Trend Analysis of Groundwater Levels in Northern Haryana, India

By

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<u>CERTIFICATE–I</u>

This is to certify that this thesis entitled **"Trend Analysis of Groundwater Levels in Northern Haryana, India"** submitted for the degree of **Master of Technology** in the subject of **Agricultural Engineering (Soil and Water Engineering)** to the Chaudhary Charan Singh Haryana Agricultural University, Hisar, is a bonafide research work carried out by **Ms. Abha Gupta** under my supervision and that no part of this thesis has been submitted for any other degree.

The assistance and help received during the course of investigation have been fully acknowledged.

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CERTIFICATE–II

This is to certify that this thesis entitled **"Trend Analysis of Groundwater Levels in Northern Haryana, India"** submitted by **Ms. Abha Gupta** to the Chaudhary Charan Singh Haryana Agricultural University, Hisar in partial fulfillment of the requirements for the degree of **Master of Technology** in the subject of Agricultural Engineering (Soil and Water Engineering), has been approved by the Student's Advisory Committee after an oral examination of the same.

MAJOR ADVISOR **EXTERNAL EXAMINER**

HEAD OF THE DEPARTMENT

DEAN, POST-GRADUATE STUDIES

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LIST OF ABBREVIATIONS AND SYMBOLS USED

et al.,	et alia (and others)
km^3	Cubic kilometer
%	Percentage
mm	millimetre
cm	Centimetre
m	Metre
bgl	Below ground level
°C	Degree Celsius
ha	Hectare
EC	Electrical conductivity
µS	Micro Siemens
GIS	Geographic Information System
IDW	Inverse Distance Weighting
yr	Year
kg	Kilogram
BCM	Billion cubic meter
°	Degree (for angle)
'	Minute (for angle)
"	Second (for angle)
CCS HAU	Chaudhary Charan Singh Haryana Agricultural University
CGWB	Central Groundwater Board
i.e.	Id est (that is)
t	tonnes

CHAPTER I

INTRODUCTION

1.1 General Background

Groundwater is the Earth's most important, critical and prevalent natural resource which plays an important role in all aspects of human life. It is interstitial water, occurs in the zone of saturation, where all the voids within a geologic stratum are filled with water. It provides agricultural social security due to assured irrigation and tremendous growth in groundwater use is a universal problem since 1950 (Shah, 2005). Nearly 2 billion people throughout the world rely on groundwater (Majumdar, 2021). South Asian and African countries consume roughly 2010 km^3 of groundwater every year (Mukherji and Shah, 2005). In metropolitan regions, population pressure on groundwater is much higher than in the rural areas. Groundwater levels have dropped dramatically in many developed countries and urban areas as a result of extensive exploitation and improper use. In India, during 1947, per capita water availability was 6008 m^3, but it has been dropped to 1545 and 1486 m^3 in year 2011 and 2021, respectively, which expected to drop further up to 1367 and 760 m^3 by year 2031 and 2050, respectively, which is widely recognized as one of the major challenges to social development (Patel and Rajput, 2009).

Groundwater irrigation in India, began to take off in a big way around 1960. The Green Revolution was a turning point in India's agricultural development, benefiting those who were able to embrace new seeds and fertilizers, which necessitated water security. With an estimated annual usage of roughly 230 km^3, India is the world's greatest groundwater consumer, accounting for more than a quarter of the global total (Pahuja *et al.,* 2010). The groundwater water system, has expanded immensely in the previous three to four decades, and has occupied a dominant position in India's horticulture and food security. In India, groundwater fulfills more than 80% of provincial needs and 50% of urban and mechanical requirements (Anonymous, 2021a). Groundwater is a primary source of domestic and drinking water in most of India's rural areas. According to the Central Groundwater Board (CGWB), groundwater levels in roughly 56% tube wells of India have been steadily falling since 2003 owing to excessive groundwater pumping. It is estimated that the Indian irrigation industry will consume about 74% of total groundwater by 2025 and 72% by 2050 (Vyas, 2001). In India, groundwater extraction is at 61.6% level, whereas, more than 100% in many parts, *i.e.,* Delhi (170.0%), Punjab (145.0%), Haryana (134.6%), Rajasthan (125.0%), and the union territories of Daman and Diu (107.0%) and Pondicherry (105.0%), indicating that annual groundwater extraction exceeds annual extractable groundwater recharge in these states (Anonymous, 2021a).

In Haryana state, groundwater level is declining in north-eastern and southern districts, indicating overexploitation of groundwater resources. Anonymous (2021b) reported a decline in groundwater depth in fresh water belts, whereas, it is rising in salty groundwater zones of the state. The groundwater, on the other hand, is creating water logging problem in the state's central and western region. Nearly 60% of the state's blocks are over-exploited in terms of groundwater extraction, with the state's overall stage of groundwater extraction at 134.56% (Anonymous, 2021a). The highest groundwater extraction stage of 246% has been observed in Kurukshetra district where the water table is declining at a rate of 1.11 m per year due to the intensive rice and wheat cultivation by groundwater irrigation (Gautam and Singh, 2019). Groundwater irrigation is becoming increasingly important in Haryana's agricultural industry. The percentage of cultivated land area that is irrigated in Haryana is about 80% (Anonymous, 2021b). Rice, wheat, cotton and sugarcane are almost entirely irrigated in Haryana, whereas, barley is approximately 80% irrigated and mustard and sorghum are 60% irrigated.

1.2 Most Relevant Review of Literature

Groundwater extraction is continuously increasing to alleviate water stress, resulting in serious threat of the increasing groundwater depth (Yang *et al.*, 2011; Panda *et al.*, 2012). World's one-third of the water demand is fulfilled through groundwater (Moreaux and Reynaud 2006; Hetzel *et al.*, 2008; Mevlut and Tayfun 2010). More than 4430 km^3 of groundwater is extracted globally per year, out of which more than 70% is used in agriculture (Kinzelbach *et al*., 2003). In India, the over-exploitation of groundwater resources has caused groundwater levels to decline at a rate more than 2 m per year in some parts of north Gujarat, south Rajasthan, Madurai district of Tamil Nadu, Kolar district of Karnataka, Delhi, Andhra Pradesh, Punjab, Haryana and western Uttar Pradesh (Aggarwal *et al.,* 2009; Chawla *et al.*, 2010; Singh and Sharma 2010). The groundwater depth in India has increased from 5 to 15 m over the last 20 years, requiring lowering of submersible pumps at deeper depths which further imposes additional economic burden and threat to the sustainability of groundwater resources (Goyal *et al.,* 2010). To meet the demands of increasing population and its increasing living standards, India will have to increase its production of agricultural commodities by 30% till 2050 (Chand, 2012) which will put additional stress on groundwater resources to ensure water security to irrigation.

Groundwater level in Punjab, has been increasing continuously, which could be accounted to excessive use of groundwater in irrigation of paddy (Krishan *et al.*, 2015).

Groundwater has significantly contributed to the development of irrigated agriculture in Haryana (Ravish *et al.*, 2018), due to which the groundwater levels are declining in the state. The groundwater levels in Haryana ranged from 0.16 to 65.97 m below ground surface and estimated the percentage of land with a groundwater level depth greater than 10 m (critical category) around 56 and 64% in year 2004 and 2012, respectively (Singh and Kasana, 2017). Groundwater depth has considerably increased in the Karnal district of Haryana, due to increased groundwater pumping (Patle *et al.*, 2015), while the maximum decline of 108.9 cm per year, for the period 1990-2013 was found in Kurukshetra district due to intensive rice and wheat cultivation by groundwater irrigation (Singh *et al.*, 2015). There has been a phenomenal rise in the number of tube-wells in the Kurukshetra district and the groundwater status is in the category of 'over-exploited' (Singh *et al.*, 2019). Groundwater depletion has been caused by both anthropogenic and climatic factors.

