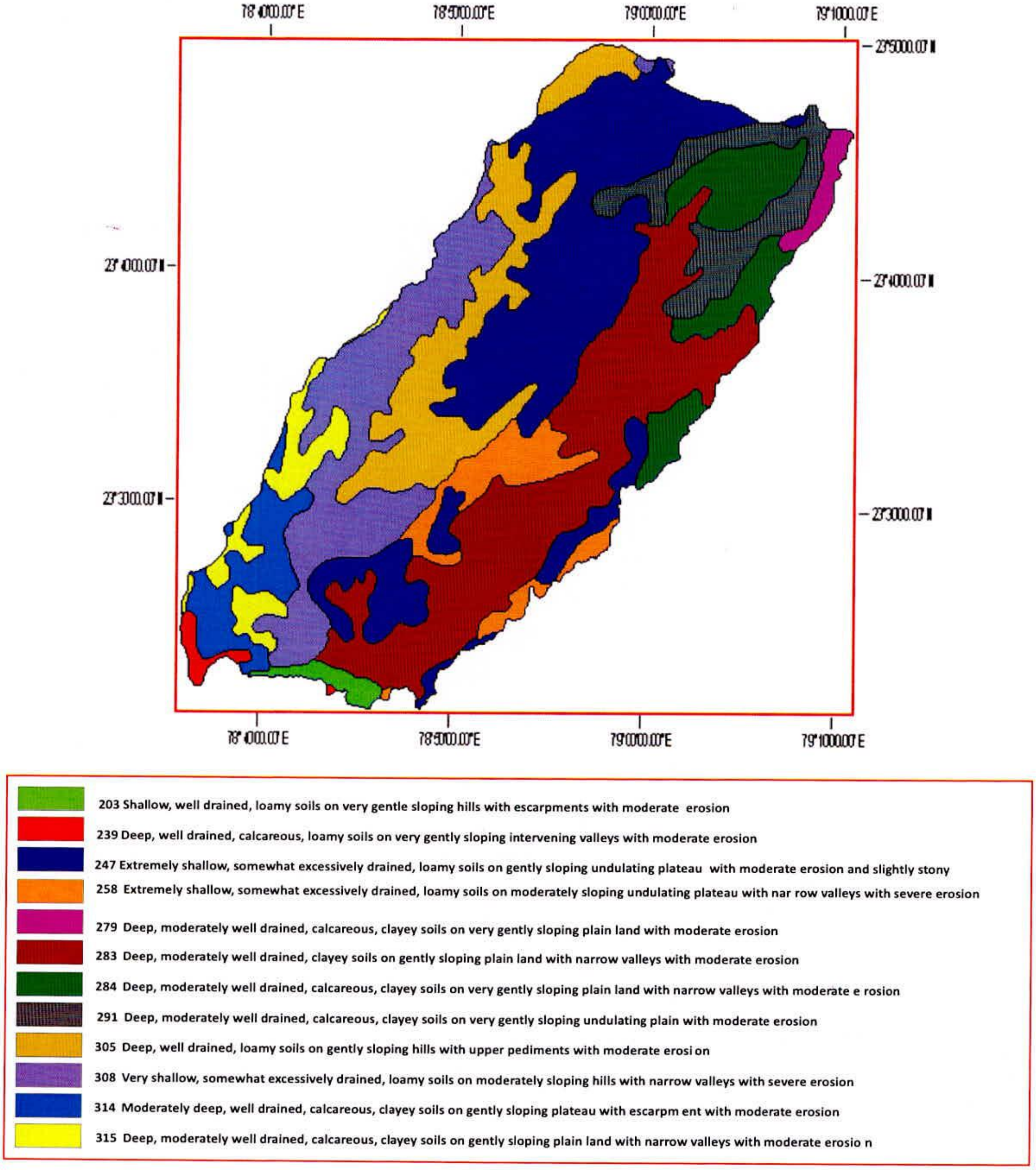


Fig. 6. Soil map of the Sonar sub-basin

The main geological formation of the basin is Deccan trap with basaltic flows followed by Vindhyan group mainly shale and sandstone. The geological map and stratigraphic details are given in Figure 7 and Table 1 respectively.

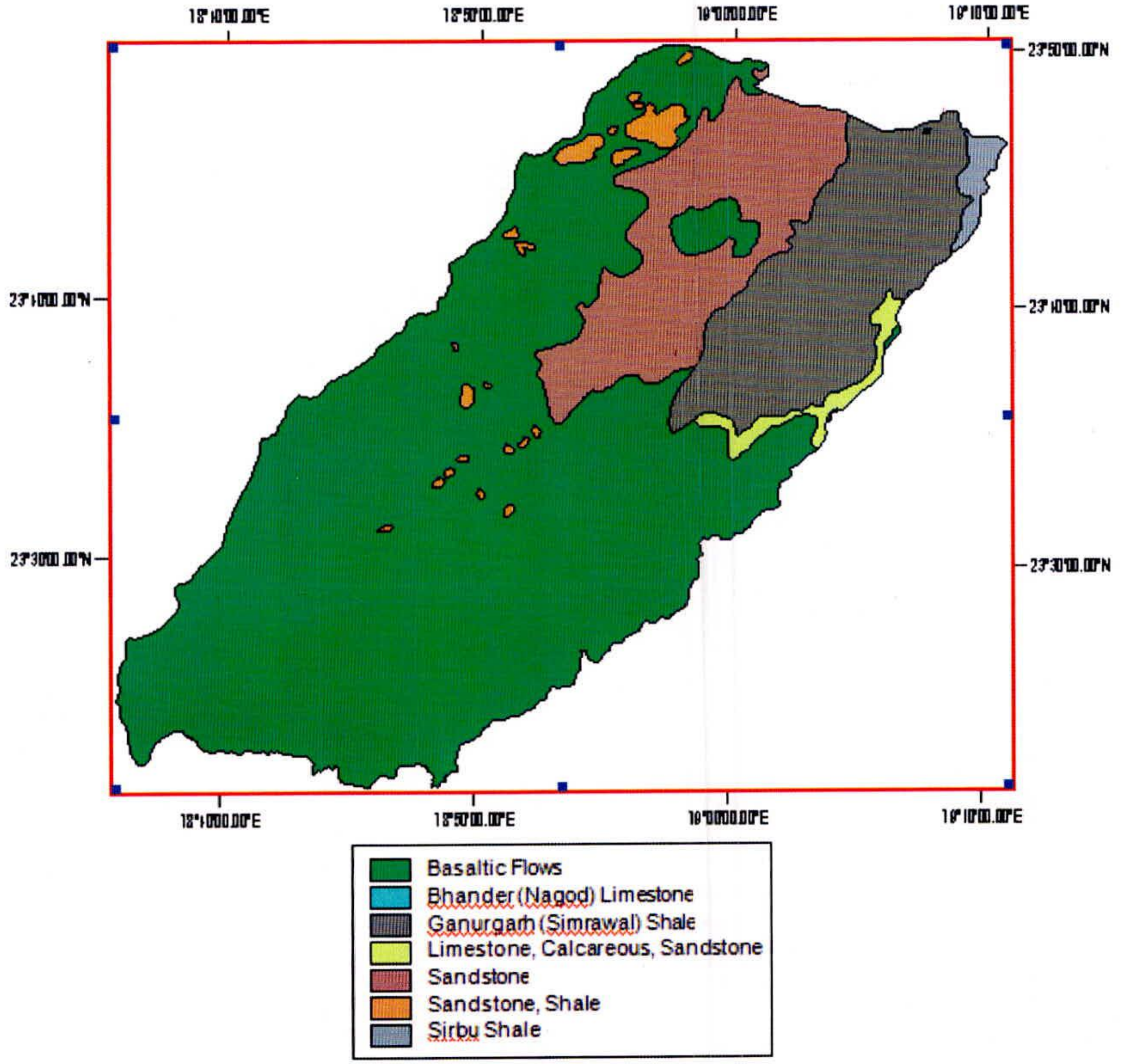


Fig. 7. Geological map of the Sonar sub-basin

The land use details of the basin (Figure 8) shows 63% agricultural land, 23% forest land, 13% waste land, 0.4% settlement and 0.06 % water body. Forest is generally found in the upper catchment and on ridges. The land use details are used in the estimation of groundwater recharge.

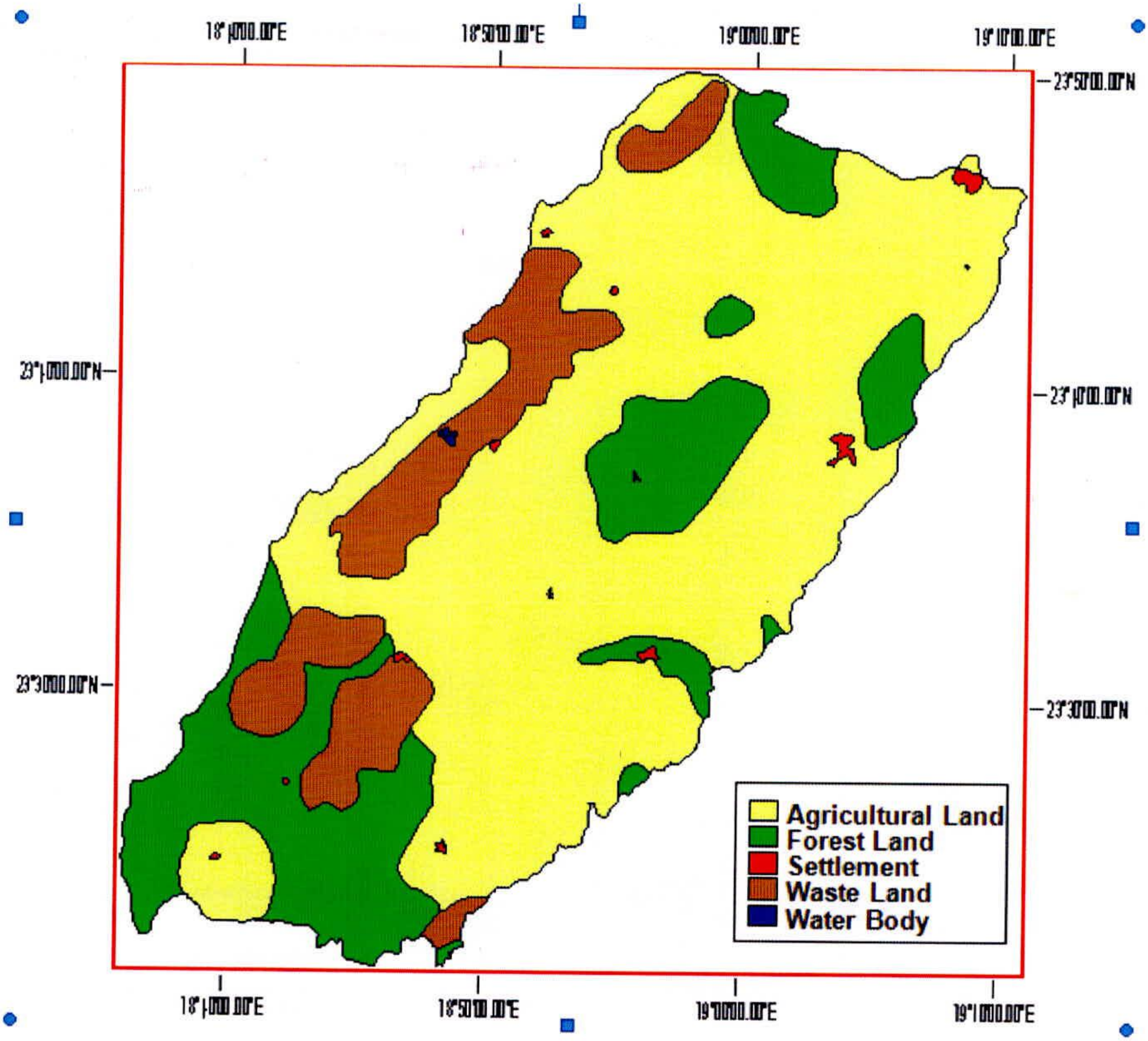


Fig. 8. Land use map of the Sonar sub-basin

There are total 18 wells in the basin owned by State Groundwater Survey Department, Madhya Pradesh out of which 05 are piezometer wells and 13 are observation wells (Figure 9). These wells are used to monitor the groundwater levels in the basin. The groundwater levels of the wells are available for the period 1984 to 2003. These data have been used for the groundwater level simulation in the study area. Average well density in the basin is 1 well/85sq.km.

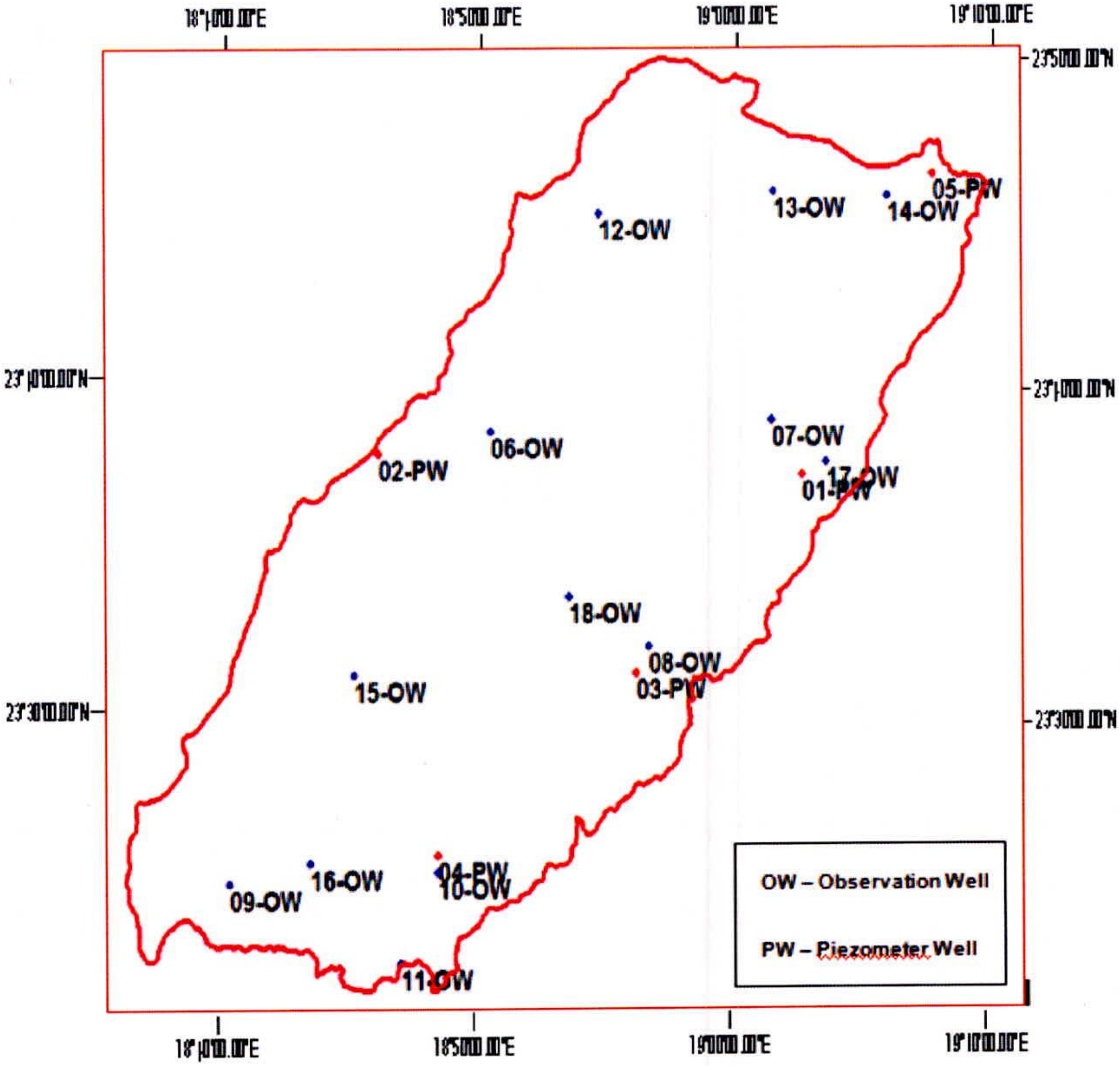


Fig. 9. Location of wells in the Sonar sub-basin

There are five rain gauges located in and around the basin out of which Kesli, Deori, Rehli and Garhakota stations are owned by the state department while Sagar station is owned by India Meteorological Department (IMD). The theissen map of the rain gauge stations is shown in Figure 10. The long-term rainfall and temperature data for the Sagar station are available and hence the meteorological data of this station are used for climate change analysis in the subsequent sections.

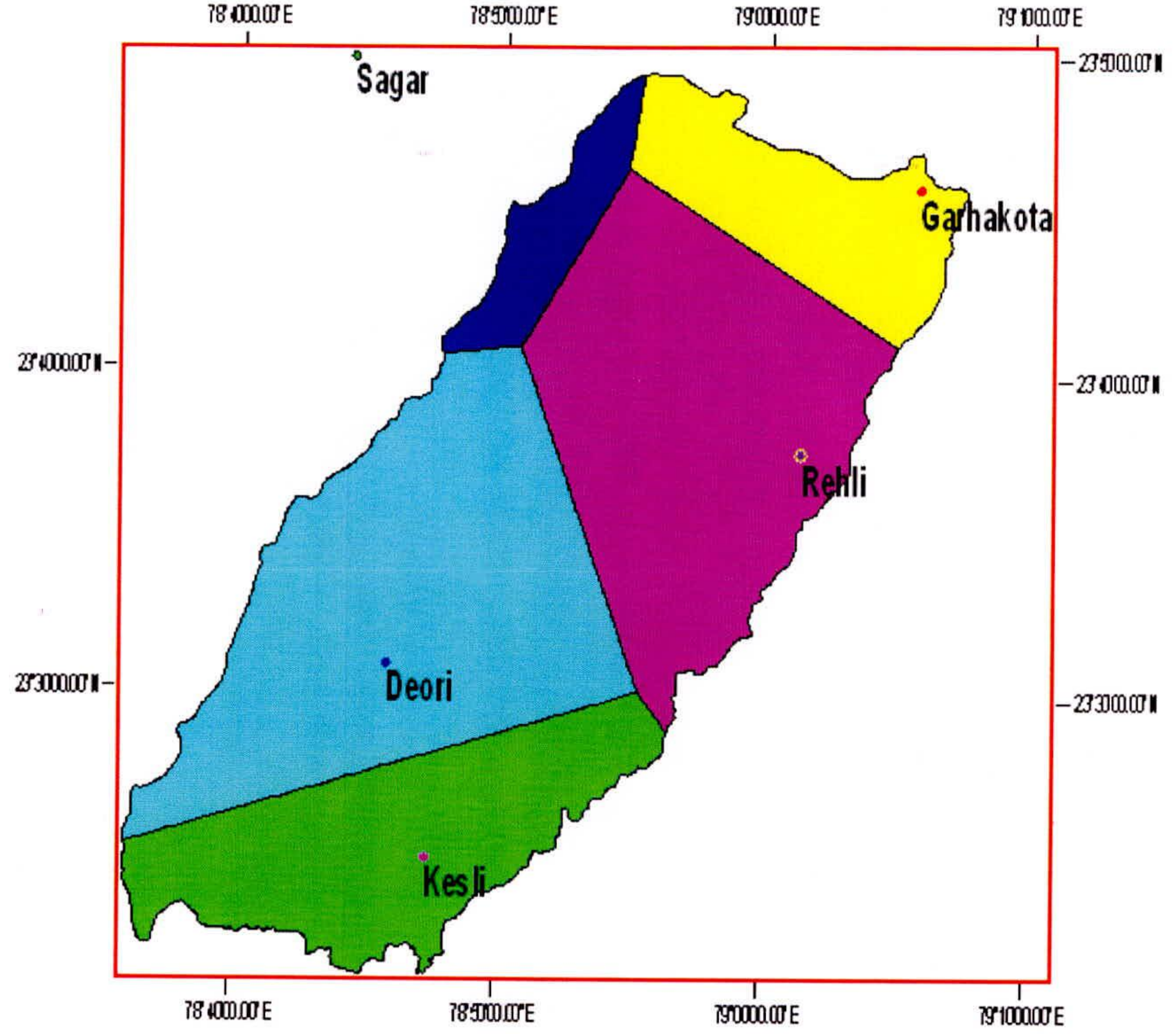


Fig. 10. Theissen polygon map of rain gauge network of the Sonar sub-basin

The Geological Survey of India (GSI) map was used to prepare the geo-hydrological map of the basin. Geo-hydrological details of the basin indicate that 1399 sq.km portion has low to moderately high permeability with poor to moderately good groundwater potential and 139 sq.km has cumulative high permeability with good to excellent groundwater potential (Figure 11).