1.3 Significance of the Study

Surface water resources are not only becoming deficient, but also not available to many parts of Haryana. Whereas, demand for irrigation water is increasing due to agricultural high yielding variety and intensification. Resultantly, there has been considerable increase in the utilization of natural groundwater resources to sustain agricultural productivity, thereby putting massive pressure on the groundwater resources. For assessing the groundwater depth in a region, the data are collected from certain number of observation wells and they do not provide detailed information on extent of area affected. Thus, it necessitates the use of spatial interpolation methods like Geo-statistics for generating the spatial variability maps of groundwater level and area estimation under different groundwater level, which also offers efficient tools for evaluating the adequacy of the existing observation well network, finding out the optimal location for possible reduction in observation wells without affecting the present level of accuracy (Kumar *et al.*, 2005). Therefore, this study was planned to analyse the groundwater trends and its dependency on various factors and find out the possible remedial measures, which could be helpful for ensuring food security of the state.

1.4 Objectives

In light of these facts, the following objectives will be pursued in the current study "Trend Analysis of Groundwater Levels in Northern Haryana, India":

1. Spatial and temporal mapping of groundwater levels and its trend analysis.
2. To enumerate the magnitudes of changes by using parametric and nonparametric tests.

CHAPTER II

REVIEW OF LITERATURE AND PATENT SEARCH

Groundwater extraction in the Northern part of Haryana is mainly for irrigation purposes and it is the fastest growing source of irrigation, which has led to over-exploitation of the natural resource. Taking this background into account, it is important to plan its use in a judicious and sustainable manner. Furthermore, to provide background information for formulating the objectives, the existing literature has been reviewed and arranged in this chapter under the following themes:

2.1 Groundwater Levels Variability and Trends

2.2 Influence of Natural and Anthropogenic Factors on Groundwater Levels

2.3 Use of GIS in Spatio-Temporal Analysis of Groundwater Level Trends

2.4 Statistical Analysis of Groundwater Levels

2.1 Groundwater Levels Variability and Trends

The groundwater resource problem in Haryana was assessed by Bhalla, (2007) and the results revealed that both waterlogging and declining trends of groundwater levels were observed simultaneously in the state. The declining water level was observed due to the increasing number of tubewells, but in Mahendergarh district, it was due to its rocky type topography. Naik *et al.,* (2008) conducted a study to determine the groundwater levels of Solapur (Maharashtra) and observed significant rising trends in the main city due to increased recharge and decreased extraction, whereas falling trend outside the city due to increase in extraction for agriculture purposes. Kaur and Vatta (2015) revealed severe groundwater decline in Punjab due to intensive rice cultivation and its irrigation majority by groundwater resources and very little by canals. Patle *et al.,* (2015) conducted a study to determine groundwater trends in the Karnal district of Haryana, India, both during the pre-monsoon and post-monsoon seasons, and found a considerable decrease in water level, which was attributed to increased groundwater pumping. However, there was no evidence of decline in water level as a result of climate change. Rzepecka *et al.,* (2017) analyzed groundwater level variations in the Sudety Mountains for the period of 2002-2015 and observed a decline in the groundwater level of approximately 13 cm in 13 years. Trend in groundwater level and regional groundwater drought characteristics in the drought-prone Ghataprabha river basin, India was estimated by Pathak and Dodamani, (2018) and observed significant decreasing in more than 61% of the wells with average decline of 0.21 m in 30 years. The Standardized Groundwater Level Index (SGLI) investigation revealed that wells in clusters 1 and 2 were subjected to recurring droughts, which was attributed to decreased rainfall and over-exploitation of groundwater resources.

2.2 Influence of Natural and Anthropogenic Factors on Groundwater Levels

2.2.1 Influence of cropping patterns on groundwater levels: Spatial and temporal analysis of groundwater levels for Dhaka city, Bangladesh for 20 years of groundwater level data was done by Akther *et al.*, (2009) and continuously depleting of water table was recorded. Despite the aquifer having ample sources of recharge, it is depleting due to three factors, *i.e.*, (a) aquifer was confined by silt clay formations and has now been dewatered, (b) the amount of recharge has decreased as the hydraulic resistance has increased due to reduced hydraulic conductivity in the uppermost strata where pores get filled with air and obstruct water flow, (c) slow recharge due to a complicated water table caused by excessive pumping throughout the area, resulting in the creation of a cone of depression. Krishan *et al.*, (2015) performed spatial analysis of groundwater levels in Punjab, for the period 2006 to 2013 and observed a declining and fluctuating groundwater level especially in the months of June and July in all districts, which was accounted to excessive use of groundwater in irrigation of paddy crop. Mukherjee *et al.*, (2015) studied the groundwater systems of the Indian subcontinent and discovered that the groundwater levels have dropped by more than 4 m between 1950 and 2000 due to intensive agricultural activities. The study revealed that between 1950 and 2000, the crop production increased from 50 to 204 m tonnes, putting a strain on groundwater resources. They recommended aquifer-based-common pool resource method for groundwater management and emphasized the importance of a strong groundwater governance structure. Singh and Kasana, (2017) found that groundwater levels in Haryana ranged from 0.16 to 65.97 m below ground surface and estimated the percentage of land with a groundwater level depth greater than 10 m (critical category) around 56 and 64% in year 2004 and 2012, respectively. The average yearly decline in groundwater level was discovered to be greater than 32 cm per year, with Kurukshetra district experiencing the highest decline (108.9 cm per year).

2.2.2 Influence of number of tubewells and rainfall on groundwater levels: Groundwater level trend in the Kurukshetra district of Haryana state was investigated by Singh *et al.*, (2015) and reported 0.81 m per year declining rate of water table for the period 1990-2013, which could be attributed to the intensive rice and wheat cultivation by groundwater irrigation. They also reported phenomenal rise in the number of tubewells in the district and the groundwater status to be in the category of 'over-exploited'. They found groundwater level show poor response to incident rainfall. Ndlovu and Demlie (2018) analyzed the trend in groundwater changes and its relationship with rainfall across Kwazulu-Natal Province, South

Africa and discovered that the decline in groundwater level is directly linked to a decrease in rainfall, resulting in a reduction in groundwater recharge reaching the aquifer. Gibrilla *et al.,* (2018) studied the trend of rainfall, temperature and groundwater levels in Upper East Region of Ghana. In all of the monitoring wells, no significant positive or negative trends in groundwater levels were recorded on a yearly basis. Groundwater levels in most wells were increasing at rates ranging from 0.0 to 0.6 cm per year, according to ARIMA model. Lasagna *et al.,* (2020) investigated the impact of natural and anthropogenic factors on Italy's groundwater supplies and concluded that rainfall and irrigation patterns have the greatest impact on the groundwater level.

2.2.3 Influence of climate change on groundwater levels: According to a study conducted by Taylor and Alley, (2001) it is revealed that groundwater systems are dynamic and adjust continually to short-term and long-term changes in climate, ground-water withdrawal and land use. They emphasized on the importance of long-term and systematic water level measurements, which provide critical data for evaluating resource changes over time, developing groundwater models and forecasting trends as well as designing, implementing and monitoring the effectiveness of groundwater management and protection programs. Chen *et al.,* (2004) studied the impacts of temperature and rainfall on groundwater levels in the Winipeg area, Canada and revealed that groundwater level is significantly correlated with climatic factors. Tabari *et al.,* (2012) revealed that groundwater level decline with increase in air temperature and decrease in relative humidity in Iran. Sivarajan *et al.,* (2019) examined climate change impact on the variability of groundwater level in the Ahmednagar district of Maharashtra from 1996 to 2016 and found the groundwater level of major part of the area between 6 to 15 m below ground level (bgl) and the level has fallen drastically over the period. The average groundwater depth increased from 6.53 m bgl to 8 m bgl in the twenty years (from 1996 to 2016). They also reported 0.61 cm per year decrease in groundwater recharge which could be accounted to decrease in precipitation and decadal rise in temperature of about 0.1°C. Increasing trend of 9.6 mm per year was observed for evapotranspiration. The increase in temperature leads to increase in evapotranspiration which leads to declining groundwater levels. They reported groundwater decline show coherent variability with evapotranspiration and temperature.

2.3 Use of GIS in Spatio-Temporal Analysis of Groundwater Level Trends

Toleti *et al.*, (2001) prepared the Integrated Groundwater Resource (IGWR) map indicating groundwater prospects, quality and depth for Gurgaon district (Haryana) India by using Remote Sensing and GIS Techniques. They discovered that remote sensing and GIS technology to be very effective in the scientific formulation of groundwater prospective area mapping and management plans area. They suggested certain water harvesting practices and planning for groundwater resource.

Goyal and Chaudhary, (2010) performed a study using GIS, to analyse spatio-temporal changes in groundwater depth and quality for the Kaithal district of Haryana and observed that the groundwater levels declined from 9 to 16 m bgl in the period of 1992-2007, which could be possibly accounted to excess paddy cultivation. High EC and a shallow water table in Rajaund and Kalayat blocks can be accounted to inadequate groundwater exploitation, poor drainage, leaching, and geo-hydrological setting of the area. They recommended to regulate groundwater withdrawal and artificially recharge aquifers, as well as raising awareness and implementing proper groundwater management strategies.

Bui *et al.,* (2012) performed spatio-temporal analysis of groundwater level trend in Vietnam using GIS and reported declining trends of groundwater levels in major part, which reflected unsustainable use of groundwater. They also highlighted the importance and need of a groundwater monitoring network whose data should be systematically organized and easily available for research purposes.

Karatas *et al.*, (2013) performed a spatio-temporal study by using GIS to analyse the depth and salinity of the groundwater of Western Turkey for the period 1995-2006 and discovered that while there was no current concern with the depth and salinity of the groundwater in the research region in general, there may be future danger of this problem.

Yao *et al.,* (2014) conducted a study in north-west China using geospatial techniques of GIS and revealed declining groundwater levels.

Nayak *et al.,* (2015) mapped the groundwater fluctuations in Bina basin of Madhya Pradesh by using Kriging technique for interpolation of groundwater level for pre- and post-monsoon levels and generated groundwater fluctuation maps. They revealed declining groundwater table in central to northwest parts of the watershed and suggested the construction of percolation tanks and farm ponds in the lowermost corner of agricultural areas to promote groundwater recharge.

Reeta and Chaudhary, (2016) performed spatio-temporal mapping of groundwater depth in Hisar district of Haryana. They made detection maps using Inverse Distance

Weightage (IDW) technique of interpolation of ArcGIS software and found an increasing trend of groundwater level from 12.9 m bgl to 8.1 m bgl for the period 1990-2014 and revealed the reason to be e poor quality of groundwater, thus, preventing farmers from its use.

Amiri *et al.,* (2017) studied the spatial and temporal variations in groundwater salinity in Mazandaran Plain, Iran for a period of 1987 to 2013 by using ArcGIS. They concluded that long-term irrigation with this groundwater can reduce rice yields, putting rice production at danger. The Mann-Kendall and Sen test revealed a declining trend of groundwater depth in the area of Mazandaran plain with EC more than 1 dS m^{-1}, indicating an improvement in the quality of groundwater in the plain.

Manda and Patil, (2018) performed analysis of groundwater level differences in the Ganga basin by using geo-statistical modelling which comprise of three parts namely modelling, estimation and simulation. They used kriging method as an interpolation technique. They observed declining trend in water level from north to south and from east to west. They suggested the use of micro irrigation and laid emphasis on regulation of using groundwater by the industries in the area.

Rasel *et al.,* (2019) performed geospatial analysis of groundwater level variations by using Kriging method of GIS software, in a district of north western part of Bangladesh for the period 2009-2018 and reported a falling trend of groundwater in all the regions of the district, which is attributed to lack of rainfall in the region, drought conditions and thus excessive exploitation of groundwater.

Kumar *et al.,* (2019) performed a study to analyse the geospatial and temporal changes in groundwater level for the period 1984-2013, in the Dindigul district of Tamil Nadu. The changes were analyzed using the IDW technique of GIS software. The study reported significant groundwater level decline for the periods 1984-1993 and 2004-2013 in most blocks of the district, which could be because of increasing number of industries in the area and increasing domestic water usage. They reported major decline in the Western Ghats due to hilly area, where water drains out and infiltration is very low. The study suggested the change of cropping pattern, usage of water harvesting systems and modern irrigation techniques for effective water management and improves the water balance.

Anand *et al.,* (2020) performed a study to analyse, long-term trend detection and spatiotemporal variation of groundwater levels by using Geographical Information System (GIS) and performing statistical tests for the lower Bhavani river basin, Tamil Nadu, India. They found that the average annual groundwater level has lowered beyond 15 m bgl which highlights less rainfall infiltration and overexploitation of groundwater. They recommended for the implementation of large scale rainwater harvesting system in the lower Bhavani river basin to augment groundwater resources.

Mulani *et al.*, (2020) performed a study to analyse the changes in groundwater level for the period 1990-2006, in Sangola tehsil, Solapur, Maharashtra by using GIS software. IDW technique was used for interpolation of groundwater level data and it was examined for spatial and temporal changes. The study revealed that the over utilization and excessive pumping of water from shallow aquifer lead to decline of groundwater level.

Majumdar, (2021) performed groundwater modelling by using GIS in Kolkata and reported water table falling from 7 to 11 m in the period 1958-2003 which could be due to unscientific and excessive exploitation of groundwater. The groundwater profile showed bowl like feature in the city, which could result in land subsidence. The study suggested the use of artificial groundwater recharge, proper monitoring of tube-wells and preventing groundwater pollution.

Arkoc, (2022) studied spatio temporal variations of groundwater levels using GIS in Ergene Basin, Turkey and revealed the groundwater levels are low due to the excessive pumping of the wells drilled in the industrial zone located in the north east part of the study area.

2.4 Statistical Analysis of Groundwater Levels

Thakur and Thomas, (2011) analyzed groundwater level trend for Sagar district in Madhya Pradesh. They used non parametric Kendal rank correlation test and parametric linear regression test for trend detection and observed significant declining trend at Sagar, Khurai and Bina despite no falling trend was found in the rainfall. The decline of groundwater trend could be accounted to over-exploitation and excessive irrigation by groundwater. They suggested artificial recharge and consumptive use to relieve the groundwater from the additional stress conditions.

Bui *et al.,* (2012) applied Mann-Kendall test and Sen’s slope estimator to analyse groundwater level trend in Vietnam and reported declining trends of groundwater levels in major part. They reported land subsidence and groundwater pollution due to recharge from wastewater sources as obvious impacts.

Karatas *et al.*, (2013) applied Mann-Kendall test and Sen’s slope estimator to perform trend analysis of depth and salinity of the groundwater of Western Turkey for the period 1995-2006 and discovered that while there was no current concern with the depth and salinity of the groundwater in the research region in general, there may be future danger of this problem.

Singh *et al.,* (2019) conducted a study in Haryana, India, to compute the magnitudes of groundwater level trends and find abrupt change points and found a large fall in groundwater level, which confirms the state's unsustainable groundwater development. For trend analysis and determining rate of change in groundwater level Mann–Kendall test, Sen’s slope estimator and simple linear regression were used, whereas, the abrupt change point detection analysis was carried out by using Pettitt’s test, standard normal homogeneity test, Buishand’s range test and Von-Neumann ratio test. The analysis of groundwater levels for abrupt change points indicates that distinct change points exist, with maximum change points occurring between the years 2000 and 2006 during the pre and post-monsoon seasons. This can be attributed to farmers transplanting rice crops far ahead of the rainy season's start. Groundwater depletion has been caused by both anthropogenic and climatic reasons.

Yilmaz *et al.,* (2020) performed spatio-temporal analysis of groundwater level trend in Sharjah, UAE. They used non-parametric test (Mann-Kendall test) to find the temporal trend in groundwater levels and found declining water level trend in almost all fields. They also revealed 90% decrease in groundwater extraction in last 15 years and also found salinization of groundwater due to sea water intrusion because of significant decline in water levels of wells close to the coastline, be a major problem. They suggested remedial measures such as artificial recharge of groundwater, harvesting rainfall water in small dams and natural recharge of the aquifers.

Zakwan (2021) used Mann-Kendall, Spearman-Rho, Sen’s slope estimator and innovative trend analysis to analyse the water level of five wells in Churu, Rajasthan, India. Water levels were found to be falling significantly in four wells, with only one showing a positive trend. All of the trend tests results were in good accordance with one another. Unlike other trend tests, which indicated monotone trends, innovative trend analysis revealed different trends for low, medium and high water levels, offering a full understanding of the region's continuous hydrologic changes.