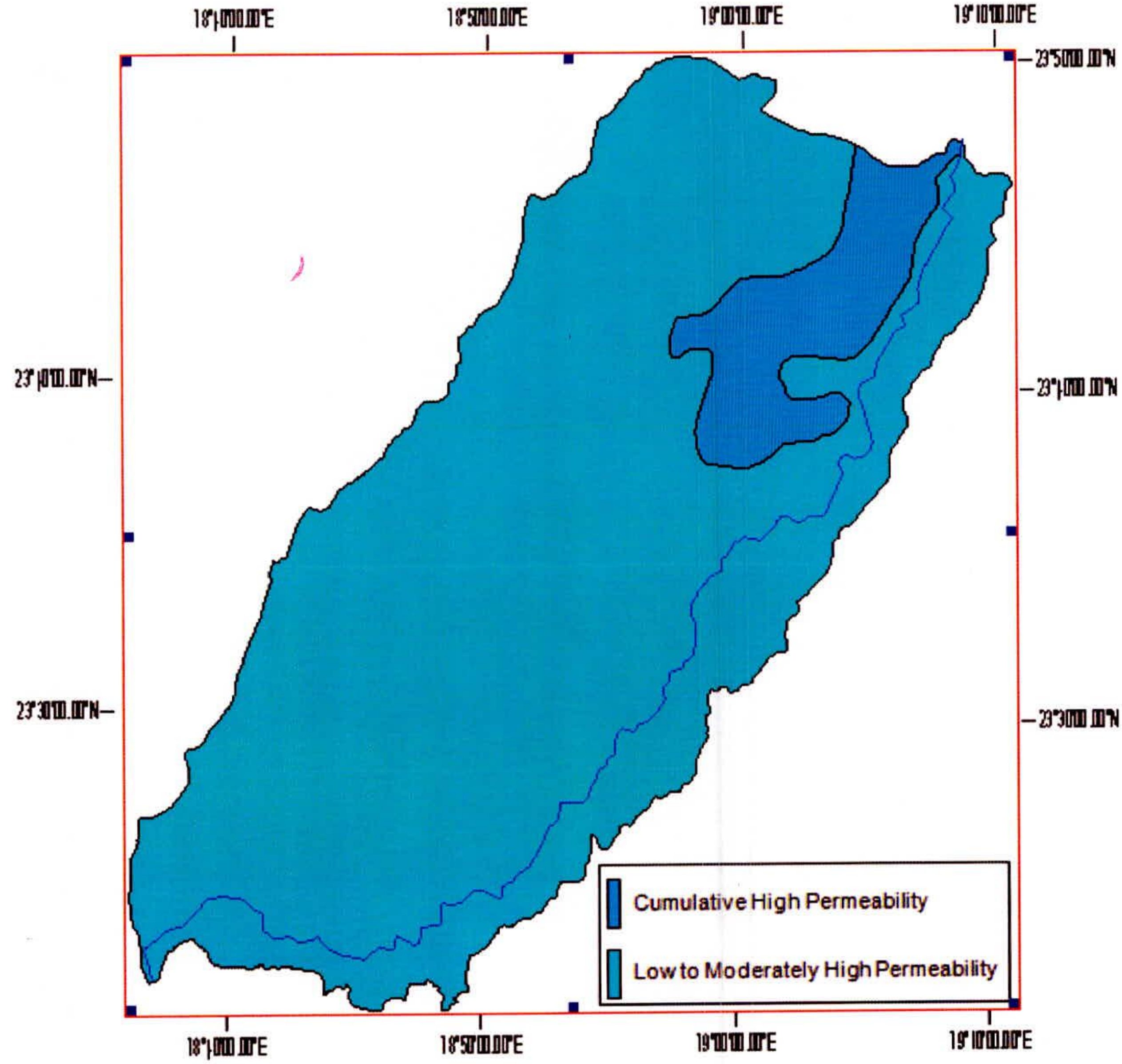


Fig. 11. Geo-hydrological map of the Sonar sub-basin

The digital elevation model (DEM) of the basin, as shown in Figure 12, is prepared from the SRTM downloaded data in the ArcGIS 9.2 software. The DEM shows that the elevation of the basin varies from 325 m in the lower portion to 680 m in the upper part of basin. The blue areas indicate the ridge areas while the yellow areas are the low lying areas and are generally flat.

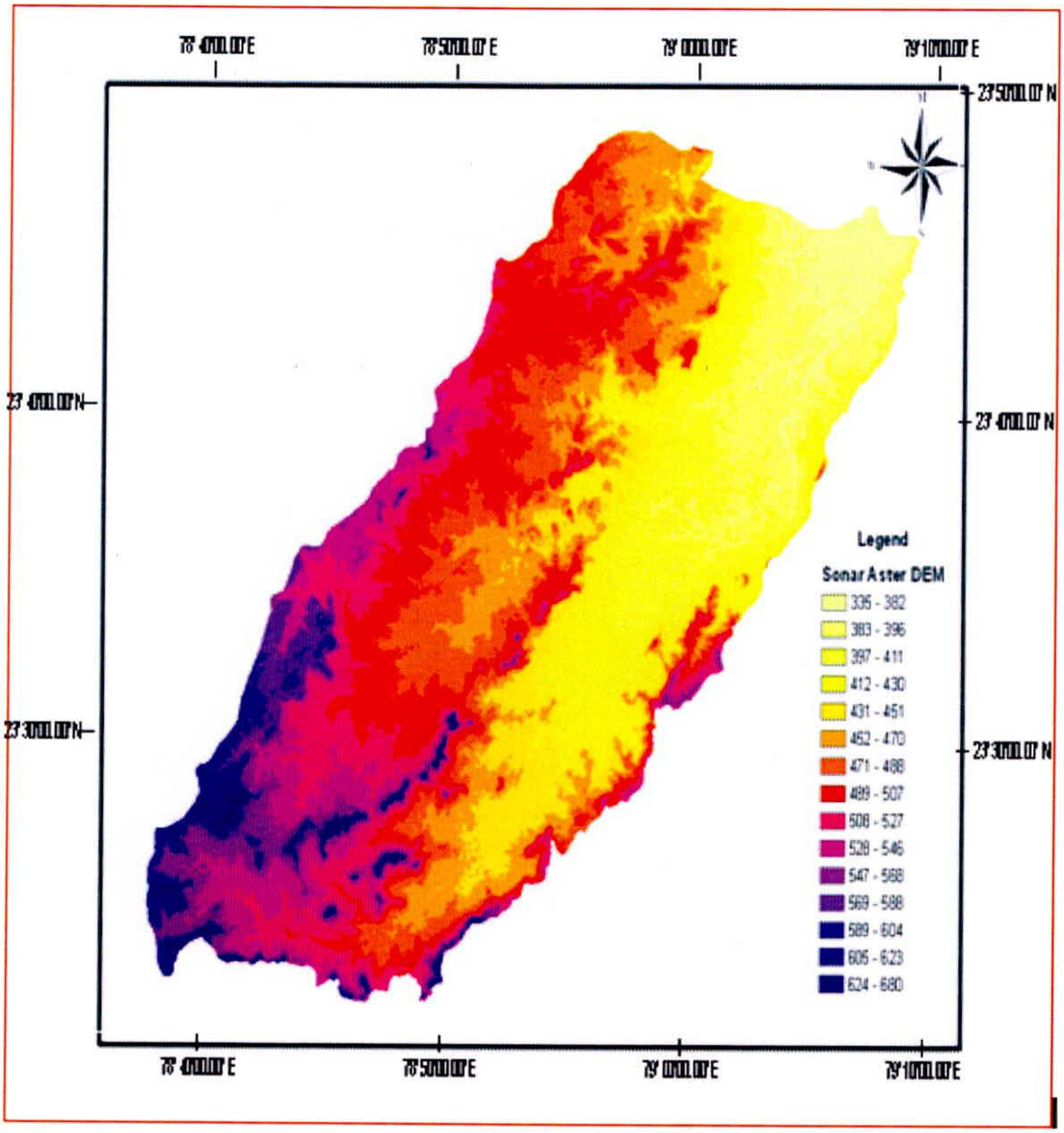


Fig. 12. Digital elevation model (DEM) of the Sonar sub-basin

The slope map of the basin is shown in Figure 13 which is derived from the DEM. It is seen from the figure that the slope varies up to 45% in the basin. The up-reach basin areas are mostly hilly and undulating region.

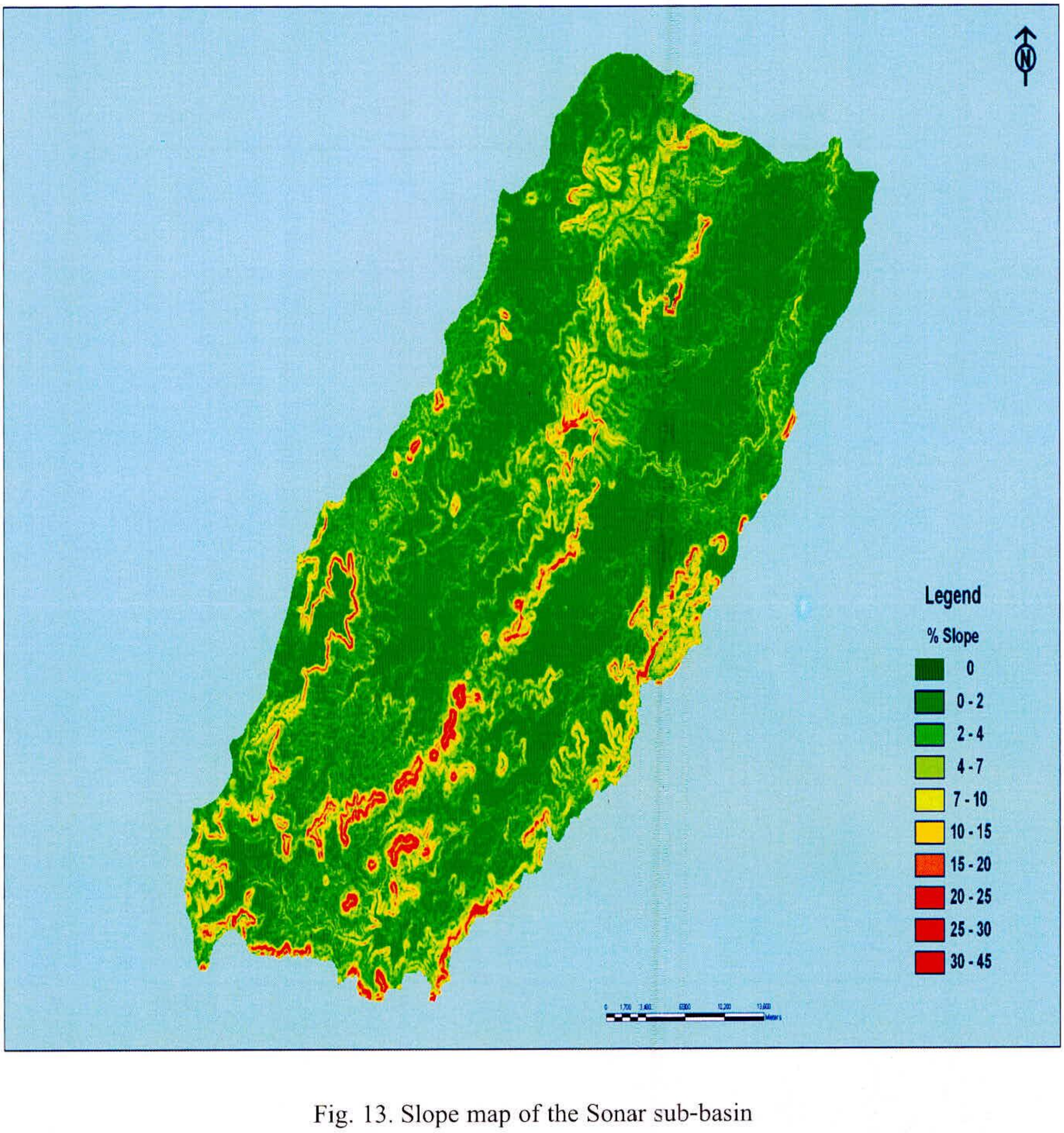


Fig. 13. Slope map of the Sonar sub-basin

In order to estimate the site-specific recharge rates in the basin, twelve sites were identified for conducting the soil tests. These sites are identified based on the soil types such that at least one site is located in each soil group (Figure 14). At these sites, tests were conducted for hydraulic conductivity using the Guelph Permeameter and soil samples were also collected for grain size analysis. The grain size analysis of these samples was done in the Soil and Water Laboratory of the National Institute of Hydrology, Roorkee. Soil profiling was also done at each of these sites. The results of the soil tests are given in the Table 2 and 3. It is observed that most of the soils fall under the silty loam and graveled silty loam and the hydraulic conductivity varies from 0.0000362 cm/sec to 0.005432 cm/sec. All these twelve sites are used for the estimation of site-specific groundwater recharge using the VHELP model. The details of the type of soil for each site are already given in Figure 6.

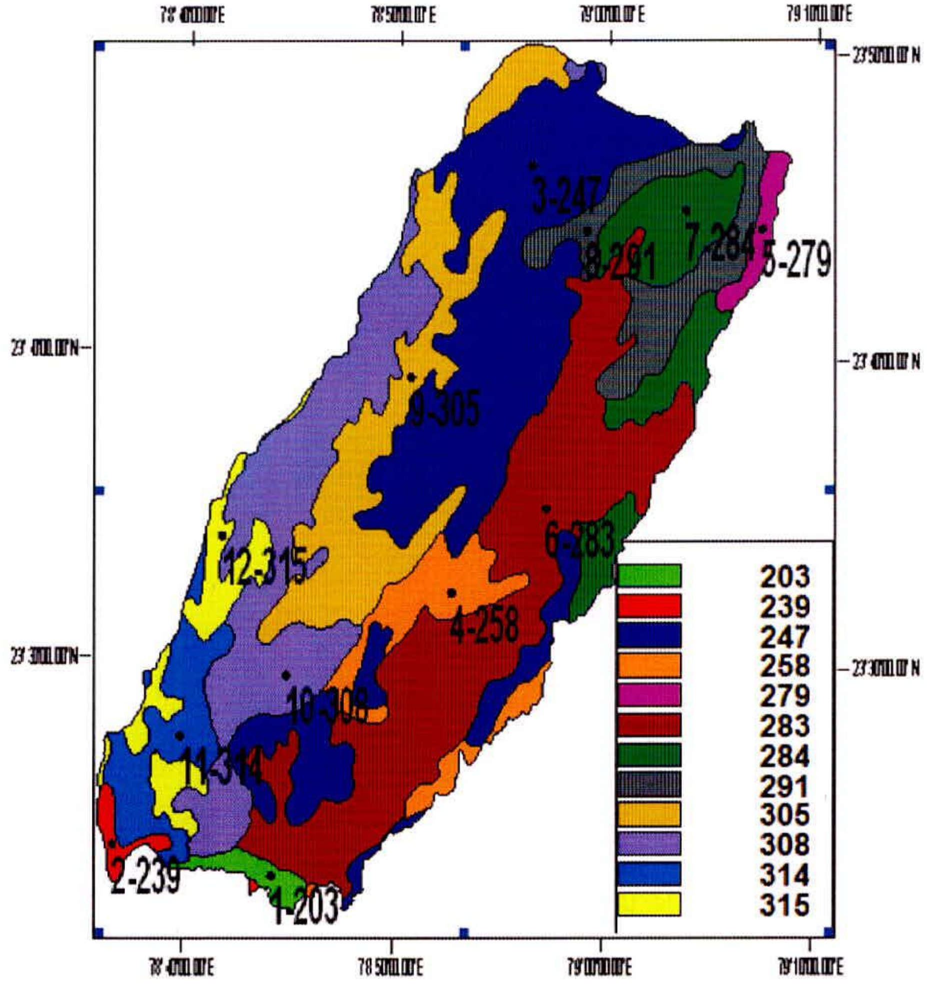


Fig. 14. Sites identified for conducting the soil tests in the Sonar sub-basin

5.1 Generation of Rainfall and Temperature for Future Scenarios

Since the long-term rainfall and temperature records were available for the Sagar station only, the meteorological data of this station were used for carrying out the meteorological analysis. The daily rainfall of the Sagar was available from 1901 to 2007 and temperature was available from 1972 to 2007. For generation of future scenarios of rainfall and temperature, the time period 1972-2003 was considered as the baseline period. Rainfall and temperature have been generated for the years 2039, 2069 and 2099 based on Mirza (2002) for GCM SRES scenarios south Asia region (Table 4). The scenarios have been undertaken for winter and summer season for both temperature and precipitation for the two extreme scenarios A1F1 and B1.

Both these scenarios indicate that winter rainfall will decrease while monsoon rainfall will increase but the increase in temperature will be more in winter than in summer.

Figures 15 and 16 show long-term mean monthly and mean annual rainfall variation from 1901 to 2003. The general observation from the long-term data 1901 to 2003 indicates that more than 90% rainfall occurs in the monsoon season (Figure 16) from June to September.

It is seen from the Figure 16 that linear trend of rainfall is positive during 1901-2003. However, the rainfall trend for the baseline period (1972-2003) as shown in Figure 17 indicates a declining rainfall trend. Man-Kendall's trend analysis also indicates a declining rainfall trend during this period which indicates that the groundwater recharge will be affected in future years if the present trend of rainfall continues.

Scenarios for rainfall and temperature were generated for future time slices 2004-2039, 2040-2069 and 2070-2099 based on baseline data, A1F1 and B1 scenarios (Table 4) using the weather generator based statistical downscaling technique. It is based on statistical principles and considered to be computationally less demanding technique as compared to other downscaling techniques.

Figures 18 and 19 show long-term variations of annual mean minimum and maximum temperature from 1972 to 2003. The general observation of the long-term minimum and maximum temperature data shows a rising trend.

Figure 20 to 22 show long-term mean monthly temperature for the period 1972 to 2003.