Gautam *et al.,* (2022) analyzed groundwater trend in Jhakam river basin of Southern Rajasthan. They used Kendall rank correlation and linear regression to analyse periodic trends by using XLSTAT, and IDW interpolation technique in Arc GIS 10.4 software for interpolating the point data and generate spatial maps. They found no strong relation between rainfall and groundwater. The average rate of water table decline was found to be 0.245 m per year in pre-monsoon and 0.050 m per year in post monsoon.

The literature reviewed in this chapter highlights the use and scope of GIS in spatial and temporal trend analysis the groundwater resource. However, there has been no such study conducted for the northern Haryana region. The present study was conducted taking into account the anthropogenic and climatic parameters. This study also included the statistical analysis using parametric and non-parametric tests.

Patent Search

No patent issue is related to the present study “Trend Analysis of Groundwater Levels in Northern Haryana, India”.

CHAPTER III

MATERIALS AND METHODS

For the present research problem "Trend Analysis of Groundwater Levels in Northern Haryana, India", the materials and methods, described in the following sections were used to study the proposed objectives. The previously published research papers on similar topics by several researchers provided a good understanding and knowledge of the research problem and also facilitated in selection of most appropriate methodologies.

3.1 Study Area

Haryana is an Indian state lying in the north-western part of the country. It covers area of 44,212 km^2 and accounts for 1.35% of the country's total land area. The Indo-Gangetic plain covers around 97% of the state's land area. The state is located in the Ganga and Indus basins. The average annual rainfall ranges from over 1000 mm in the north to less than 300 mm in the south. There are quite thick and geographically extensive confined/unconfined aquifers down to a depth of more than 300 m in the north eastern and eastern regions of the state, with yield potential of about 150 m^3 per hr. The state's net annual groundwater availability has been estimated at 9.80 BCM (billion cubic meters). The present study was conducted for Northern Haryana, which comprises of Panchkula, Ambala, Yamuna Nagar and Kurukshetra districts (Anonymous 2021a).

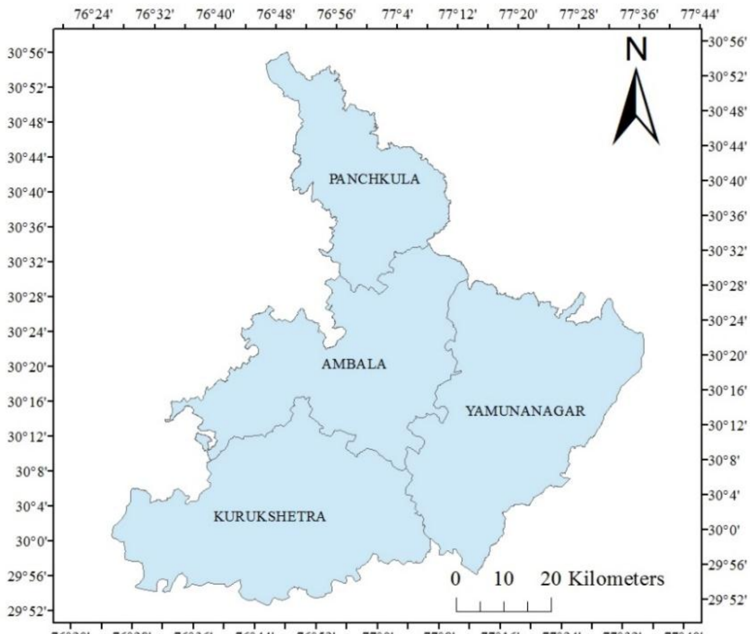


Fig. 3.1: Location of northern Haryana (study area), India

3.1.1 Ambala district

The Ambala district of Haryana is located between the latitudes of 30° 10' to 31° 35' N and the longitudes of 76° 30' to 77° 10' E. The district covers a total size of 1595.85 km^2. The district's average annual rainfall is 1076 mm, which is distributed unevenly over the region. The average number of rainy days is 44. Indo-Gangetic alluvium and flat topography dominate the district's landscape. Dissected undulating plains of the Siwalik range occupy a small region in the district's extreme north-eastern corner. The district has extensive alluvial deposits. Fine-grained sediments comprise sand, clay, silt and kankar with the occasional gravel in the district's south west and western areas. Brown to golden clays with a sticky to silt texture is common. The district's east and south eastern regions, on the other hand, are underlain by medium to coarse-grained clay beds and sand layers (Anonymous 2016a).

3.1.2 Kurukshetra district

Kurukshetra district is located in Haryana's north-east corner, between the latitudes 29° 53' to 30° 15' N and longitude 76° 26'27" to 77° 07'57" E. The district covers 1682.53 km^2. The district's eastern half is in the upper Yamuna basin, while the western half is in the Ghaggar basin. Irrigation is done with both surface and groundwater. The district's average annual rainfall is 582 mm, which is unevenly spread across the land. Rainfall in the district increases from southwest to northeast in general. The area resembles a very flat alluvial plain with few prominent topographical features. The plain's average elevation ranges from 274 to 241 m above sea level. The land has a general north-east to south-west slope to it. The main river in the district, the Markanda, rises in the Nahan hills and runs in a south-western direction. Tropical arid brown soils cover the entire district. These soils are typically deep and poorly drained. These soils have low to moderate permeability and are mildly alkaline to strongly alkaline. The main *kharif* crop is paddy, while the main *rabi* crop is wheat (Anonymous 2016b).

3.1.3 Panchkula district

Panchkula district is in the northern region of the state, with latitudes ranging from 30° 26' to 30° 55' N and longitudes ranging from 76° 46' to 77° 10' E. The district covers an area of 898 km^2. The river Ghaggar and its tributaries drain the majority of the district. The Panchkula district is blessed with abundant water resources, both surface and underground. In the district, groundwater is a primary source of irrigation. The district's average annual rainfall is 1057 mm, evenly divided over 49 days. The Siwalik hill ranges, which are located on the northern and north-eastern outskirts of Panchkula district, reach heights up to 950 m above mean sea level. In comparison to the nearby alluvial plains, the hills are around 500 m high. The slope runs from northeast to southwest in general. In the Siwalik range soils are deep, well-drained, non-saline, non-alkali loamy sand to sandy loam found in the transitional tract between Siwalik hills and alluvial plains (Anonymous 2016c).

3.1.4 Yamuna Nagar district

The district covers a total area of 1756 km^2. It lies between longitudes 77° 07' E to 77° 59' E and latitudes of 29° 92' N to 30° 48' N. The district's eastern half is in the upper Yamuna basin, while the western half is in the Ghaggar basin. Only groundwater is used for irrigation. Yamuna Nagar district has a subtropical monsoon climate, mild and dry winters, scorching summers, and a sub-humid climate, which is mostly dry with hot summers and chilly winters except during the monsoon season when moist air from the ocean enters the district. The district's average annual rainfall is 1107 mm, which is distributed unevenly over the territory (Anonymous 2016d).

3.2 Data Collection

This study is based on secondary data which have been procured for the period of 1974-2020 from different departments of Government of India and Government of Haryana, and various reports published by the government.

3.2.1 Rainfall data

District wise data of average annual rainfall from 1974-2020 was obtained from the Statistical Abstract of Haryana issued by the Economic and Statistical Adviser, Planning Department, Government of Haryana for the respective years available in the library of CCS HAU, Hisar and is shown in Appendix I. The average annual rainfall for the Northern Haryana was computed by the weighted mean average of the four districts in the study area.

3.2.2 Groundwater depth data

The village wise groundwater level data for the period of 1974 to 2020 for June (pre-monsoon) and October (post-monsoon) was obtained from Groundwater Cell, Department of Irrigation and Water Resources, Government of Haryana, from the regular monitoring of 235 observation wells. It was analyzed and interpreted to examine the trend, fluctuation and dynamics of groundwater level. The location of all 235 observation wells is shown in Figure 3.2.