Rainfall and temperature have been generated for the baseline as well as A1F1 and B1 SRES scenarios (Table 4) for the time-slices 2004-2039, 2040-2069 and 2070-2099 but the results and

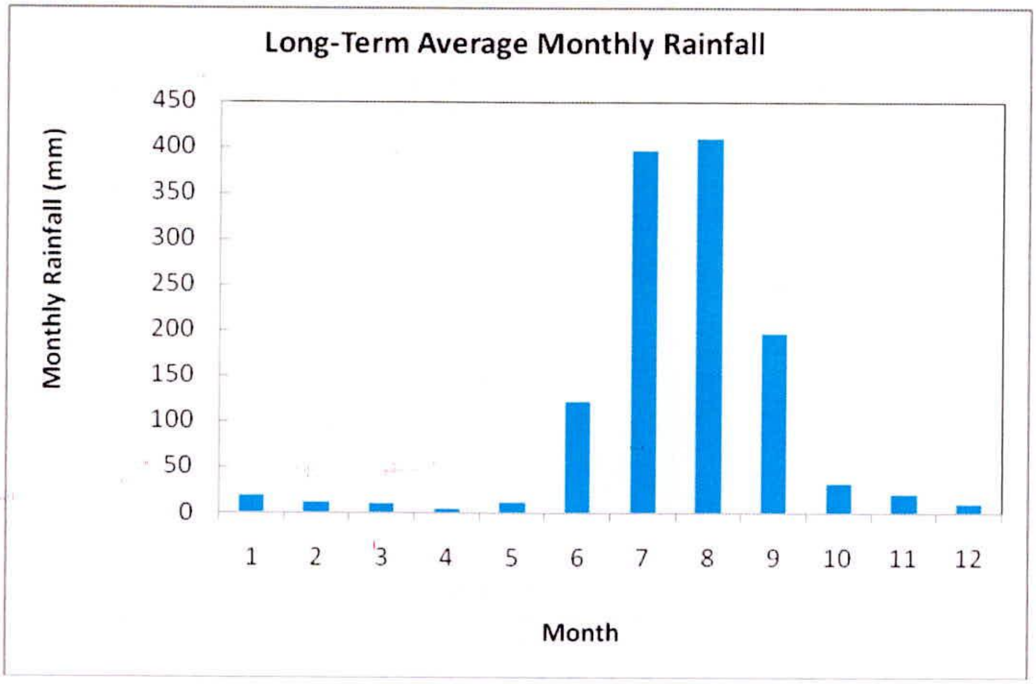


Fig. 15. Long-term mean monthly rainfall of Sagar

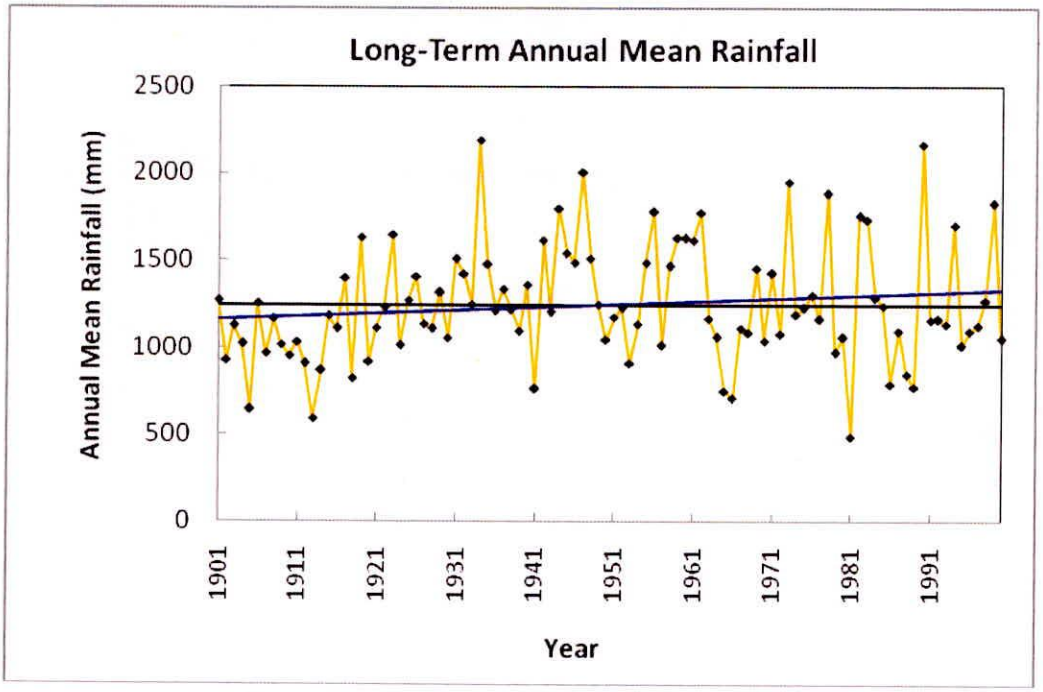


Fig. 16. Long-term mean annual rainfall of Sagar

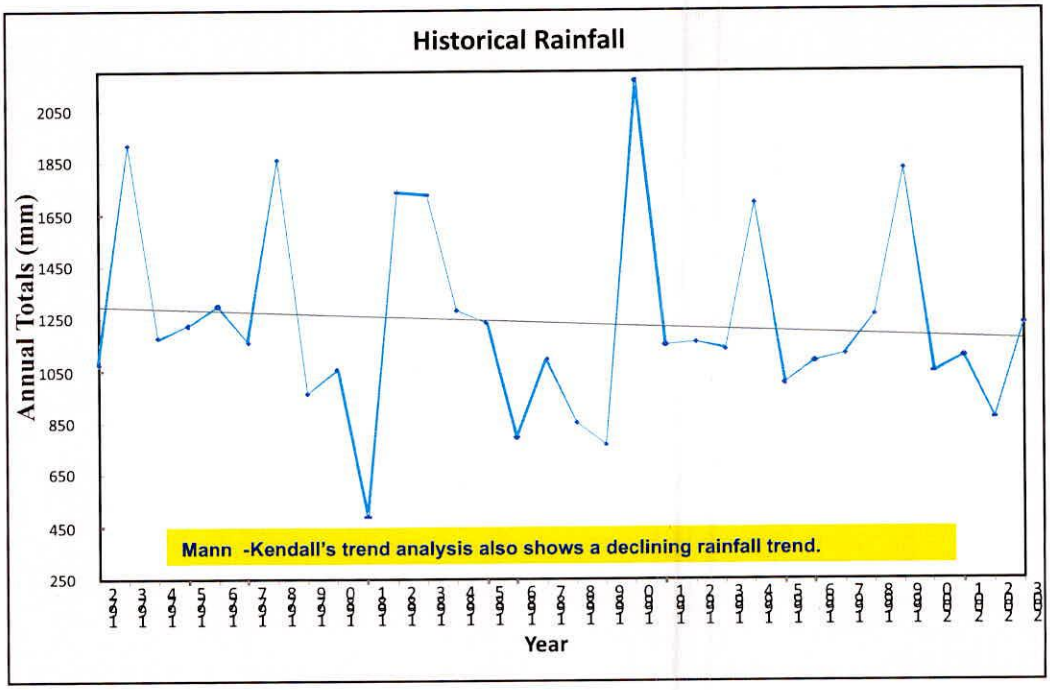


Fig. 17 Mean annual rainfall of Sagar for the baseline period

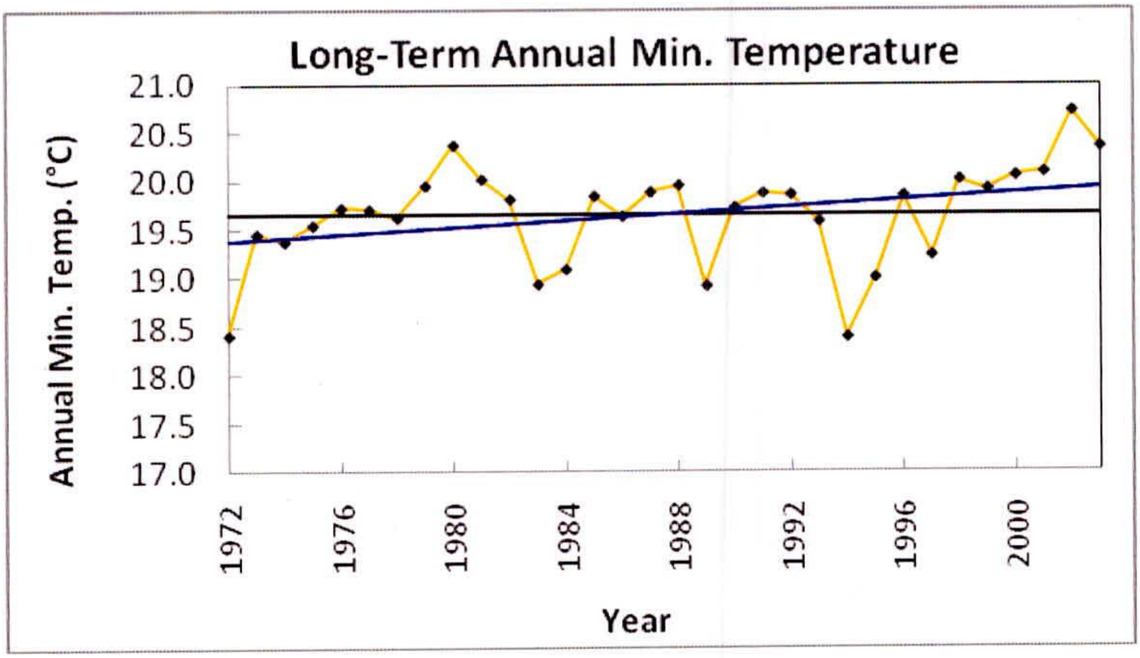


Fig. 18. Long-term mean annual minimum temperature

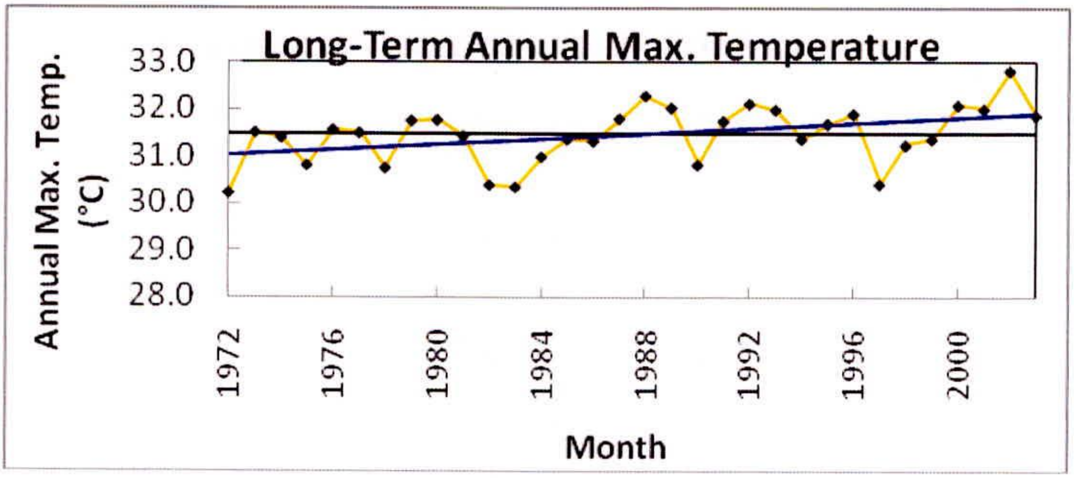


Fig. 19. Long-term mean annual maximum temperature

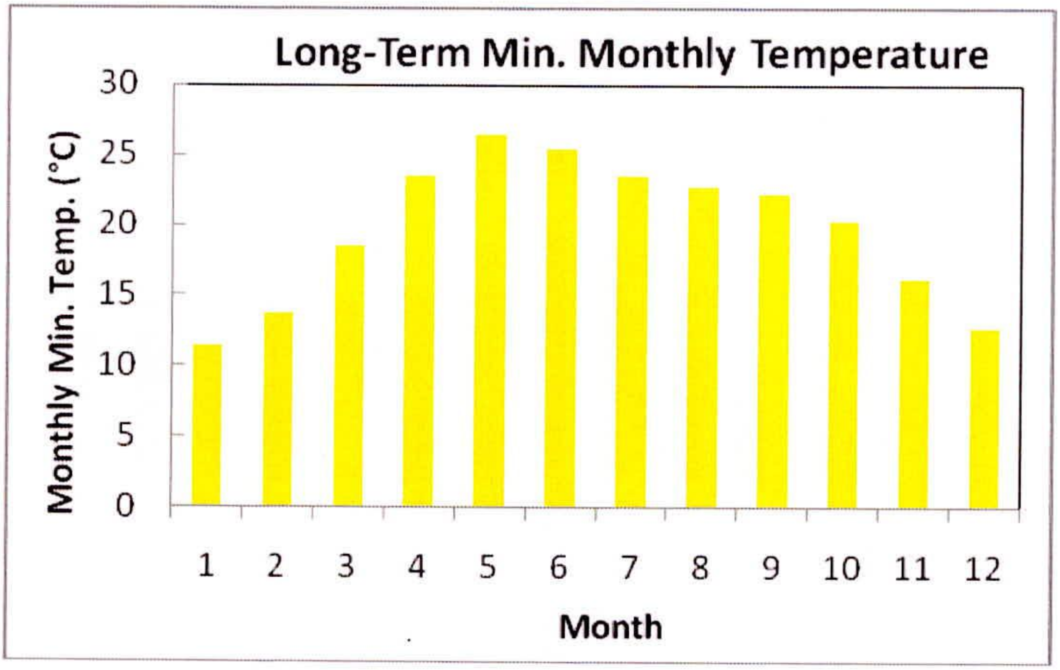


Fig. 20. Long-term mean monthly minimum temperature

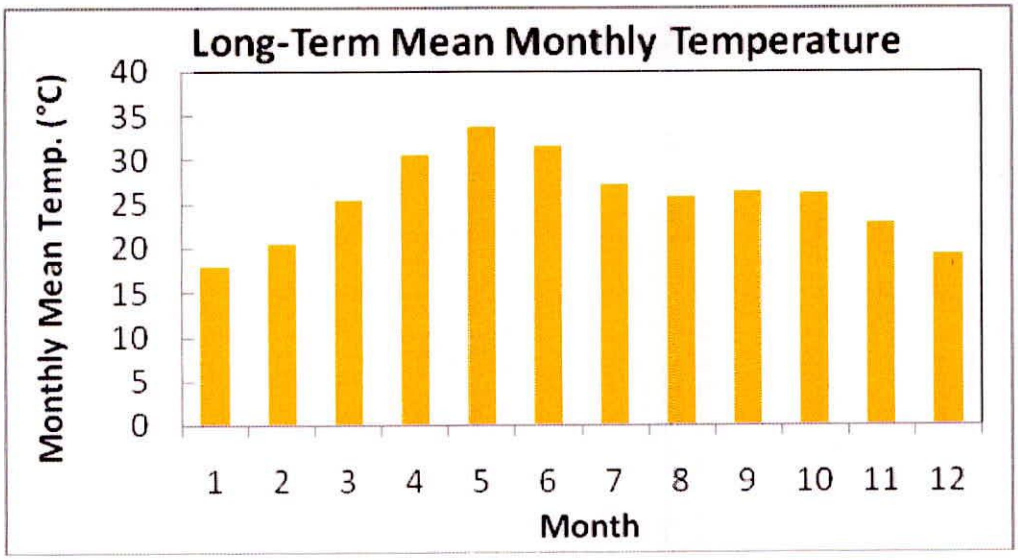


Fig. 21. Long-term mean monthly temperature

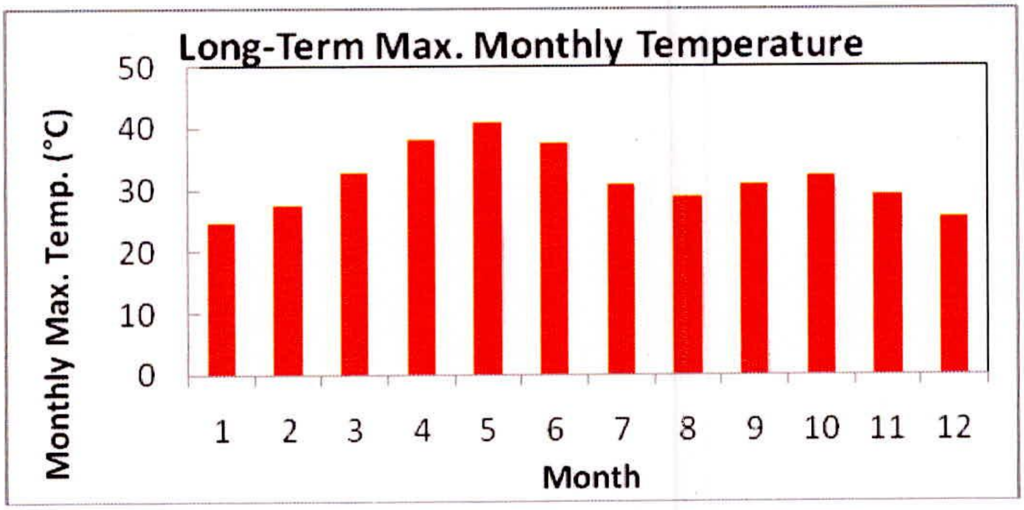


Fig. 22. Long-term mean monthly maximum temperature

discussions have been presented here for the time-slice 2004-2039 only so as to avoid the complexity arising due to handling of very large times series data and repetition of results for other time-slices. The downscaled results for the time-slice 2004-2039 are shown in Figures 23 to 25 for rainfall and Figures 26 to 28 for temperature. These time series have been developed on a daily time scale and then converted to monthly and annual time scale for the presentation of results. It is seen from these Figures that the future rainfall shows a declining trend of rainfall for all the three scenarios, i.e., baseline, A1F1 and B1. However, the temperature is showing a rising trend. These time series of rainfall and temperature have been further used by the VHELP model for the estimation of groundwater recharge at twelve locations in the basin on a daily time scale.

A comparison of mean monthly observed and generated rainfall and temperature for the three scenarios and their standard deviation are shown in Figures 29 and 30.

A complete annual series of rainfall and temperature for both observed and generated data from 1972 to 2039 for all the three scenarios are shown in Figures 31 and 32 and their percent change from the baseline scenario are shown in Figures 33 and 34, respectively. The time series have been used in further analysis for estimation of the groundwater recharge and quantification of the impact of climate change.

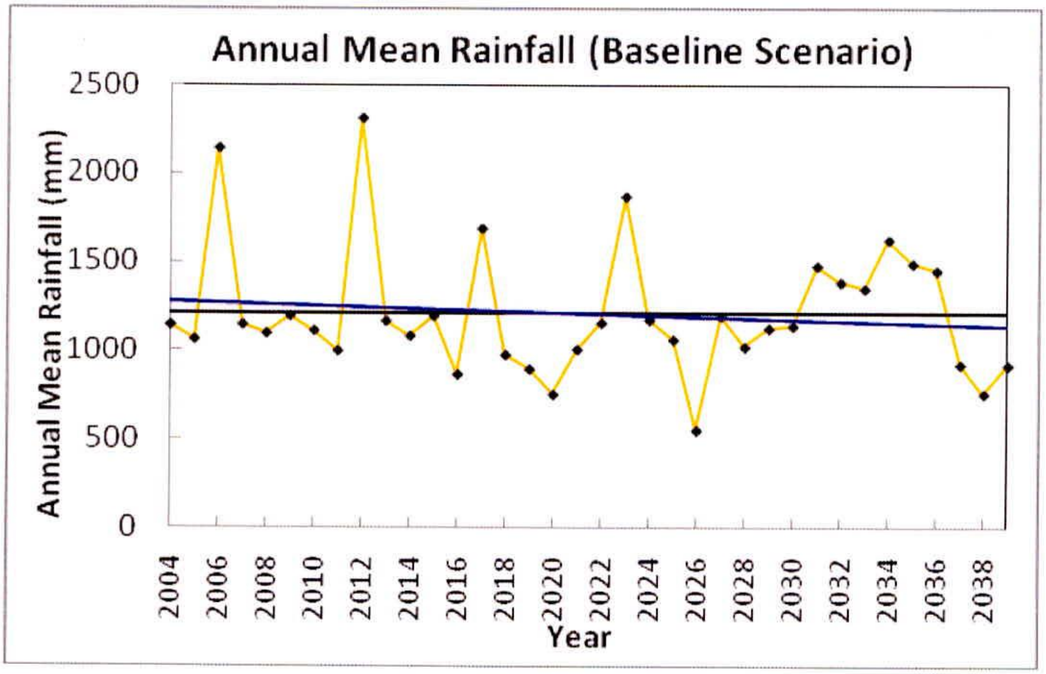


Fig. 23. Generated mean annual rainfall for baseline scenario

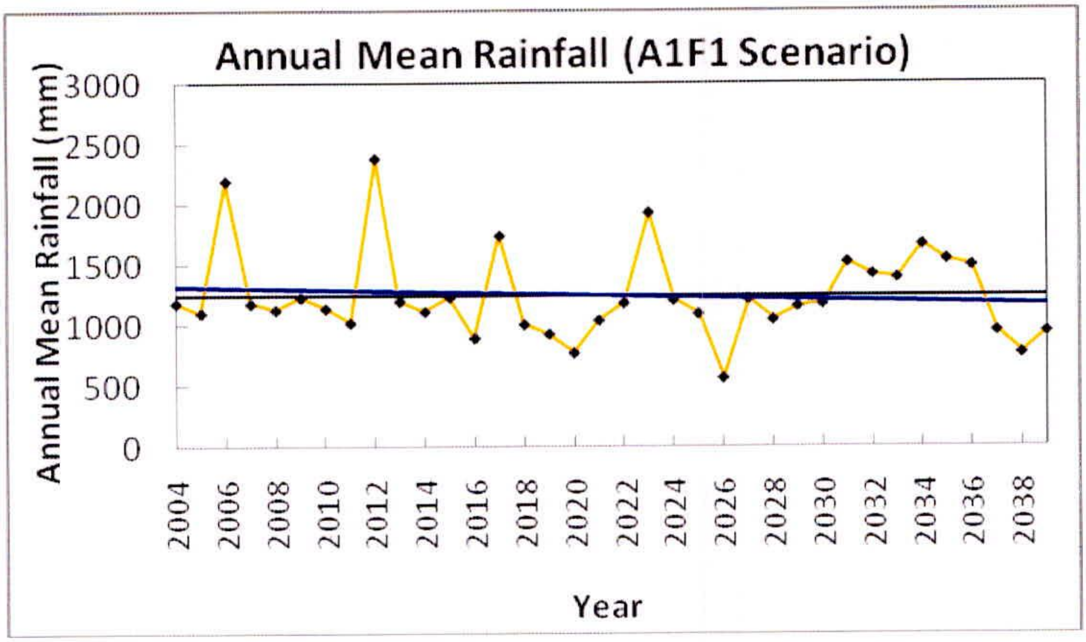


Fig. 24. Generated mean annual rainfall for A1F1 scenario

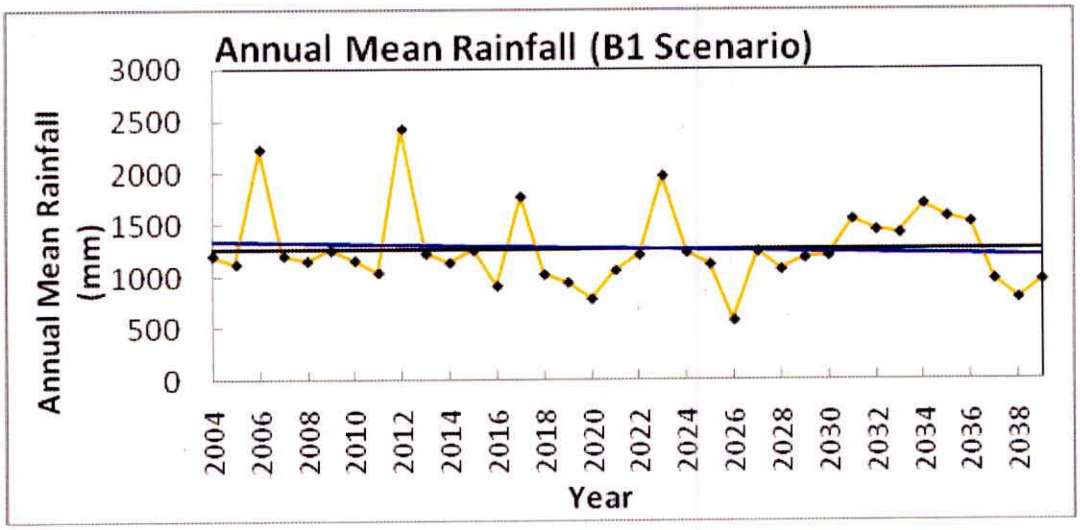


Fig. 25. Generated mean annual rainfall for B1 scenario

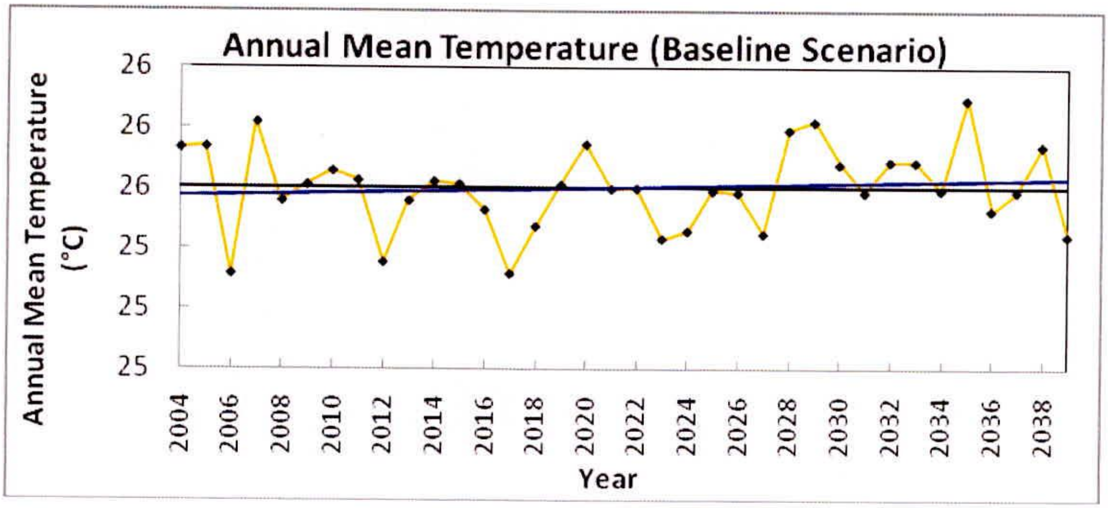


Fig. 26. Generated mean annual temperature for baseline scenario

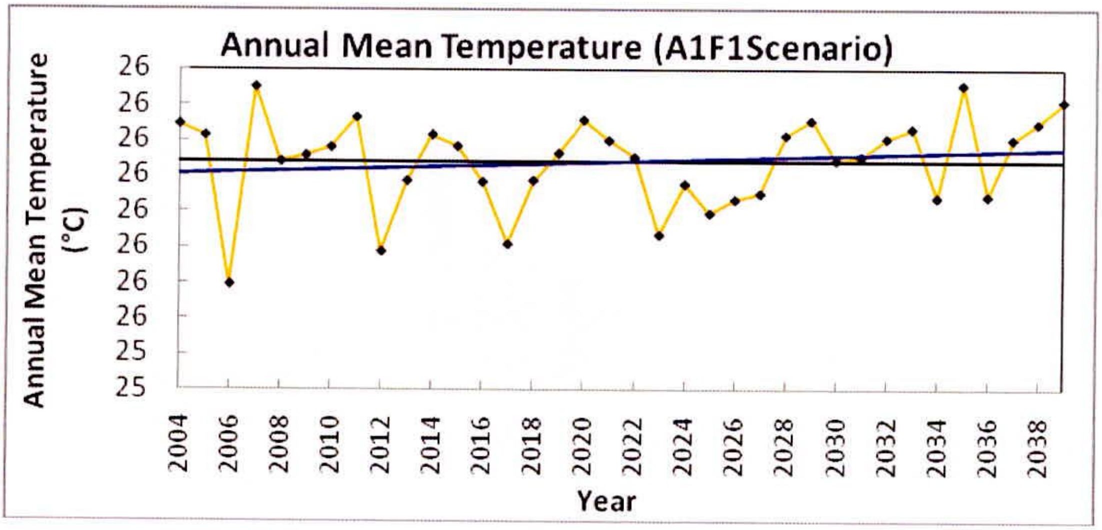


Fig. 27. Generated mean annual temperature for A1F1 scenario

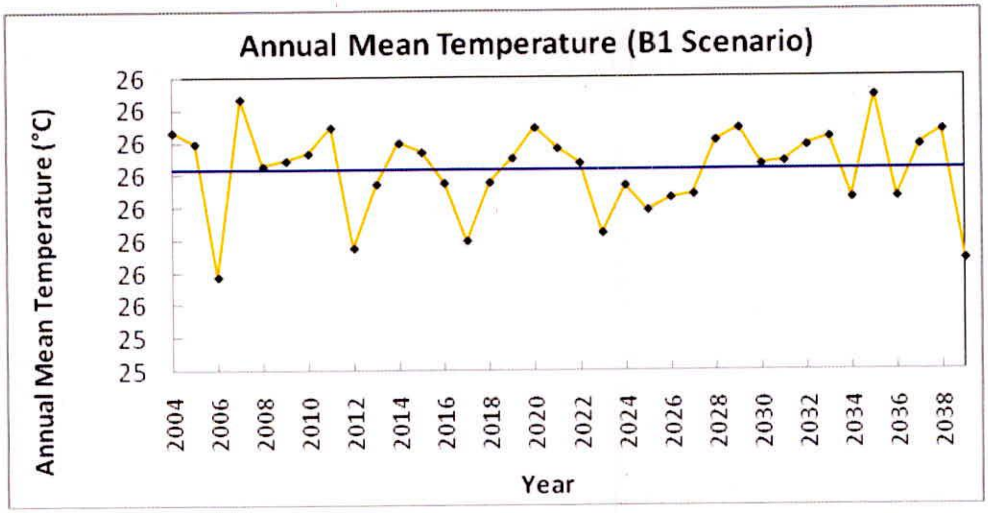


Fig. 28. Generated mean annual temperature for B1 scenario

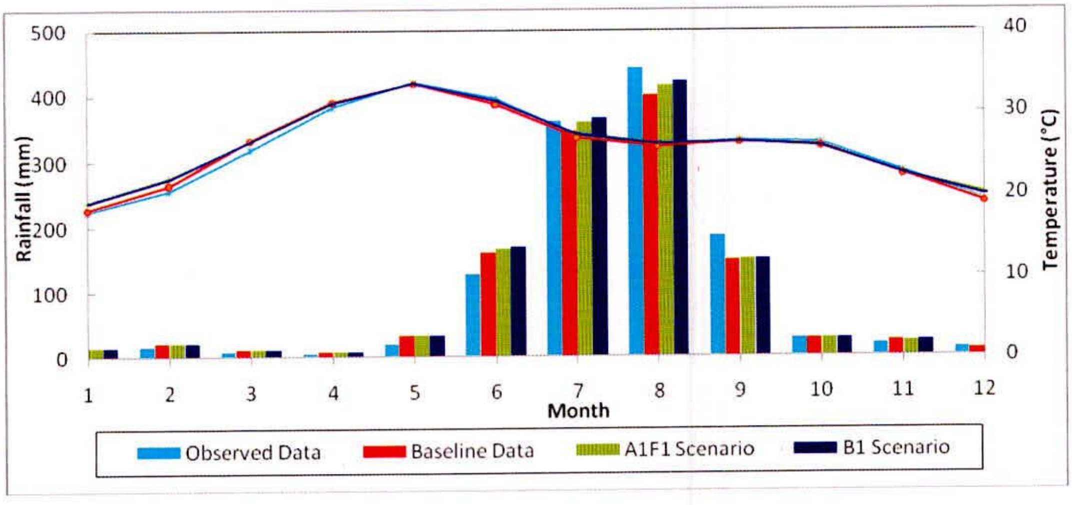


Fig. 29. Comparison of different future scenarios of rainfall and temperature

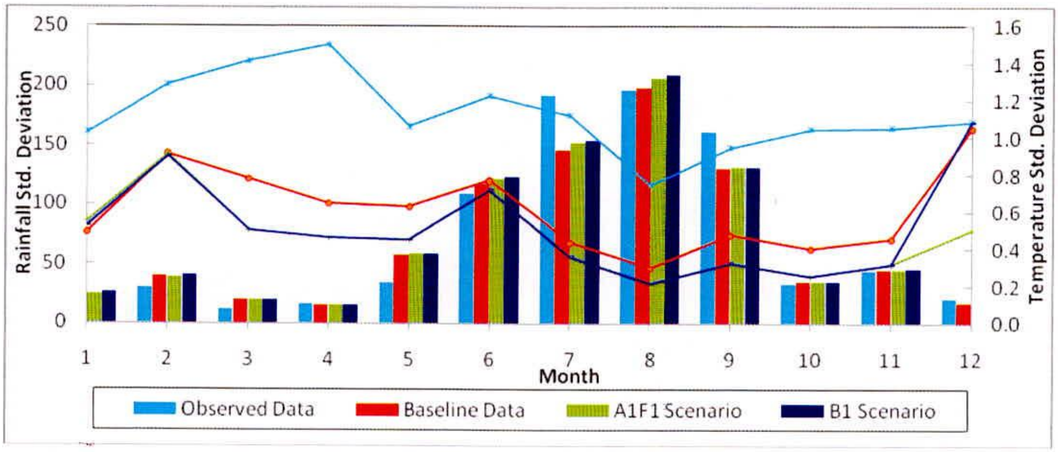


Fig. 30. Comparison of Std. deviation of different future scenarios of rainfall and temperature

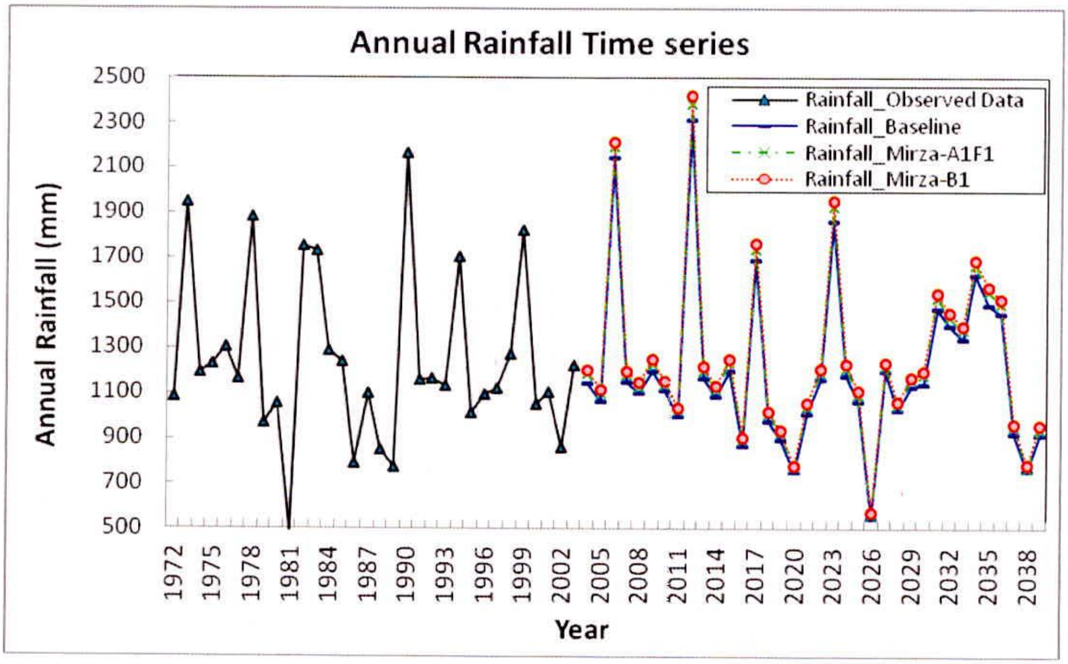


Fig. 31. Observed and generated rainfall series for different scenarios

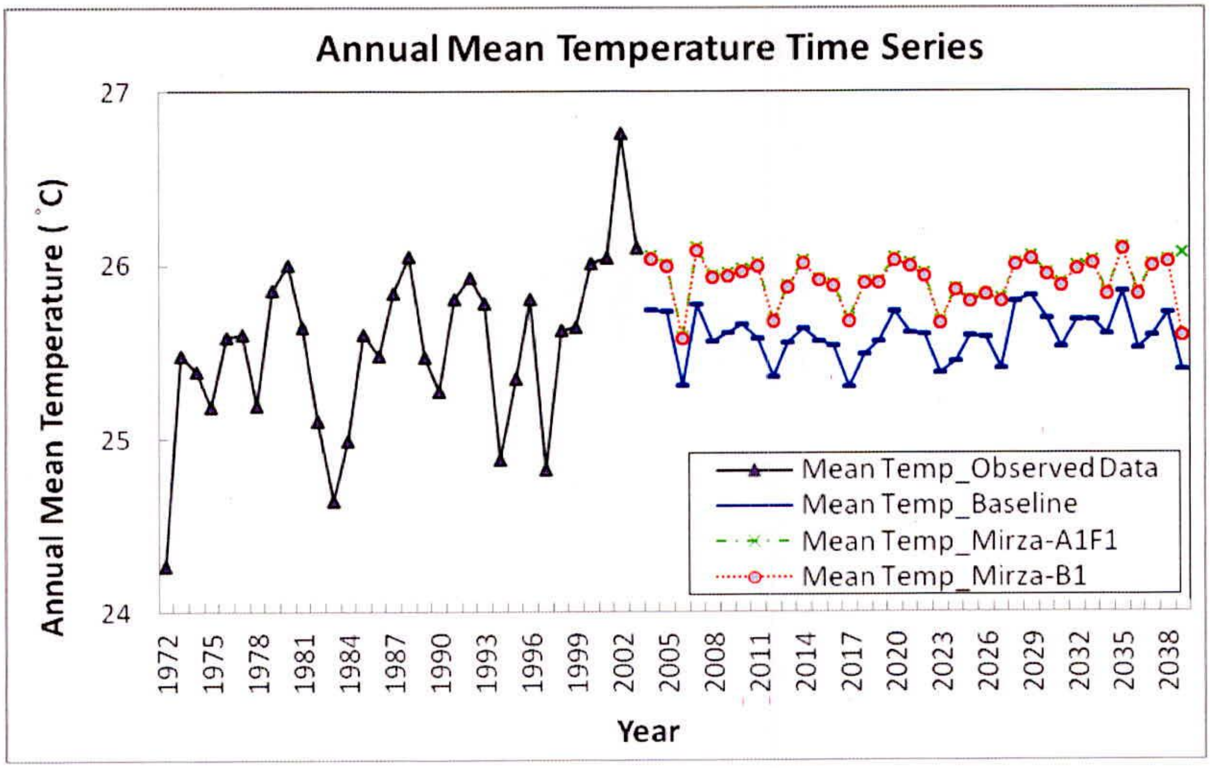


Fig. 32. Observed and generated temperature series for different scenarios

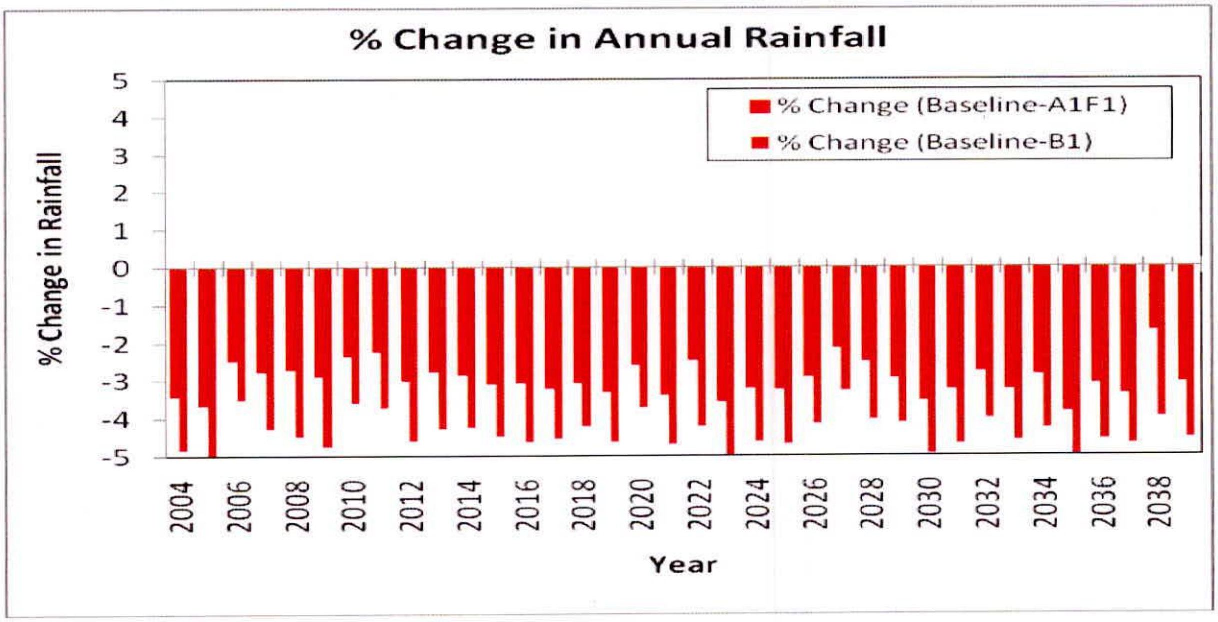


Fig. 33. Percent change of generated rainfall of different scenarios from baseline