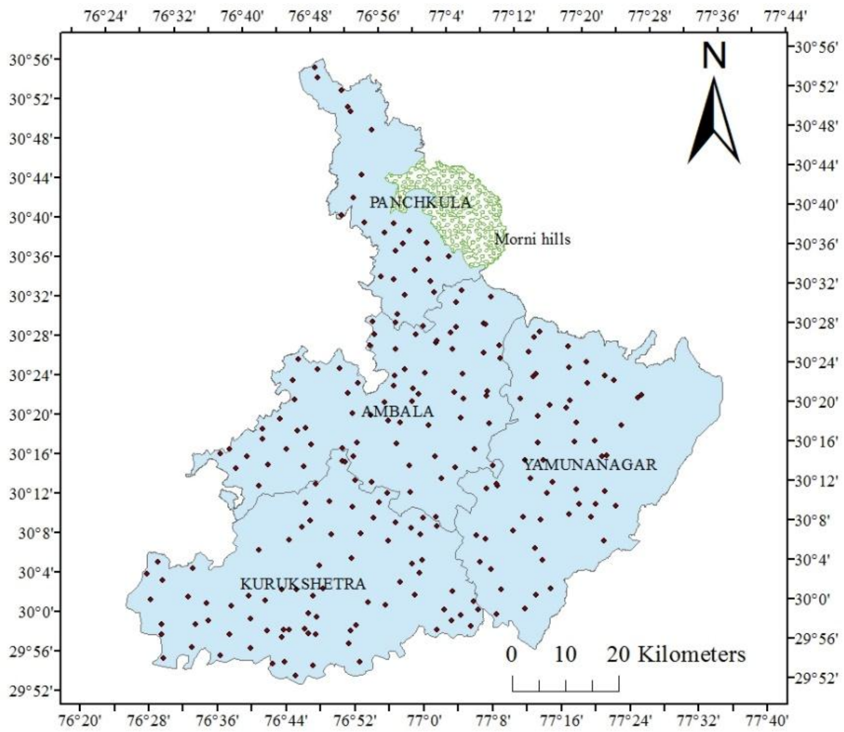


Fig. 3.2: Location of observation wells in the study area

3.2.3 Land use data

The district wise anthropogenic data for the period 1974-2020 for forest cover area, area under principal crops (rice, wheat, maize and sugarcane) have been collected from the Statistical Abstract of Haryana issued by the Economic and Statistical Adviser, Planning Department, Government of Haryana for the respective years available in the library of CCS HAU, Hisar and is shown in Appendix II.

3.2.4 Irrigation related data

Data of number of tube wells in the region (electric, diesel and total), net area under irrigation, gross area under irrigation, area irrigated by different irrigation sources (canals, tanks, wells and tube wells) was obtained from the Statistical Abstract of Haryana and is shown in Appendix III.

3.2.5 Data for the year 2020

Groundwater data relating to annual extractable groundwater resources and annual groundwater extraction, details of groundwater recharge, details of groundwater draft was obtained from Report on Dynamic Groundwater Resources of Haryana state as on 31st March, 2020 published by the Groundwater Cell, Department of Irrigation and Water Resources, Haryana and CGWB, North Western region, Chandigarh and is shown in Appendix IV.

3.3 Preparation of Thematic Maps

A thematic map is a map which portrays the geographic pattern of a particular subject matter (groundwater depth in this case) in a geographic area. It involves the use of map symbols to visualize selected properties of geographic features that are not naturally visible. The groundwater depth data of 235 observation wells obtained from Groundwater Cell, was digitized in GIS interface using ArcGIS 10.3 software. The spatial distribution maps were prepared for groundwater depth for the intervals of 10 years *i.e.* for the years 1974, 1984, 1994, 2004, 2014 and 2020 and groundwater depth fluctuation maps were prepared for the comparison of water table depth at 10, 20, 30, 40 and 46 year interval with reference to groundwater depth of 1974 as a base year. Pre-monsoon and post-monsoon spatial distribution maps were made at 1 year interval from the year 2001 to 2020 to observe the seasonal effect of monsoon. The maps were prepared using IDW (Inverse Distance Weightage) technique of interpolation of the Spatial Analyst Tool in ArcGIS. Then the maps were analyzed to examine rise or fall of water table in the region and to delineate over-exploited and critical areas.

3.4 Preparation of Graphs

The graphs of various factors *i.e.* total forest cover area, average annual rainfall, number of tubewells (diesel and electric), area irrigated by different irrigation sources (canal, wells, tanks and tubewells) area under principal crops (rice, wheat, maize and sugarcane), district wise average groundwater depth trend, block-wise average groundwater depth trend, area under different groundwater depths were made for the period of 1974-2020 were prepared using MS-Excel. Irrigation related graphs of net area irrigated and gross area irrigated were also made for the period of 1974-2020. Further graphs relating to district wise values of total annual groundwater recharge, total natural discharge, annual extractable groundwater recharge, total groundwater extraction and stage of groundwater extraction were made for the year 2020 to analyse the current situation of groundwater resources in the study area.

3.5 Non-Parametric Tests

Two non-parametric tests i.e. Mann-Kendall test and Sen’s slope estimator were used to understand the trend and rate of change in the groundwater depth, using MS-Excel and XL-STAT software.

3.5.1 Mann-Kendall test

It is frequently used to identify upward or downward or non-null or null trends of hydrological variables in a series of observed values (Subash and Sikka, 2014). The null hypothesis shows no variation in the data, whereas alternative hypothesis shows an upward or downward trend (Silva *et al.,* 2015; Helsel and Hirsh, 2002). A monotonic upward or downward trend means that the variables are consistently increasing or decreasing, respectively, through time, but the trend may or may not be linear. It is widely used to identify the significance of monotonic trends in time series data (Park *et al.,* 2011; Bui *et al.,* 2012; Pathak and Dodamani, 2018; Anand *et al.*, 2019).

It is highly appropriate for trend detection in hydrological variables for reasons mentioned below:

(a) It does not require normally distributed data,

(b) It supports multiple observations per time period,

(c) It allows missing values and censored observations in the time series (Helsel and Hirsch, 2002).

In this test, each data value in the time series is compared with all the other values. At first, the test statistics (S) is assumed to be zero, and if a data value in subsequent time periods is higher than a data value in previous time period then S is increased by 1, *i.e.*, +1, and vice versa *i.e.*, -1. The result of all these operations will give the final value of Mann-Kendall statistics (S) which has been defined as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k)$$

$$sgn(x_j - x_k) \begin{cases} +1, & if\ x_j - x_k > 0 \\ 0, & if\ x_j - x_k = 0 \\ -1, & if\ x_j - x_k < 0 \end{cases}$$

Where, x denotes particular data point, x_j and x_k are data values at time j and k (j > k), respectively, n is length of time series, and sgn represent the signum function.

Positive values of S show an increasing trend, while negative values indicate a decreasing trend. This test assumes that there are not many tied values within the dataset. The variance of S is computed as:

$$Var(S) = \frac{[n(n-1)(2n+5) - \sum_r r(r-1)(2r+5)]}{18}$$

Where r and Σ_r stand for extent of any given tie and summation of all ties, respectively. A tie is a set of sample data having the same value. In cases, where the sample size n>10, the standard normal variable Z_S is computed as:

$$Z_S = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, & if\ S > 0 \\ 0, & if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, & if\ S < 0 \end{cases}$$

To indicate the strength of trend, level of significance is used, which is 5% (α = 0.05) for this test, and in cases of $Z_S > Z_{1-\alpha/2}$, null hypothesis stands rejected. The trend categorization according to the Z_S values is shown in the table below:

Table 3.1: Trend categorization according to the $Z_S$values

Significantly increasing trend	$Z_S \geq 1.96$
Non-significantly increasing trend	$0 \leq Z_S < 1.96$
No trend	$Z_S = 0$
Non-significantly decreasing trend	$-1.96 \leq Z_S < 0$
Significantly decreasing trend	$Z_S < (-1.96)$

3.5.2 Sen's slope estimator

The magnitude of trend in a time series can be determined by the non-parametric test, Sen's slope estimator (Sen, 1968). It is a powerful, unbiased and precise tool to develop the linear relationship rather than the regression slope in the sense that it is not much affected by gross data errors and outliers. Therefore, this has been widely used to find change in slope per unit time in a time series (Tabari *et al.,* 2012; Singh *et al.,* 2016; Amirataee and Zeinalzadeh, 2016; Biswas *et al.,* 2018; Ndlovu and Demlie, 2018; Pathak and Dodamani, 2018). The slope Q of all datasets is computed as:

$$Q = Median\left\{\left[\left[\frac{x_j - x_k}{j-k}\right]_{k=1}^{k=n-1}\right]_{j=k+1}^{j=n}\right\}$$

If n is odd, then Sen's slope estimator is computed as:

$$Q_{med} = \frac{1}{2} Q_{[\frac{n+1}{2}]}$$

If n is even, then Sen's slope estimator is computed as:

$$Q_{med} = \frac{1}{2} Q_{[n/2]} + Q_{[\frac{n+2}{2}]}$$

If Q > 0, it indicates an increasing trend; and if Q < 0, it indicates a falling trend.