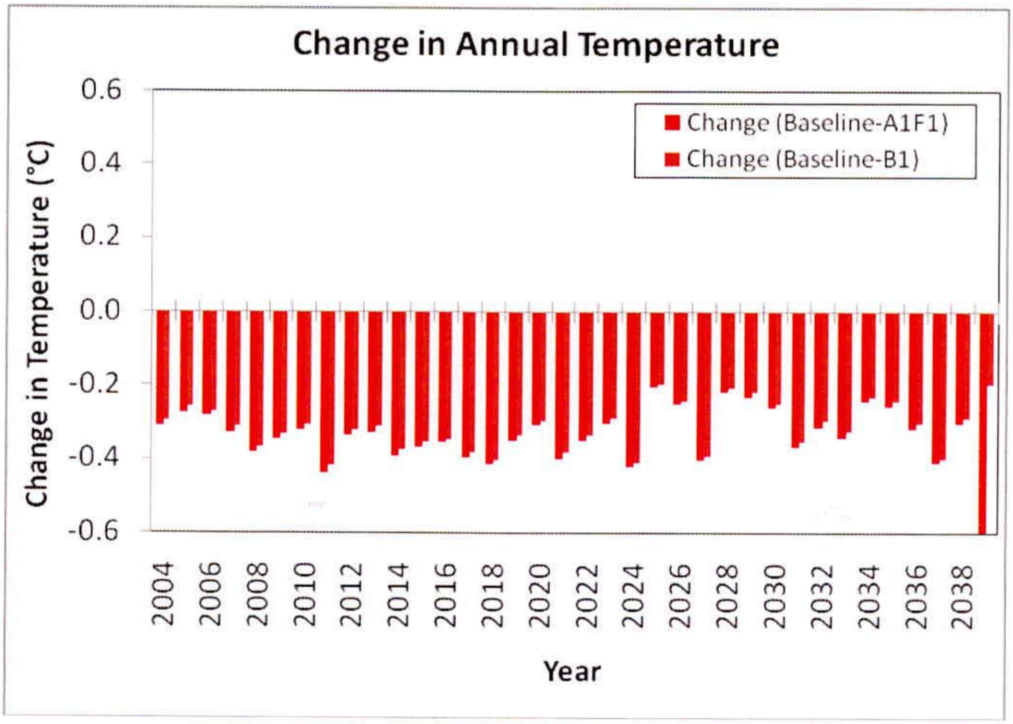


Fig. 34. Percent change of generated temperature of different scenarios from baseline

It is estimated that due to the climate change projections, change in temperature under A1F1 and B1 scenarios is +1.27 and +1.22 °C, respectively and change in rainfall under A1F1 and B1 scenarios is +3.0 and +4.4%, respectively as compared to baseline scenario for the time-slice 2004-2039.

Figure 35 shows a comparison of both observed and simulated rainfall and shows a quite comparable match.

5.2 Estimation of Groundwater Recharge in the Sonar Sub-Basin

As mentioned earlier that this study is carried out to quantify the impact of climate change on groundwater. For this purpose, the time-slice 1972 to 2003 is used as the historical baseline period. The groundwater recharge is estimated for 1972 to 2003 as historical baseline period and 2004 to 2039 as future period. The groundwater recharge is then estimated for future projections of rainfall under the future baseline, A1F1 and B1 scenarios and the difference under the A1F1 and B1 scenarios is estimated as compared to the future baseline scenario. VHELP model is used to estimate the site-specific groundwater recharge. VHELP model was given weather data, vegetation details and soil profile properties as inputs. The model was then run to estimate the groundwater recharge.

The results of groundwater recharge estimation for baseline, A1F1 and B1 scenarios are presented in 5 to 6. It is seen that the total groundwater recharge varies between 14 to 32 % of the total

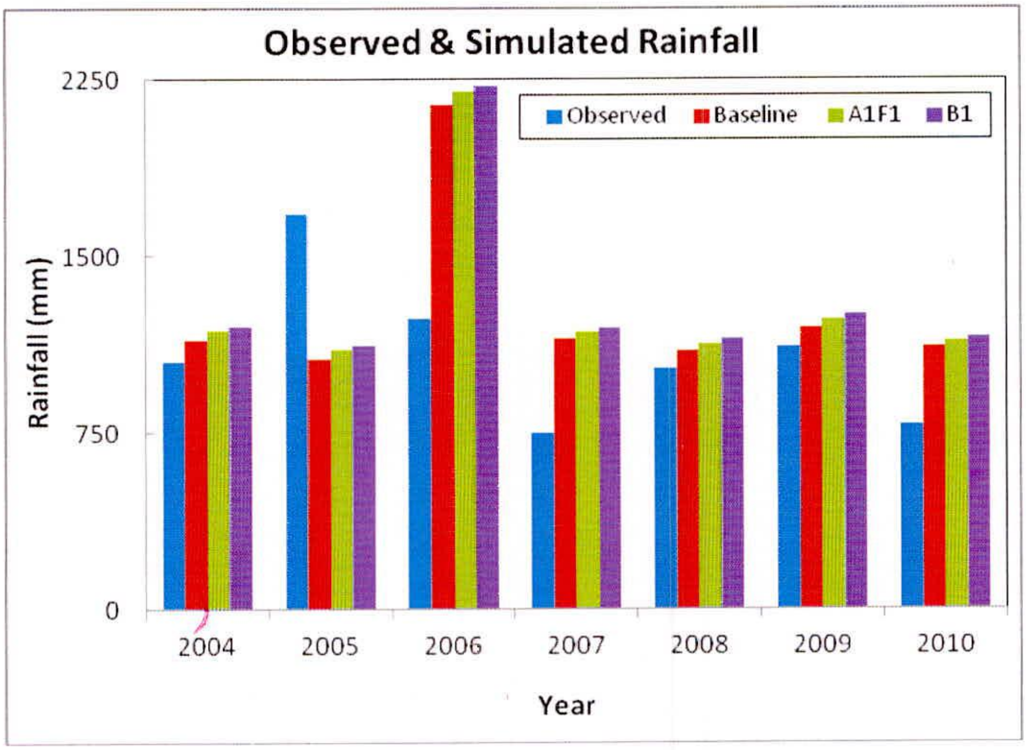


Fig. 35. Comparison of observed and generated rainfall for different scenarios

rainfall during historical period at the twelve identified sites. It is observed that the minimum and maximum recharge rates are found at 157 and 349 mm/year at Kothi Kha and Inchalpur, respectively for the historical period. The possible reason for less recharge at Kothi Kha is that the slope in this region is high and more water goes in runoff.

Figures 36 to 38 show annual total values, accumulated values and average monthly values of the rainfall recharge to the groundwater in the Sonar sub-basin, respectively. It is seen that the annual groundwater recharge in the basin varies from 7.6 to 598.8 mm with an average of 276 mm. It is seen from the Figure 38 that most of the groundwater recharge (96%) occurs in the basin during monsoon, i.e., July to October months.

The estimated results of groundwater recharge for baseline, A1F1 and B1 scenarios are presented in Table 7 to 8.

It is seen that the total groundwater recharge varies between 10 to 32 % of the baseline rainfall during future period at the twelve sites.

It is seen from the Table 8 that groundwater recharge varies between 122 to 377, 127 to 385 and 130 to 389 mm/year under the baseline, A1F1 and B1 scenarios, respectively. The groundwater

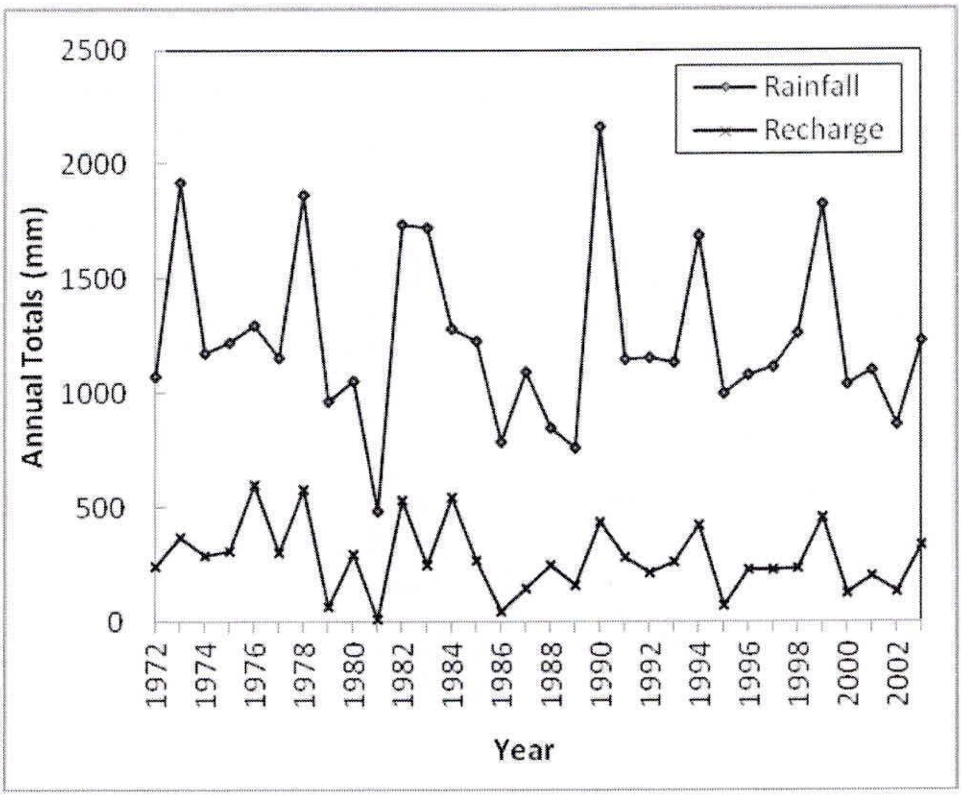


Fig. 36. Annual totals of groundwater recharge in the basin for Akala site

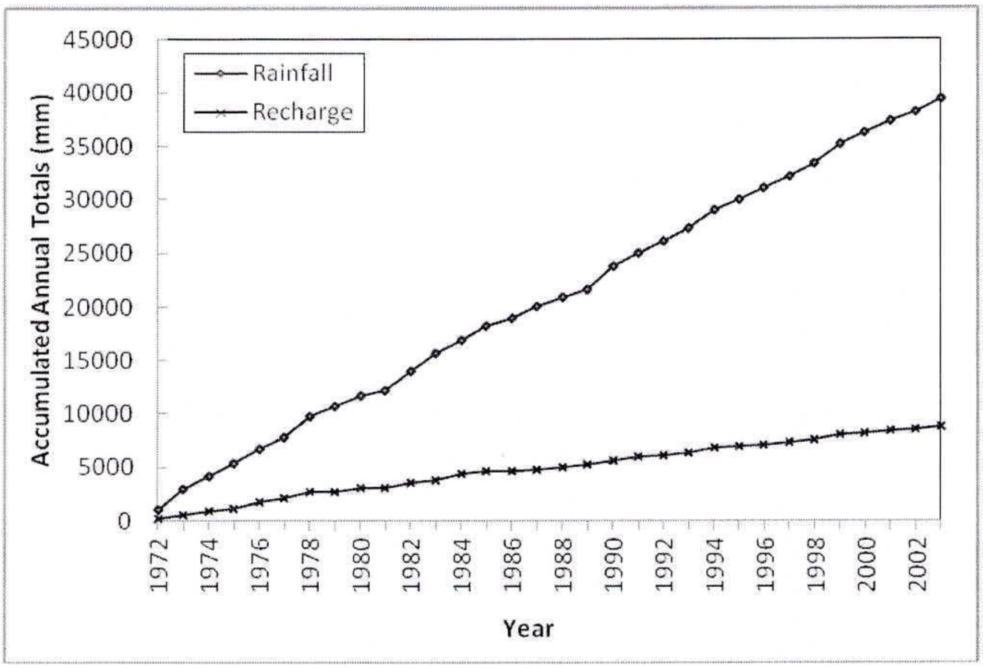


Fig. 37. Annual accumulated values of rainfall recharge in the basin for Akala site

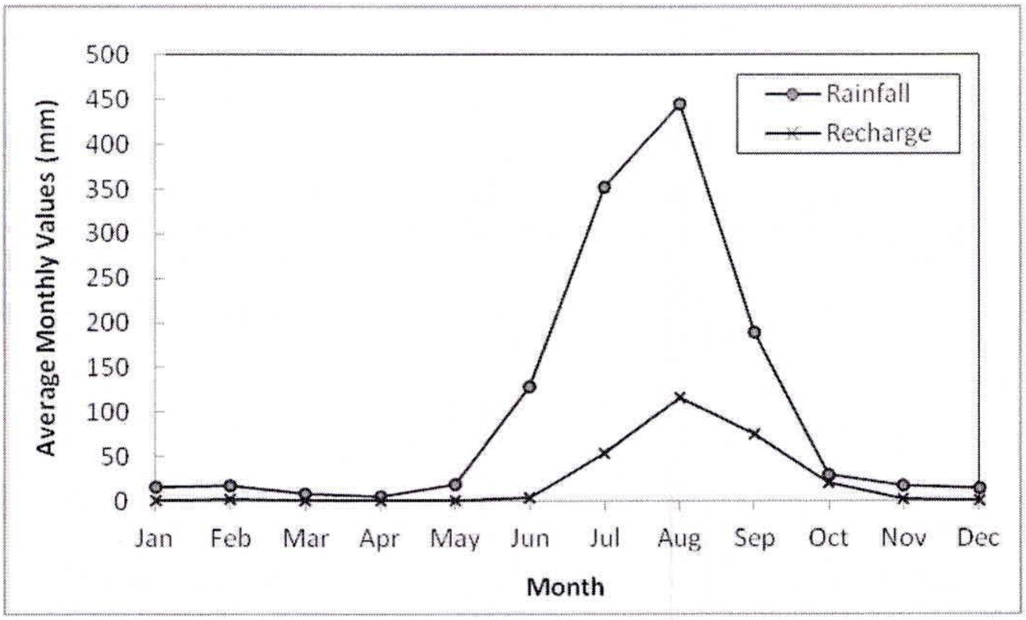


Fig. 38. Average monthly rainfall and recharge in the basin at Akala Site

recharge is also quantified in the volumetric terms, which indicates that the groundwater recharge at Dadhonia, Inchalpur and Kukwara sites is more as compared to other sites (Figure 39). This is because of the higher recharge rates and more zone area under these test sites.

Table 9 shows the change in groundwater recharge as estimated under different scenarios. It is observed that the change in groundwater recharge for the times-slice 2004 to 2039 under A1F1 and B1 scenarios range between +2.1 to +3.8% and +1.8 to + 6.1%, respectively as compared to the baseline scenario.

5.3 Groundwater Level Simulation

In order to quantify the impact of climate change on the groundwater levels, the groundwater level simulation is done in the Sonar sub-basin. The whole basin is divided into twelve zones (Figure 40). These zones are developed as polygons based on the sites of groundwater recharge estimation. It is seen from the Figure 40 that each zone has at least one observation well except for the zones 2 and 12. Therefore the groundwater level simulation has been carried out for all the zones except these two zones. The simulation of groundwater levels has been done based on the water balance method for each zone.