3.6 Parametric Tests

Simple linear regression, a parametric test can be applied to observe the monotonic trend in data series, whereas Pettitt's test, Standard Normal Homogeneity test and Bushiand Range test can be applied to detect abrupt change points in the data series and are discussed as follows:

3.6.1 Simple linear regression

It is a common and major parametric method applied for observing the monotonic trend in data series. It is often carried out to develop an association between two variables (independent and dependent) by fitting a linear equation to the observed data, which shows the average periodic variation of the measured parameter. Positive gradient indicates rising trend and negative gradient indicates falling trend.

3.6.2 Pettitt's test

The Pettitt's test is a powerful non-parametric test for detecting abrupt changes in the middle of any time series (Pettitt, 1979; Winingaard *et al.*, 2003). Moreover it detects a significant change in the mean of a time series when the exact time of the change is unknown. Ifx_1,x_2, x_3 ……… x_n is a series of observed data with a change point at t such that x_1,x_2, x_3 ……… x_t has a distribution function $F_1(x)$ that is different from the distribution function $F_2(x)$ of the second part of the series x_{t+1},x_{t+2}, x_{t+3} ……… x_n. Mathematically, this test statistic (U_t) can be expressed as:

$$U_t = \sum_{i=1}^{t} \sum_{j=t+1}^{n} sgn(x_i - x_j)$$

$$sgn(x_i - x_j) \begin{cases} +1, & if\ x_i - x_j > 0 \\ 0, & if\ x_i - x_j = 0 \\ -1, & if\ x_i - x_j < 0 \end{cases}$$

Where, x_i denotes data value at time *i*.

The test statistic K and the associated confidence level *(ρ)* for the sample length (n) may be defined as:

$$\text{K} = \text{Max}\,|U_t|$$

$$\rho = exp\left(\frac{-K}{n^2 + n^3}\right)$$

Where, ρ is smaller than the specific confidence level, the null hypothesis is rejected. The approximate significance probability (P) for a change point is defined as:

$$P = 1 - \rho$$

It is apparent that where a significant abrupt change point exists, the series is wedged at the location of the change point into two sub-series. The test statistic K can also be compared with standard values at different confidence level for detection of change point in a time series. This test is extensively used in hydrological and climatological change point detection (Zhang *et al.*, 2008; Guerreiro *et al.*, 2014).

3.6.3 Standard Normal Homogeneity (SNH) test

According to Alexandersson, (1986) for test statistic (T_t) in the SNH test, the time series if first divided into two parts: first from 1 to t years (z_1) and second from t to n – t years (z_2). Then, means of these two series are compared using the following mathematical expression:

$$T_t = tz_1^2 + (n-t)z_2^2$$

Where z_1 and z_2 are computed as:

$$z_1 = \frac{1}{t}\sum_{i=1}^{t}\frac{(x_i - \bar{x})}{\sigma x}$$

$$z_2 = \frac{1}{(n-t)}\sum_{i=t+1}^{n}\frac{(x_i - \bar{x})}{\sigma x}$$

Where, $\bar{x}$ and σ_x are the mean and standard deviation of the time series. The year t can be considered as a change point and consists of a break where the value of T_t attains the maximum value. To reject the null hypothesis, the test statistic should be greater than the critical value, which depends on the sample size (n).

3.6.4 Buishand Range test

This is a non-parametric test and is suitable for variable, which follows any form of distribution (Buishand, 1982). The time series under observation are considered to be independent of each other. The test statistic B_t is mathematically computed as:

$$B_t = \sum_{i=1}^{t}(x_i - \bar{x})$$

A series may be homogenous without any change point if $B_t = 0$ because a time series is randomly distributed around its mean value on both sides of the mean series. The significance of the shift can be evaluated by calculating the rescaled adjusted range (R) as:

$$R = \frac{Max\ (B_t) - Min\ (B_t)}{\bar{x}}$$

CHAPTER IV

RESULTS

Data collected on different aspects for the study entitled “Trend Analysis of Groundwater Levels in Northern Haryana, India” was analysed by using ArcGIS, MS-Excel and XLSTAT software. The trend analysis of groundwater depth and detection of abrupt change points in groundwater depth was done through different parametric and non-parametric statistical tests. The results obtained are compiled under the following sections:

4.1 Spatial Variations of Groundwater Depth of Northern Haryana

4.1.1 Blockwise spatial variations of groundwater depth during the year 1974

Blockwise average groundwater depth, its range and standard deviation for all the four districts of the study area i.e. Ambala, Kurukshetra, Panchkula and Yamuna Nagar was calculated from the collected data and is presented in Table 4.1. The spatial distribution map of groundwater depth was made by using ArcGIS 10.3 software and is shown in Fig. 4.1.

Table 4.1: Block-wise average water table depth (m), its range and standard deviation for year 1974

District	Block	Average water table depth (m)	Range of water table depth (m)		Standard deviation
			Minimum	Maximum	
Ambala	Ambala-I	5.59	2.02	9.80	2.18
	Ambala-II	5.04	2.54	8.55	1.76
	Barara	5.70	3.01	13.05	3.39
	Naraingarh	7.22	2.46	12.25	2.80
	Saha	5.04	2.31	9.78	2.33
	Shahazadpur	7.38	3.5	12.36	2.70
Kurukshetra	Babain	11.68	8.89	16.36	2.60
	Ladwa	16.15	12.1	20.40	2.86
	Pehowa	9.54	5.25	12.74	1.93
	Shahbad	15.07	6.23	20.90	3.93
	Thanesar	11.86	8.14	18.52	3.16
Panchkula	Barwala	10.78	4.94	24.95	6.45
	Pinjore	13.14	4.98	21.00	4.76
	Raipur Rani	10.30	3.12	19.00	4.95

Yamuna Nagar	Bilaspur	6.38	3.05	10.67	2.19
	Chhachhrauli	7.47	3.73	11.90	3.06
	Jagadhri	7.25	3.02	13.76	3.78
	Mustafabad	6.86	3.5	10.37	2.26
	Radaur	5.97	4.02	12.03	2.58
	Sadhoura	6.47	4.05	11.02	2.32

During 1974, in Ambala district, shallowest (2.02 m) and deepest (13.05 m) groundwater level was found in Ambala-I and Barara blocks, respectively. In Kurukshetra district, shallowest (5.25 m) and deepest (20.90 m) groundwater level was found in Pehowa and Shahbad blocks, respectively. In Panchkula district, shallowest (3.12 m) and deepest (24.95 m) groundwater level was found in Raipur Rani and Barwala blocks, respectively. In Yamuna Nagar district, shallowest (3.02 m) and deepest (13.76) groundwater level were both found in Jagadhri block. Overall in the study area, shallowest (2.02 m) and deepest (24.95 m) groundwater level was recorded in Ambala-I and Barwala blocks, respectively.