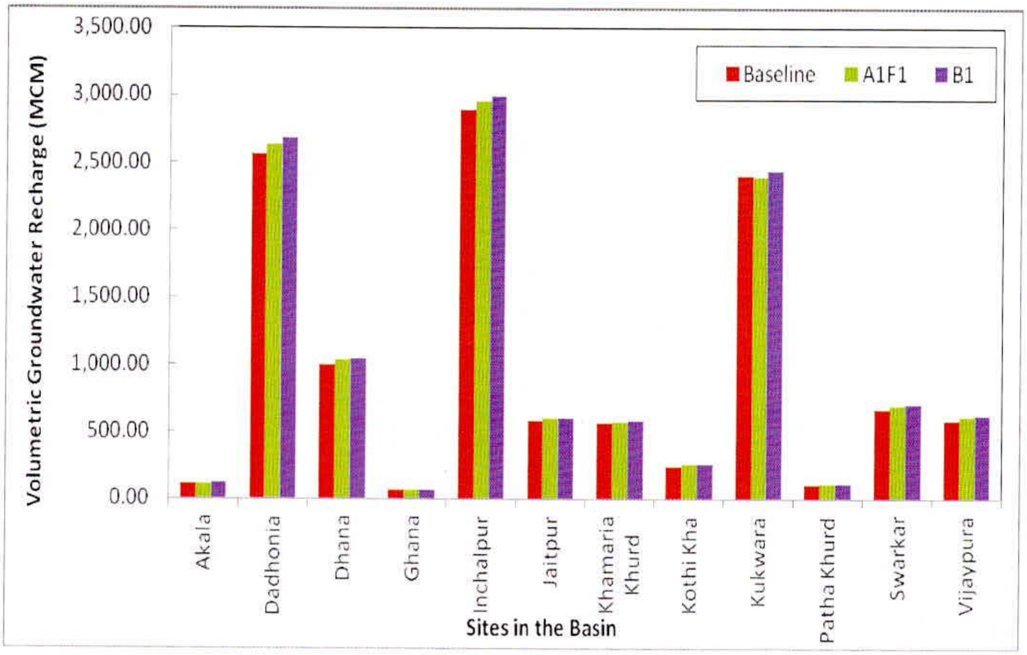


Fig. 39. Volumetric groundwater recharge in various zones of identified sites

Zone	Well Name
1-203	SGR047-OW
2-239	No Well
3-247	SGR074-OW
4-258	SGR111-OW
5-279	SAGAR011
6-283	SGR041-OW
7-284	SGR080-OW
8-291	SGR077-OW
9-305	SGR039-OW
10-308	SGR084-OW
11-314	SGR044-OW
12-315	No Well

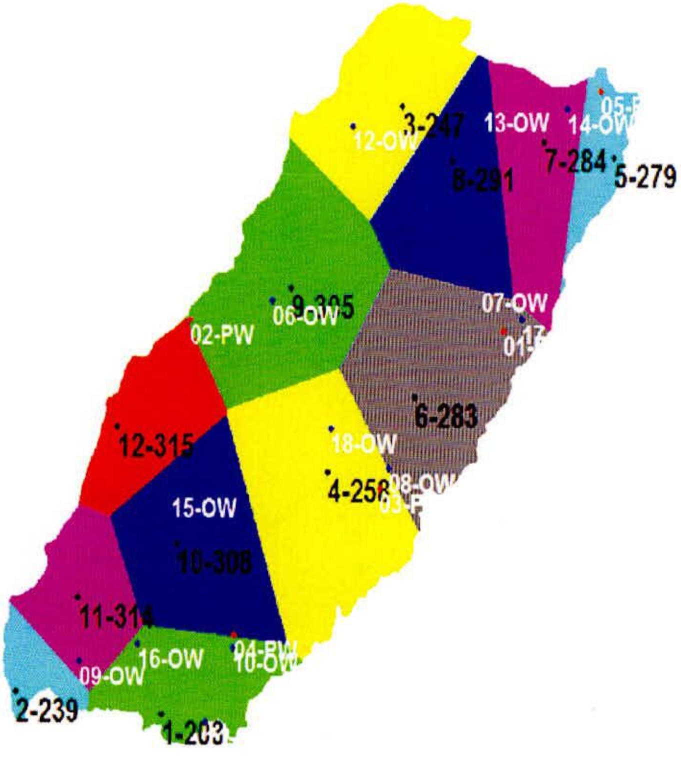


Fig. 40. Construction of zones for groundwater level simulation in the basin

There is no command area in the basin and the surface water storage structures are also very minimal. The groundwater draft used for the simulation purpose is taken from the CGWB (2009). The ground water level data for the period 1984 to 2003 were collected for the wells located in the basin from the State Ground Water Survey Department, Sagar. The following assumptions were made in the water level simulation:

1. inflow and outflow in and out of the zone was not considered.
2. Since the groundwater draft was available on an annual basis, it was considered uniform by divided equally for all the twelve months.
3. Groundwater recharge was also considered uniformly occurring over the zone area.
4. Stream or river aquifer interaction was not considered.

For the groundwater level simulation, calibration period was taken from 1984 to 2000 except for few wells where the data length was short. Figures 41 to 48 show the calibration of groundwater level simulation in different zones of the basin. There figures show a reasonable match of observed and simulated groundwater levels. Minor discrepancy in the calibration process may be attributed to the above-mentioned assumptions.

The groundwater levels have also been developed for the future period 2004 to 2039 on the monthly basis for baseline, A1F1 and B1 scenarios. For this purpose, the groundwater recharge as already estimated for the period 2004 to 2039 was used. The same uniform groundwater draft as used

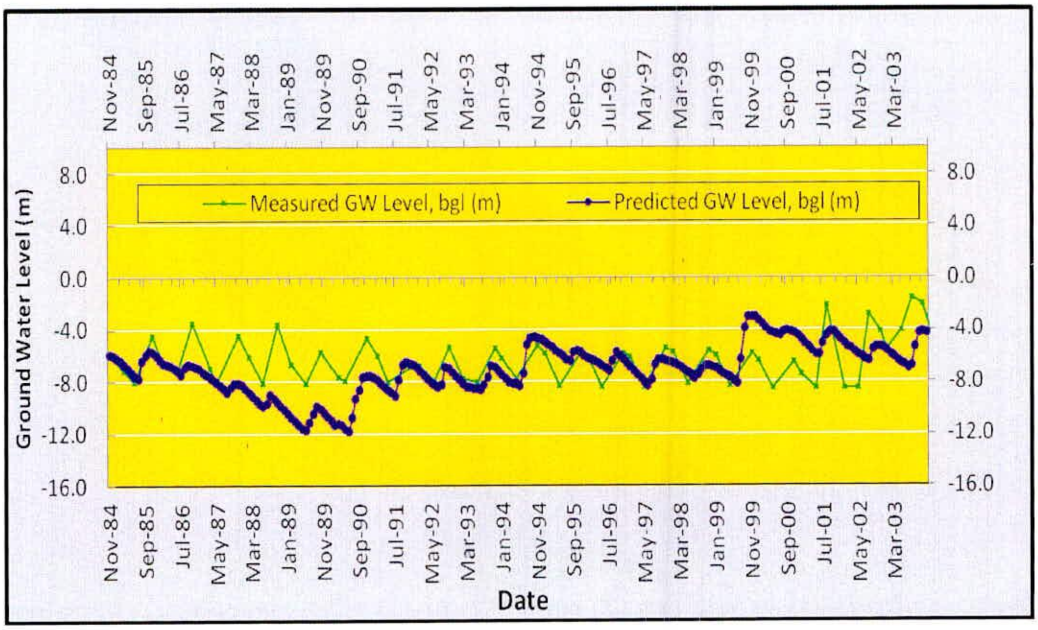


Fig. 41. Groundwater level simulation in Zone-1 of the Sonar sub-basin

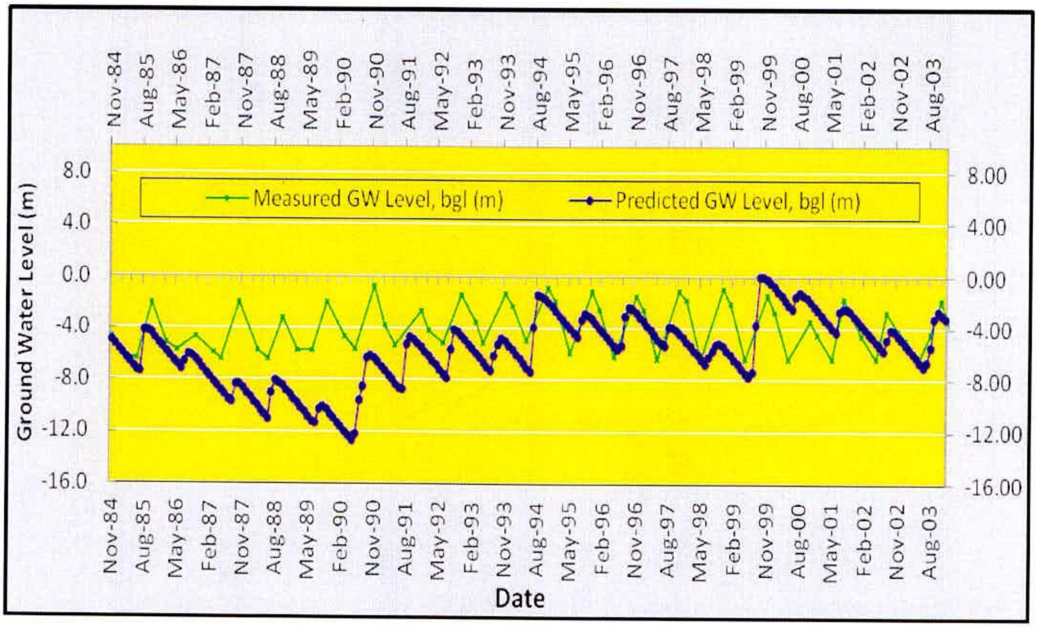


Fig. 42. Groundwater level simulation in Zone-3 of the Sonar sub-basin

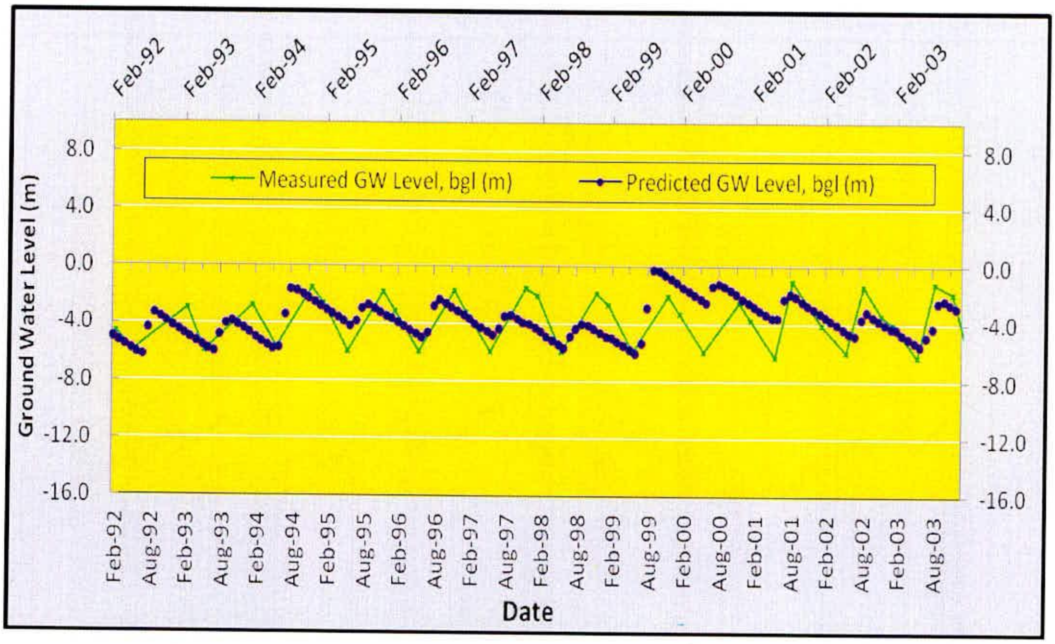


Fig. 43. Groundwater level simulation in Zone-4 of the Sonar sub-basin

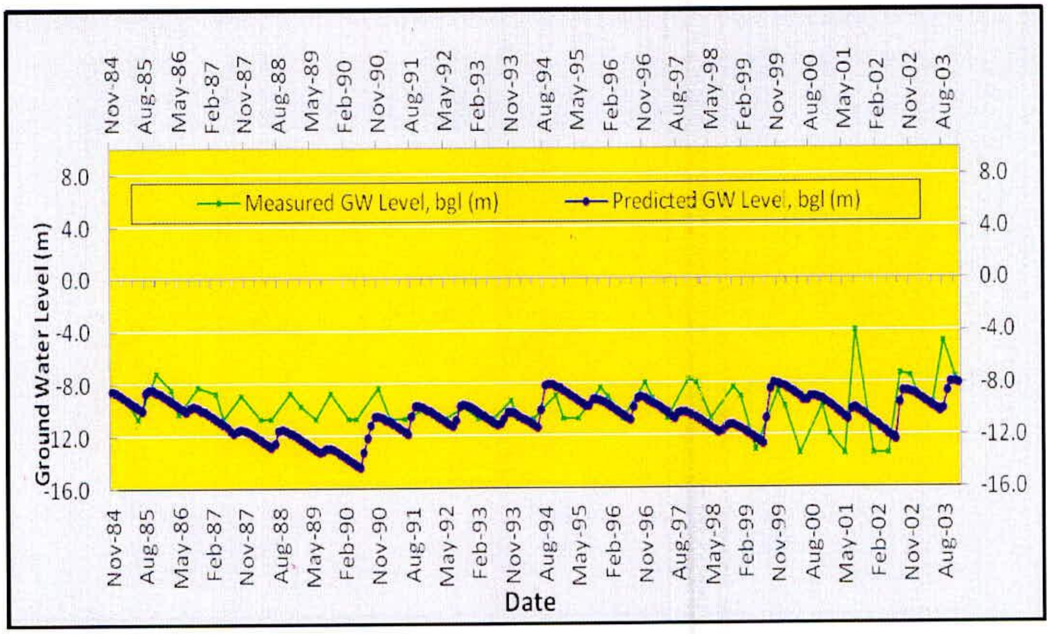


Fig. 44. Groundwater level simulation in Zone-6 of the Sonar sub-basin

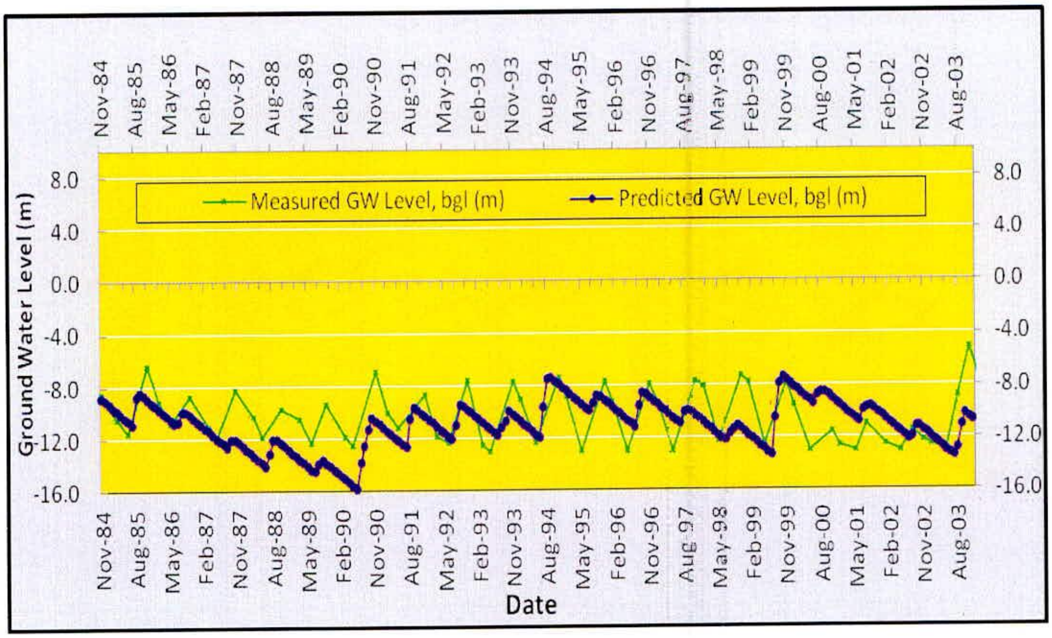


Fig. 45. Groundwater level simulation in Zone-7 of the Sonar sub-basin

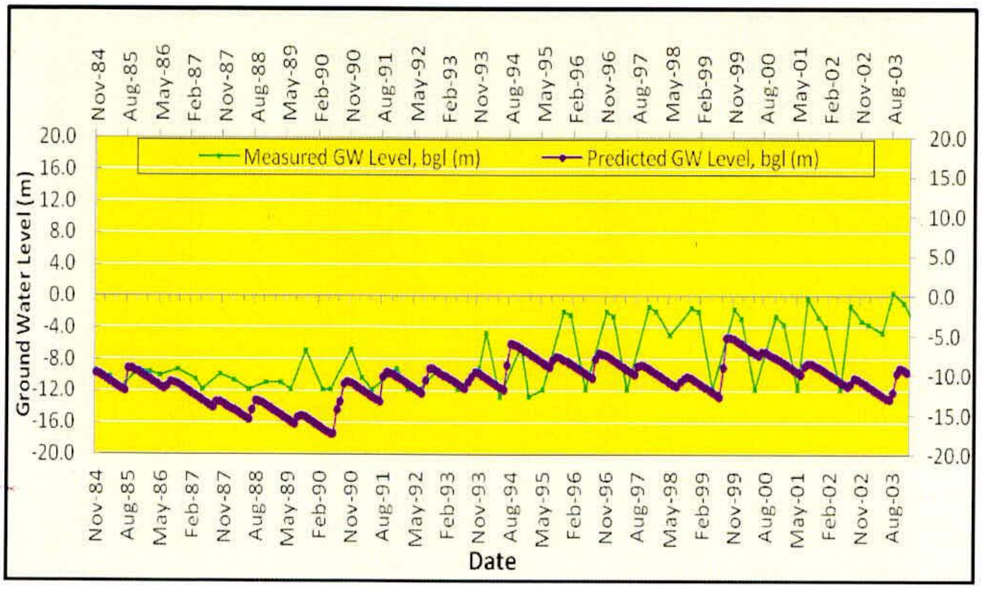


Fig. 46. Groundwater level simulation in Zone-8 of the Sonar sub-basin

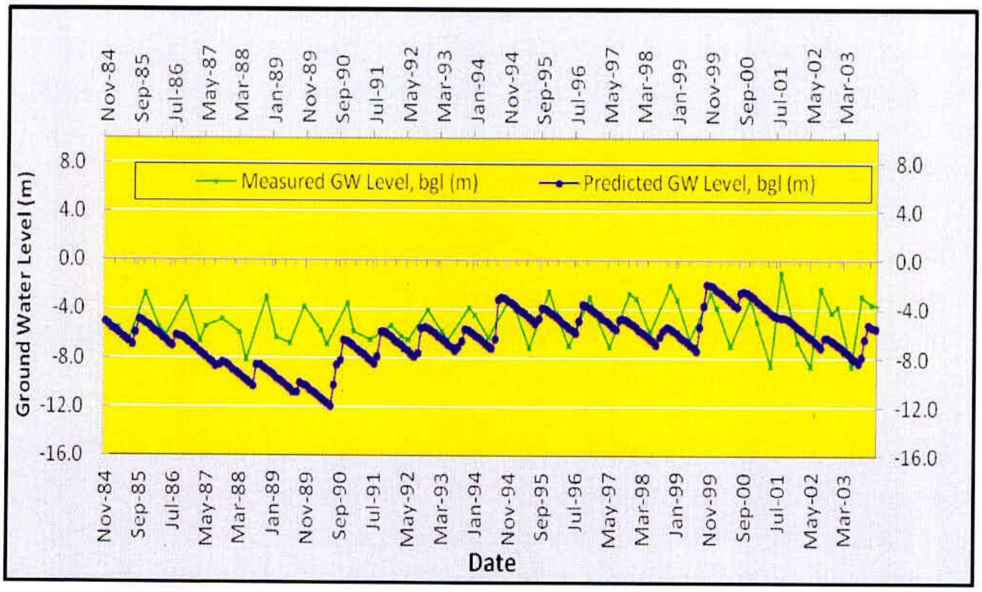


Fig. 47. Groundwater level simulation in Zone-9 of the Sonar sub-basin

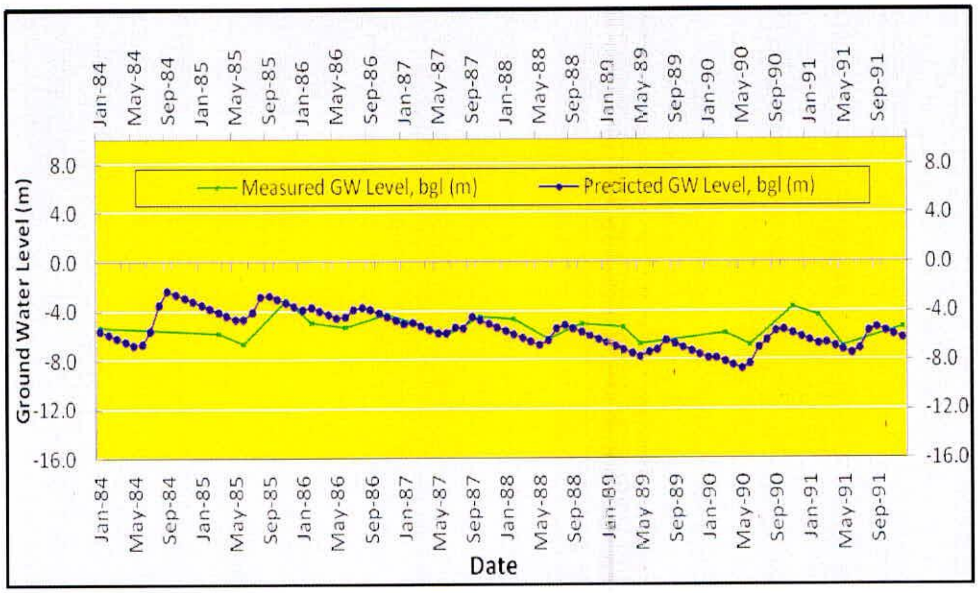


Fig. 48. Groundwater level simulation in Zone-10 of the Sonar sub-basin

earlier was considered for future also. The groundwater levels for the future period for all the three scenarios are presented in Figures 49 to 57.