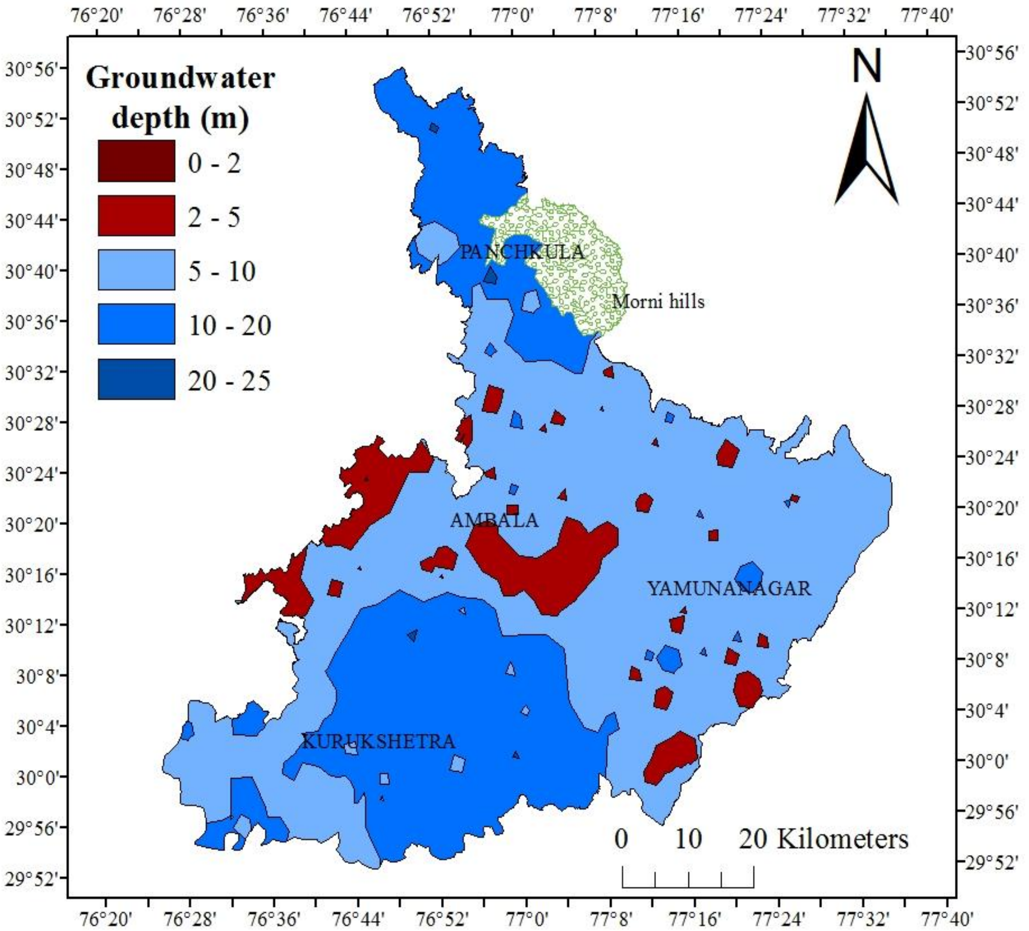


Fig. 4.1: Spatial distribution of groundwater depth in Northern Haryana in 1974

4.1.2 Blockwise spatial variations of groundwater depth during the year 1984

Blockwise average groundwater depth, its range and standard deviation for all four districts of the study area i.e. Ambala, Kurukshetra, Panchkula and Yamuna Nagar were calculated from the collected data and is presented in Table 4.2. The spatial distribution map of groundwater depth is shown in Fig. 4.2.

Table 4.2: Block-wise average water table depth (m), its range and standard deviation for year 1984

District	Block	Average water table depth (m)	Range of water table depth (m)		Standard deviation
			Minimum	Maximum	
Ambala	Ambala-I	6.28	4.22	9.96	1.76
	Ambala-II	5.43	2.35	10.97	2.40
	Barara	6.00	2.79	13.37	3.23
	Naraingarh	7.11	2.3	12.25	2.89
	Saha	4.94	2.05	8.96	2.21
	Shahazadpur	7.23	3.33	12.20	2.82
Kurukshetra	Babain	12.13	9.36	15.69	2.45
	Ladwa	14.74	10.86	18.01	2.31
	Pehowa	12.39	8.12	15.46	2.23
	Shahbad	17.18	6.23	22.58	4.30
	Thanesar	13.83	6.32	20.12	3.18
Panchkula	Barwala	11.51	5.5	24.95	6.31
	Pinjore	16.26	6.25	34.55	10.68
	Raipur Rani	10.76	6.4	19.12	4.37
Yamuna Nagar	Bilaspur	7.50	5.75	11.65	1.86
	Chhachhrauli	7.53	2.7	12.60	3.44
	Jagadhri	8.59	3.0	13.78	3.85
	Mustafabad	7.14	3.4	10.75	2.58
	Radaur	6.22	2.95	14.90	3.81
	Sadhoura	6.97	4.05	11.02	2.63

During year 1984, in Ambala district, shallowest (2.05 m) and deepest (13.37) groundwater level was found in Saha and Barara blocks respectively. In Kurukshetra district, shallowest (6.23 m) and deepest (22.58 m) groundwater level were both found in Shahbad block. In Panchkula district, shallowest (5.5 m) and deepest (34.55) groundwater level was found in Barwala and Pinjore blocks respectively. In Yamuna Nagar district, shallowest (2.7 m) and deepest (14.9) groundwater level was found in Chhachhrauli and Radour blocks respectively. Overall in the study area, shallowest (2.05 m) and deepest (34.55 m) groundwater level was recorded in Shah and Pinjore blocks, respectively.

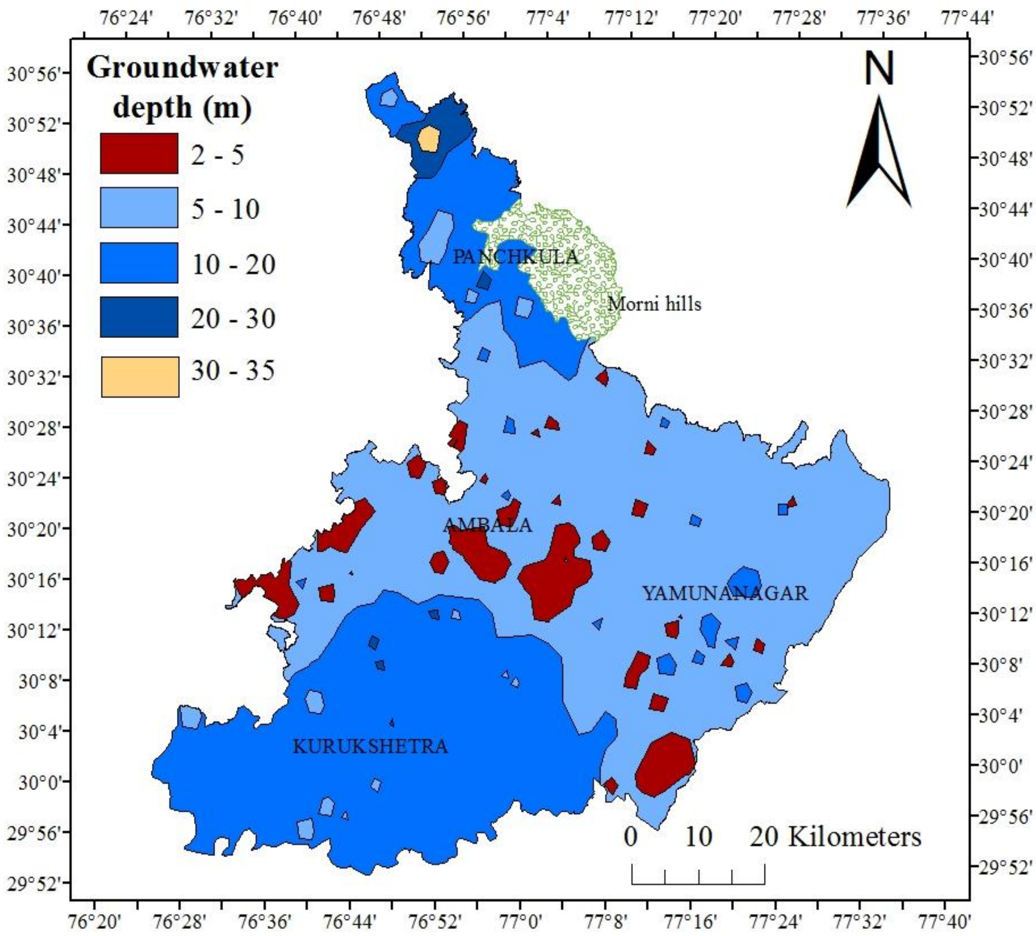


Fig. 4.2: Spatial distribution of groundwater depth in Northern Haryana in 1984

4.1.3 Blockwise spatial variations of groundwater depth during the year 1994

Blockwise average groundwater depth, its range and standard deviation for all four districts of the study area i.e. Ambala, Kurukshetra, Panchkula and Yamuna Nagar were calculated from the collected data and is presented in Table 4.3. The spatial distribution map of groundwater depth is shown in Fig. 4.3.