It is observed that for most zones, groundwater levels are showing a declining trend which is due to the decrease in amount of future rainfall. However, as stated earlier the groundwater recharge has increased under both the A1F1 and B1 scenarios as compared to the baseline scenario which is in response to the future projections of GCM SRES scenarios for the South Asia region. This increase in ground water recharge has caused a rise in ground water levels under both A1F1 and B1 scenarios compared to the baseline scenario (Figures 49 to 57).

It is estimated that the groundwater levels indicate a rising trend in all the zones for the A1F1 and B1 scenarios as compared to the baseline scenario and the estimated change in groundwater levels during the time-slice 2010-2039 under A1F1 and B1 scenarios is +8.0 and +14%, respectively as compared to the baseline scenario (Figures 58 and 59).

An analysis is also made to quantify the amount of additional quantity of water required to make the groundwater levels sustainable in different zones in future, i.e., the water level shall lie in the zone of water level fluctuation, and it is found that the additional quantity of water required for artificial recharge to maintain the sustainable groundwater levels in different zones of the basin ranges between 0.0 to 8.3% with an average of 4.3% more, which is around 0.6% of the average annual rainfall. This additional quantity of water for the artificial recharge will have to be met out from the rainwater harvesting and needs to store during the monsoon season.

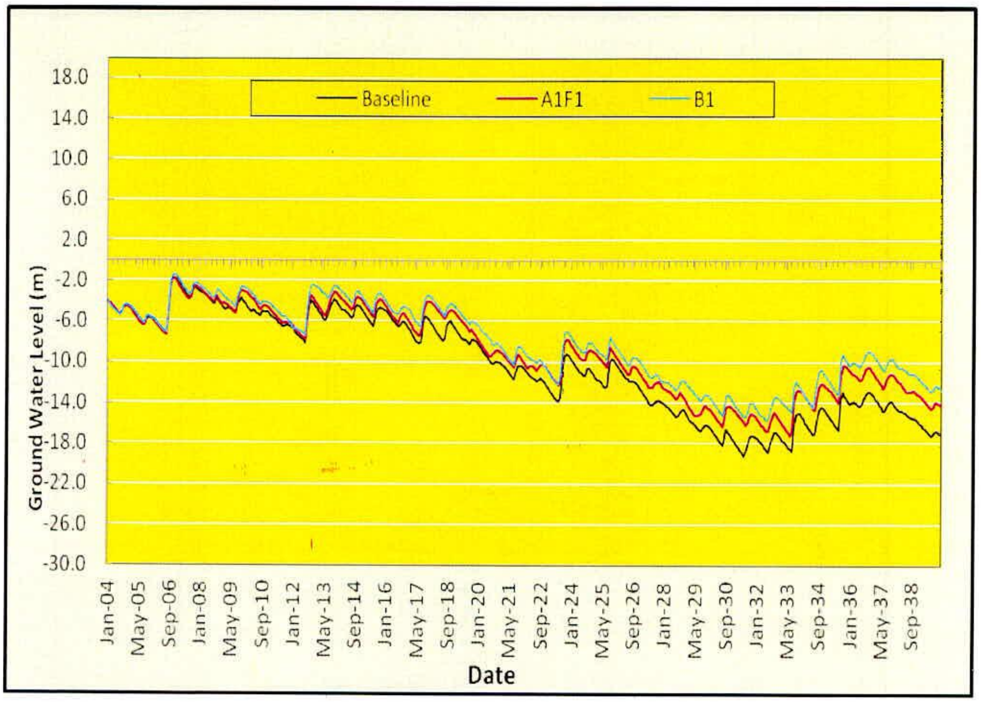


Fig. 49. Groundwater level variation in response to future rainfall in Zone-1

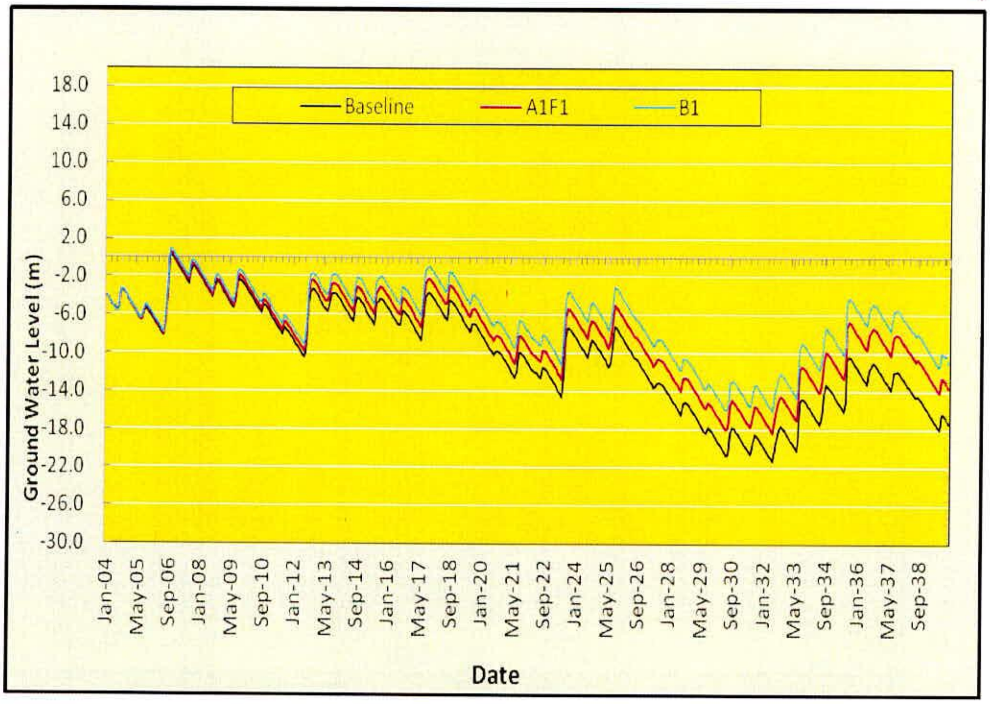


Fig. 50. Groundwater level variation in response to future rainfall in Zone-3

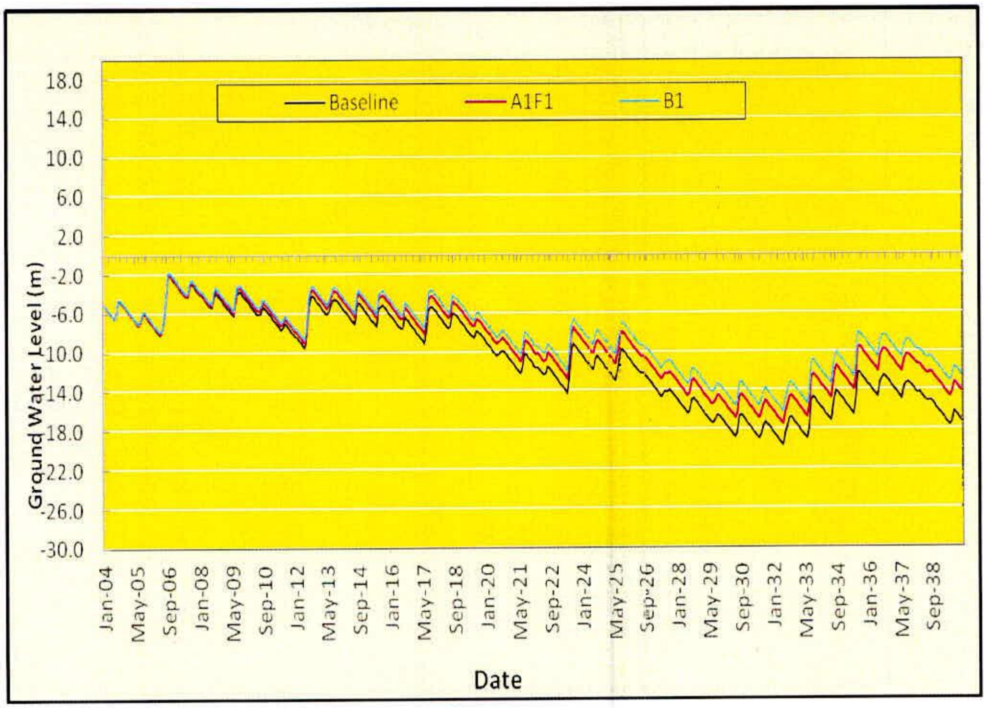


Fig. 51. Groundwater level variation in response to future rainfall in Zone-4

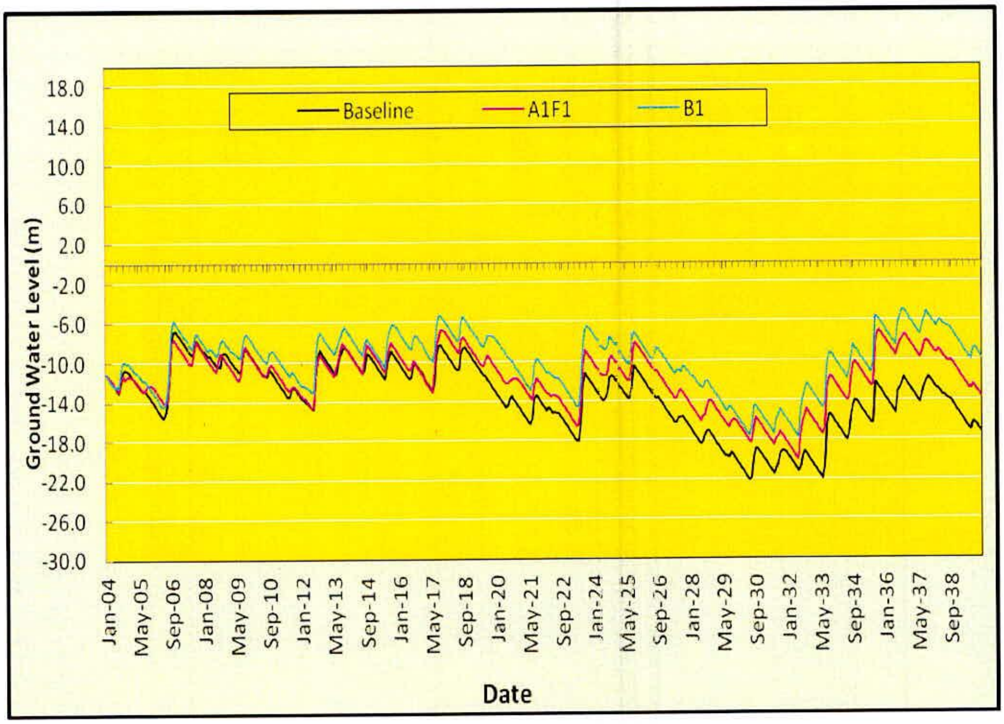


Fig. 52. Groundwater level variation in response to future rainfall in Zone-5

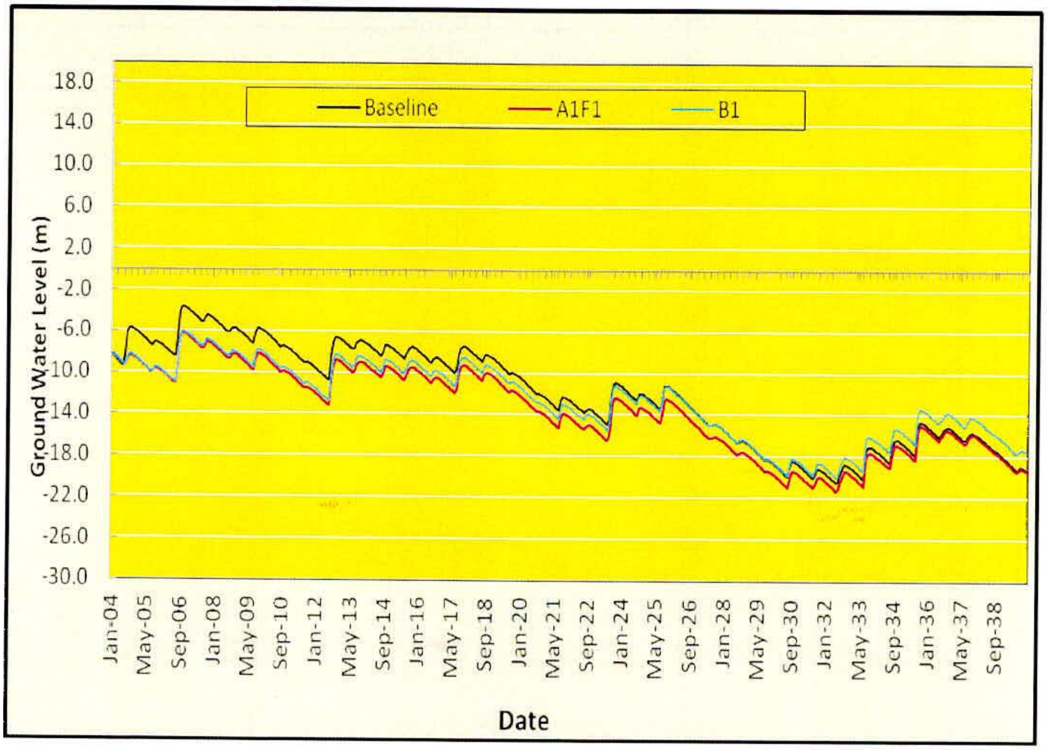


Fig. 53. Groundwater level variation in response to future rainfall in Zone-6

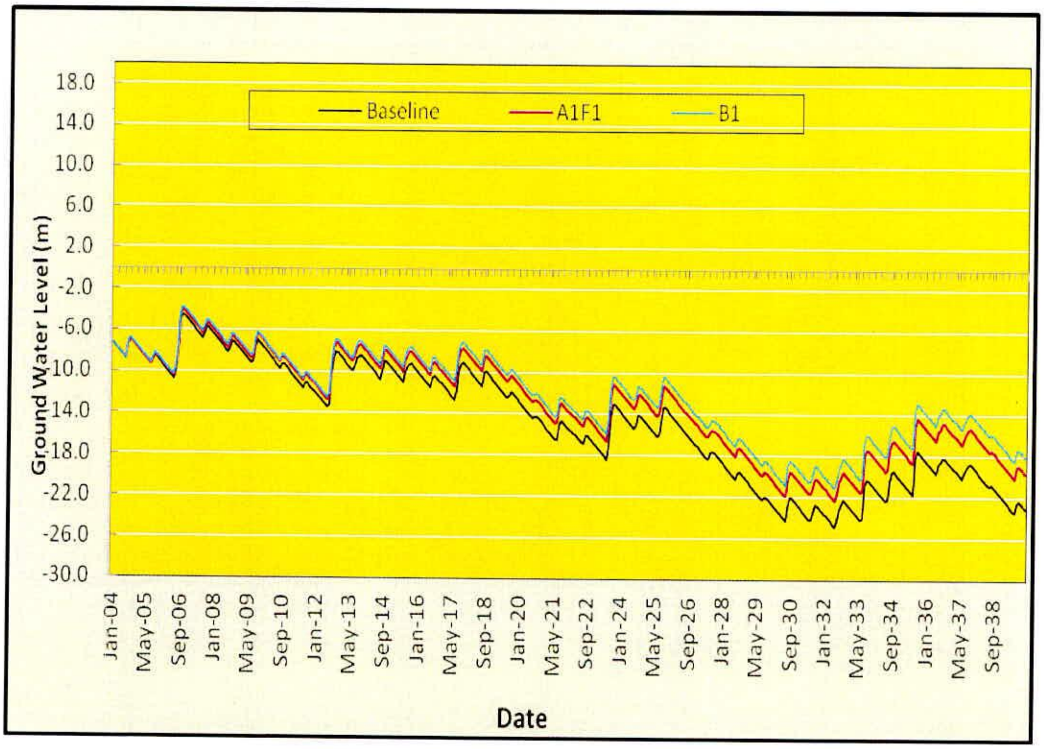


Fig. 54. Groundwater level variation in response to future rainfall in Zone-7

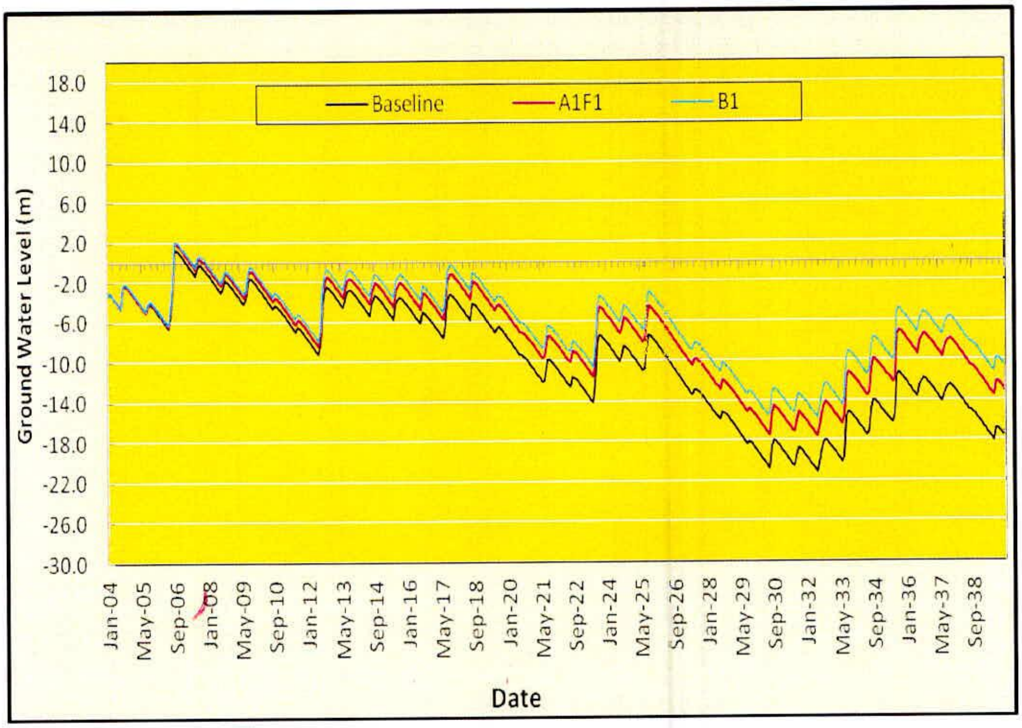


Fig. 55. Groundwater level variation in response to future rainfall in Zone-8

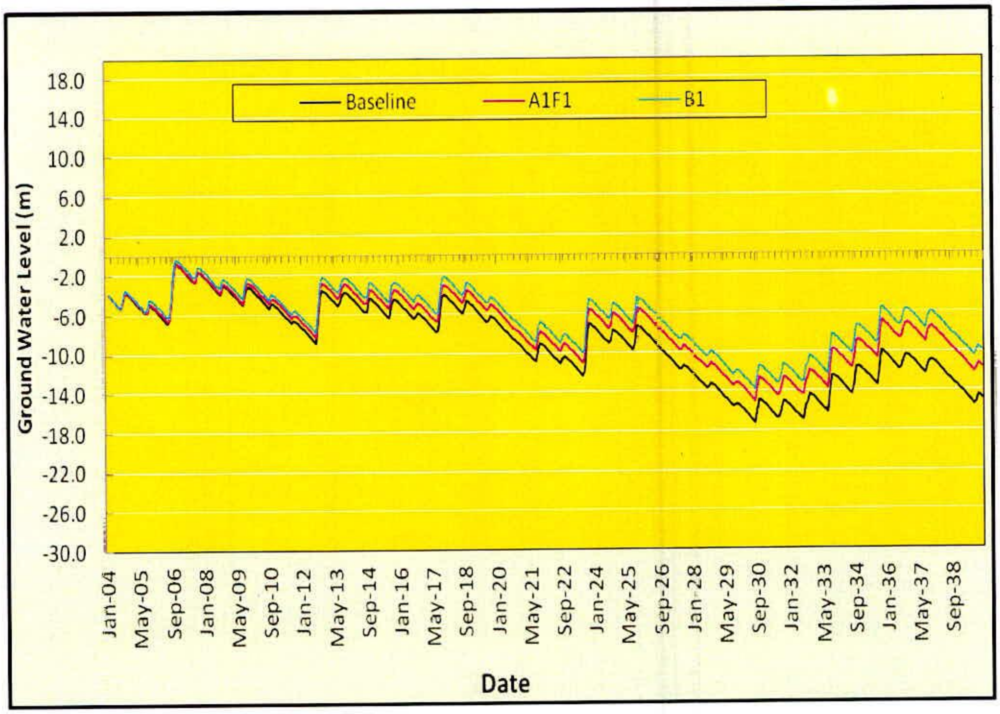


Fig. 56. Groundwater level variation in response to future rainfall in Zone-9

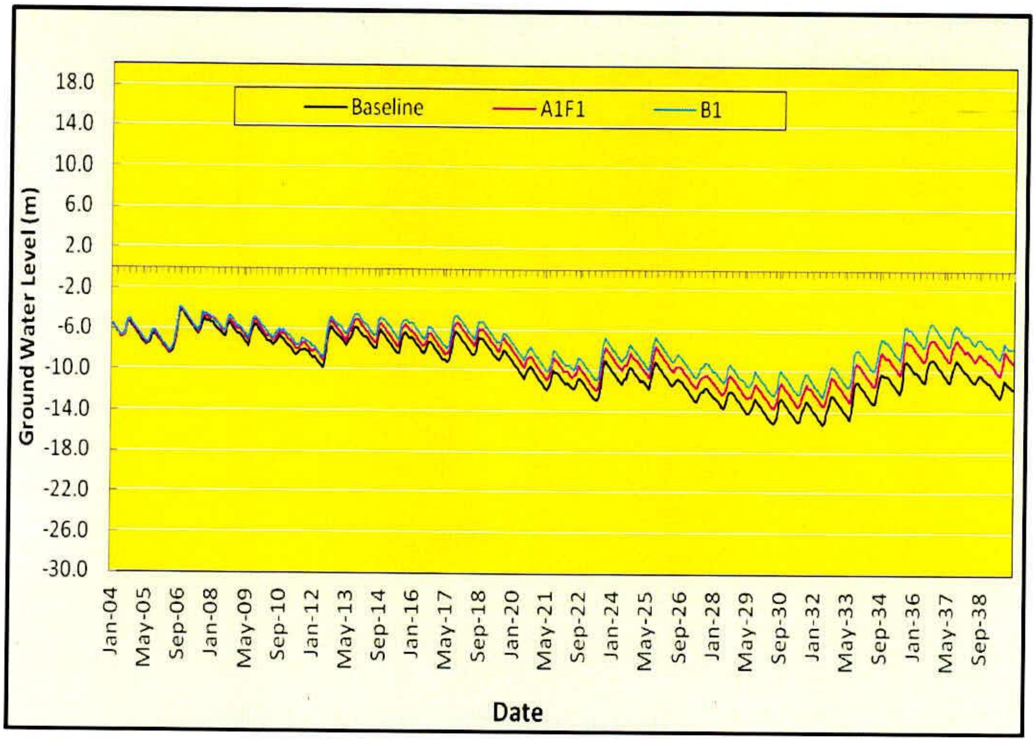


Fig. 57. Groundwater level variation in response to future rainfall in Zone-10

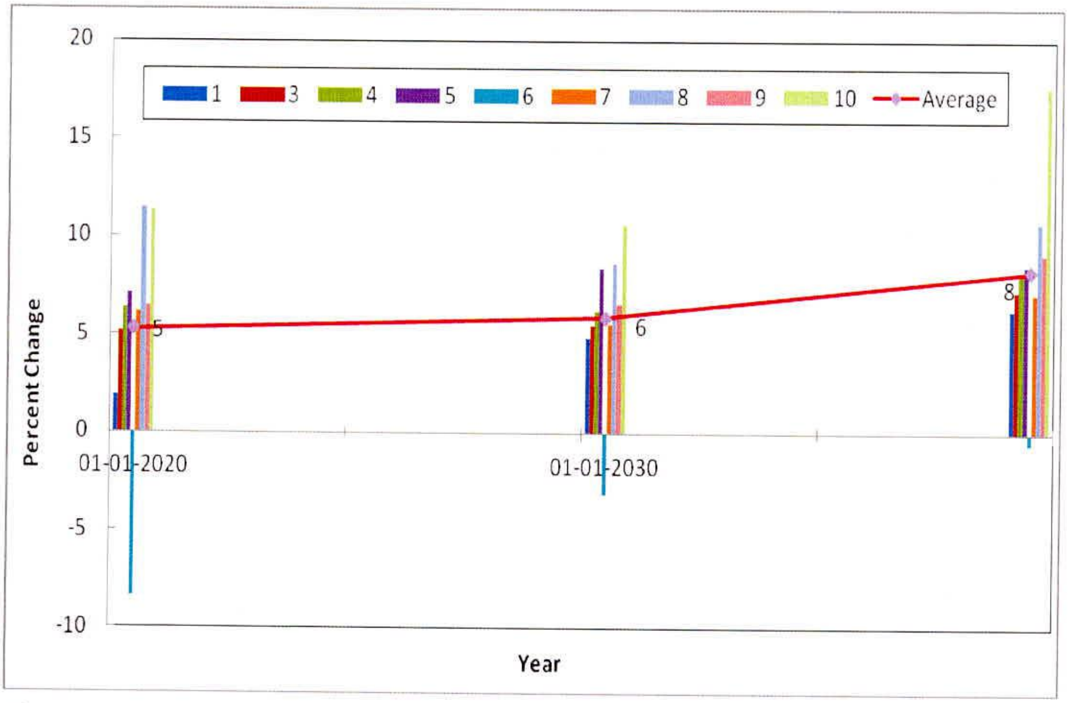


Fig. 58. Percent change in groundwater in different zones under A1F1 Scenario as compared to baseline scenario

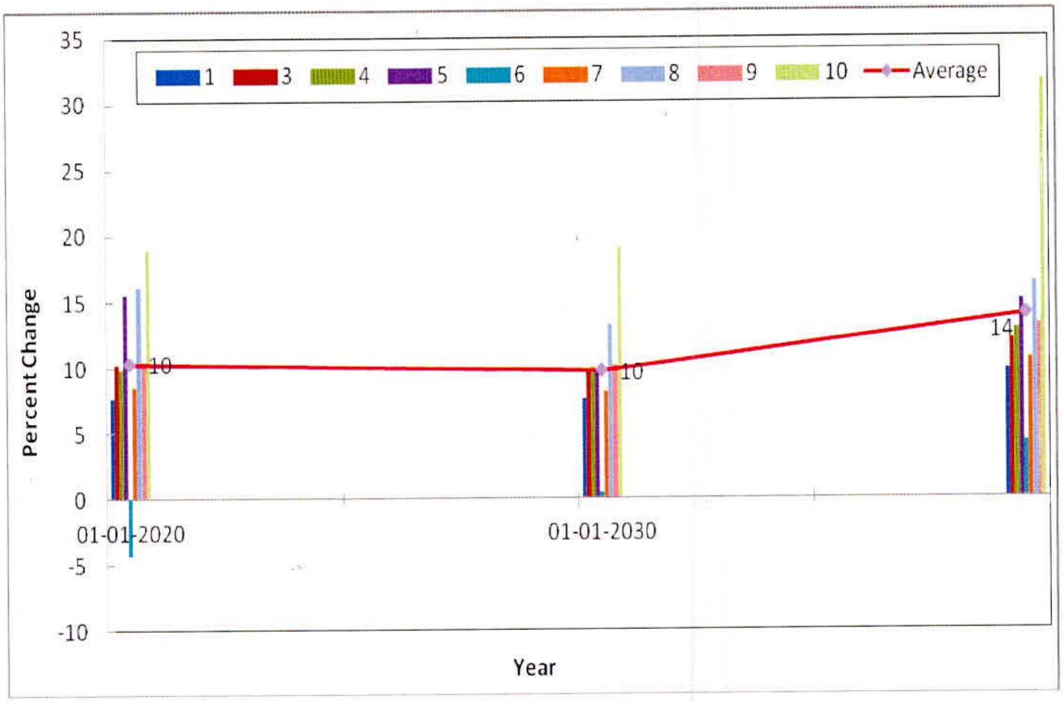


Fig. 59. Percent change in groundwater in different zones under B1 Scenario as compared to baseline scenario

6.0 SUMMARY AND CONCLUSIONS

Although climate change has been widely recognized, research on the impacts of climate change on the groundwater system is relatively limited. The reasons may be that long historical data are required to analyze the characteristics of climate change. These data are not always available. Also, the driving forces that cause such changes are yet unclear. The climatic abnormality may occur frequently and last for a period of time. Even if the required data exist, uncertainty is embedded in model parameters, structure and driving force of the hydrological cycle. Predicting the long-term effect of a dynamic system is very difficult because of limitations inherent in the models, and the unpredictability of the forces that drive the earth. A physically based model of a groundwater system under possible climate change based on available data is very important to prevent the deterioration of regional water-resource problems in the future. Although uncertainties are inevitable, new response strategies in water resource management based on the model may be useful.

The present study aims to quantify the likely impact of climate change on groundwater resources. Historical rainfall and temperature show declining and increasing trend, respectively (1972-2003), as a result future rainfall has a declining trend for the baseline, A1F1 and B1 scenarios. As compared to baseline scenario, following changes have been obtained for the time-slice 2004-2039:

- change in temperature under A1F1 and B1 scenarios is +1.27 and +1.22°C, respectively.
- change in rainfall under A1F1 and B1 scenarios is +3.0 and +4.4%, respectively.
- change in GW recharge under A1F1 and B1 scenarios is +2.1 to +3.8% and +1.8 to +6.1%, respectively.
- change in GW levels under A1F1 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%, which is around 0.6% of the average annual rainfall.

The present study may also be used as decision support for developing the scenarios of ground water levels for various recharge conditions and to quantify the volume of artificial recharge 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. This study was an attempt to quantity the climate change impacts on groundwater however, vast scope exists for refinement with regards to various data and uncertainty associated with the climate change. Further, it shall always be borne in mind that the future estimated impacts of climate change are associated with significant amount of uncertainty because of the multiple driving forces and processes involved.

7.0 ACKNOWLEDGMENTS

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Table 1. Stratigraphy and geology of the basin

Stratigraphic Status	**Lithology**	**Age of Litho Units**
Deccan Trap	Basaltic flows	Upper Cretaceous to Paleocene
Lameta Group	Limestone, Calcareous, Sandstone	Upper Cretaceous
Vindhyan Supergroup	Bhander (Nagod) Limestone	Upper to Middle Proterozoic
	Ganurgarh (Simrawal) Shale	
	Sandstone	
	Sandstone, Shale	
	Sirbu Shale	

Table 2. Grain-size analysis of soil samples collected from twelve locations

		Soil Classification						
S. N.	Site Name	Site Code	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Texture	Soil Description
1	Patha Khurd	PTKHD	16.95	19.13	50.49	13.43	Graveled Silty Loam	Dull Yellowish Brown
2	Ghana	HGANA	26.95	18.81	42.56	12.18	Graveled Silty Clay Loam	Dull Yellowish Brown
3	Dadhonia	DDHON	5.32	9.77	63.99	20.92	Silty Loam	Dull Yellowish Brown
4	Jaitpur Kachcha	JTKCH	1.52	3.17	70.61	24.7	Silty Loam	Grayish Yellow Brown
5	Akala	AKALA	8.96	4.59	70.01	16.44	Graveled Silty Loam	Grayish Yellow Brown
6	Kukwara	KKWARA	23.52	24.13	37.34	15.01	Graveled (Whitestone) Loam	Dull Yellowish Brown
7	Swarkar	SWKAR	1.94	4.1	75.42	18.54	Silty Loam	Grayish Yellow Brown
8	Vijaypura	VIJPR	0.49	4.71	71.88	22.92	Silty Loam	Grayish Yellow Brown
9	Dhana	DHANA	1.99	5.71	64.55	27.75	Silty Loam	Grayish Yellow Brown
10	Inchalpur	INCHL	17.08	29.31	41.33	12.28	Loam	Dull Yellowish Brown
11	Khamaria Khurd	KHMD	22.51	15.94	46.15	15.4	Graveled Loam	Dull Yellowish Brown
12	Kothi Kha	KTHKH	2.4	3.33	74.5	19.77	Silty Loam with Kankar	Grayish Yellow Brown

Table 3. Wilting point, field capacity and hydraulic conductivity of soil samples

S. N.	Site Name	Field Capacity (vol/vol)	Wilting Point (vol/vol)	Saturated Hydraulic Conductivity (cm/sec)
1	Patha Khurd	0.43	0.21	0.003675
2	Ghana	0.40	0.20	0.003675
3	Dadhonia	0.38	0.20	0.00128
4	Jaitpur Kachcha	0.42	0.21	0.005432
5	Akala	0.35	0.18	0.000879
6	Kukwara	0.35	0.16	0.003675
7	Swarkar	0.39	0.20	0.000439
8	Vijaypura	0.37	0.19	0.000599
9	Dhana	0.42	0.23	0.0000362
10	Inchalpur	0.45	0.24	0.002911
11	Khamaria Khurd	0.43	0.24	0.000439
12	Kothi Kha	0.38	0.17	0.000439

Table 4. Projected temperature and precipitation for South Asia in response to climate change (Mirza, 2002)

Season	**2010-2039**				**2040-2069**				**2070-2099**			
	Temp (°C)		**Precipitation (%)**		**Temp (°C)**		**Precipitation (%)**		**Temp (°C)**		**Precipitation (%)**	
GCM SRES Scenarios	A1F1	B1	A1F1	B1	A1F1	B1	A1F1	B1	A1F1	B1	A1F1	B1
Winter (Dec-Jan-Feb)	1.17	1.11	-3	4	3.16	1.97	0	0	5.44	2.93	-16	-6
Summer (Jun-Jul-Aug)	0.54	0.55	5	7	1.71	0.88	13	11	3.14	1.56	26	15

Baseline = The reference for measurable quantities from which an alternative outcome can be measured.
B1 = Most Conservative Scenario (Temp.-Rise=1.1 to 2.9 °C). We still have time to global warming.
A1F1 = Most Pessimistic Scenario (Temp.-Rise=2.4 to 6.4 °C). Sooner we will stop carbon emission.

Table 5. Total average groundwater recharge at different sites for the historical period

S. N.	Site Name	Groundwater Recharge (mm)	% of Rainfall
1	Akala	8,901.94	22
2	Dadhonia	7,811.47	20
3	Dhana	6,752.58	17
4	Ghana	7,391.14	19
5	Inchalpur	12,564.10	32
6	Jaitpur	9,434.24	24
7	Khamaria Khurd	6,328.95	16
8	Kothi Kha	5,640.81	14
9	Kukwara	8,548.58	21
10	Patha Khurd	8,071.01	20
11	Swarkar	7,477.66	19
12	Vijaypura	7,254.26	18

Table 6. Average annual groundwater recharge at different sites for the historical period

S. N.	Site Name	Area (sq.km)	Av. Recharge Rate (mm/year)
1	Akala	14.80	247.28
2	Dadhonia	385.70	216.99
3	Dhana	169.34	187.57
4	Ghana	10.55	205.31
5	Inchalpur	213.23	349.00
6	Jaitpur	69.87	262.06
7	Khamaria Khurd	67.61	175.80
8	Kothi Kha	55.99	156.69
9	Kukwara	324.72	237.46
10	Patha Khurd	15.38	224.19
11	Swarkar	105.15	207.71
12	Vijaypura	95.80	201.51
Weighted Average Recharge Rate			**233.20**

Table 7. Total groundwater recharge (mm) during 2003-2039 at different sites

S. N.	Site Name	Baseline	A1F1	B1
1	Akala	7,581.72	7,790.34	8,019.43
2	Dadhonia	6,640.70	6,826.51	6,956.18
3	Dhana	5,885.18	6,078.01	6,177.64
4	Ghana	6,211.63	6,384.71	6,504.00
5	Inchalpur	13,568.49	13,853.32	14,016.91
6	Jaitpur	8,304.07	8,533.74	8,657.70
7	Khamaria Khurd	8,307.55	8,534.20	8,678.71
8	Kothi Kha	4,400.05	4,567.61	4,668.82
9	Kukwara	7,395.43	7,384.86	7,529.60
10	Patha Khurd	6,962.77	7,138.66	7,232.43
11	Swarkar	6,321.90	6,552.37	6,658.42
12	Vijaypura	6,109.18	6,341.49	6,459.50

Table 8. Average groundwater recharge rates (mm/yr) under different scenarios at various sites

S. N.	Site Name	Baseline	A1F1	B1	Historical
1	Akala	210.60	216.40	222.76	247.28
2	Dadhonia	184.46	189.63	193.23	216.99
3	Dhana	163.48	168.83	171.60	187.57
4	Ghana	172.55	177.35	180.67	205.31
5	Inchalpur	376.90	384.81	389.36	349.00
6	Jaitpur	230.67	237.05	240.49	262.06
7	Khamaria Khurd	230.77	237.06	241.08	175.80
8	Kothi Kha	122.22	126.88	129.69	156.69
9	Kukwara	205.43	205.13	209.16	237.46
10	Patha Khurd	193.41	198.30	200.90	224.19
11	Swarkar	175.61	182.01	184.96	207.71
12	Vijaypura	169.70	176.15	179.43	201.51

Table 9. Percent change in groundwater recharge under different scenarios

S. N.	**Site Name**	**% Change A1F1 vs. Baseline**	**% Change B1 vs. Baseline**	**% Change B1 vs. A1F1**
1	Akala	2.8	5.8	2.9
2	Dadhonia	2.8	4.8	1.9
3	Dhana	3.3	5.0	1.6
4	Ghana	2.8	4.7	1.9
5	Inchalpur	2.1	3.3	1.2
6	Jaitpur	2.8	4.3	1.5
7	Khamaria Khurd	2.7	4.5	1.7
8	Kothi Kha	3.8	6.1	2.2
9	Kukwara	-0.1	1.8	2.0
10	Patha Khurd	2.5	3.9	1.3
11	Swarkar	3.6	5.3	1.6
12	Vijaypura	3.8	5.7	1.9