Table 4.3: Block-wise average water table depth (m), its range and standard deviation for year 1994

District	Block	Average water table depth (m)	Range of water table depth (m)		Standard deviation
			Minimum	Maximum	
Ambala	Ambala-I	5.71	1.8	8.38	2.21
	Ambala-II	4.89	0.67	10.74	2.44
	Barara	6.22	3.15	16.52	4.00
	Naraingarh	9.64	2.02	15.20	3.92
	Saha	5.71	3.56	8.51	1.67
	Shahazadpur	7.70	3.2	12.32	2.74
Kurukshetra	Babain	13.17	10.12	16.25	2.07
	Ladwa	24.16	15.15	31.70	5.46
	Pehowa	14.57	9.65	17.88	2.11
	Shahbad	19.40	5.57	26.53	5.08
	Thanesar	16.32	10.5	24.25	3.03
Panchkula	Barwala	12.15	5.69	26.35	6.94
	Pinjore	15.73	7.25	29.35	7.97
	Raipur Rani	11.69	5.01	18.58	4.53
Yamuna Nagar	Bilaspur	8.37	6.25	13.65	2.46
	Chhachhrauli	8.41	3.33	12.18	2.57
	Jagadhri	8.86	2.3	15.74	4.91
	Mustafabad	7.53	2.62	11.41	2.46
	Radaur	6.48	3.06	14.90	3.80
	Sadhoura	7.32	4.6	9.95	1.95

During year 1994, in Ambala district, shallowest (0.67 m) and deepest (16.52) groundwater level was found in Ambala-II and Barara blocks respectively. In Kurukshetra district, shallowest (5.57 m) and deepest (31.70 m) groundwater level was found in Shahbad and Ladwa blocks respectively. In Panchkula district, shallowest (5.01 m) and deepest (29.35) groundwater level was found in Raipur Rani and Pinjore blocks respectively. In Yamuna Nagar district, shallowest (2.3 m) and deepest (15.74) groundwater level were both found in Jagadhri block. Overall in the study area, shallowest (0.67 m) and deepest (31.70 m) groundwater level was recorded in Ambala-II and Ladwa blocks, respectively.

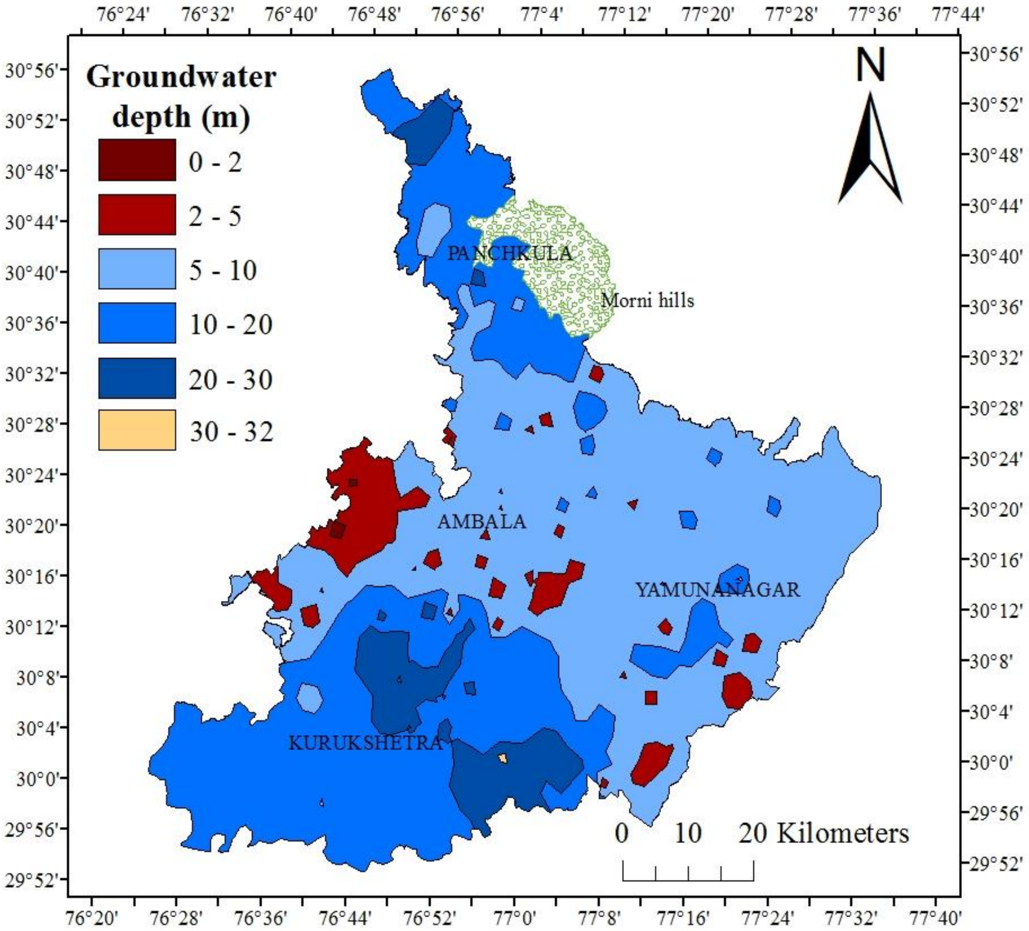


Fig. 4.3: Spatial distribution of groundwater depth in Northern Haryana in 1994

4.1.4 Blockwise spatial variations of groundwater depth during the year 2004

Blockwise average groundwater depth, its range and standard deviation for all four districts of the study area i.e. Ambala, Kurukshetra, Panchkula and Yamuna Nagar were calculated from the collected data and is presented in Table 4.4. . The spatial distribution map of groundwater depth was made using ArcGIS 10.3 software and is shown in Fig 4.4.

Table 4.4: Block-wise average water table depth (m), its range and standard deviation for the year 2004

District	Block	Average water table depth (m)	Range of water table depth (m)		Standard deviation
			Minimum	Maximum	
Ambala	Ambala-I	5.91	0.91	13.00	3.13
	Ambala-II	4.78	1.01	10.05	2.87
	Barara	10.00	3.27	27.56	8.04
	Naraingarh	10.25	5.2	20.74	4.34

	Saha	9.48	3.4	28.34	7.79
	Shahazadpur	7.64	1.61	22.59	5.08
Kurukshetra	Babain	31.54	28.9	34.00	1.67
	Ladwa	25.94	18.12	31.70	4.56
	Pehowa	24.26	20.3	31.45	2.54
	Shahbad	30.66	8.66	36.45	8.20
	Thanesar	24.77	19.1	31.75	3.76
Panchkula	Barwala	11.78	5.59	26.05	7.26
	Pinjore	14.44	2.4	27.14	8.14
	Raipur Rani	11.05	5.3	16.79	3.81
Yamuna Nagar	Bilaspur	7.24	4.58	13.60	2.83
	Chhachhrauli	6.24	3.07	11.05	2.42
	Jagadhri	10.03	2.95	15.20	4.65
	Mustafabad	8.56	5.34	13.78	2.74
	Radaur	11.77	4.5	18.45	6.99
	Sadhoura	4.73	3.2	5.72	0.90

During year 2004, in Ambala district, shallowest (0.91 m) and deepest (28.34 m) groundwater level was found in Ambala-I and Saha blocks respectively. In Kurukshetra district, shallowest (8.66 m) and deepest (36.45 m) groundwater level were both found in Shahbad block. In Panchkula district, shallowest (2.4 m) and deepest (27.14 m) groundwater level were both found in Pinjore block. In Yamuna Nagar district, shallowest (2.95 m) and deepest (18.45 m) groundwater level was found in Jagadhri and Radour blocks respectively. Overall in the study area, shallowest (0.91 m) and deepest (36.45 m) groundwater level was recorded in Ambala-I and Shahbad blocks, respectively.

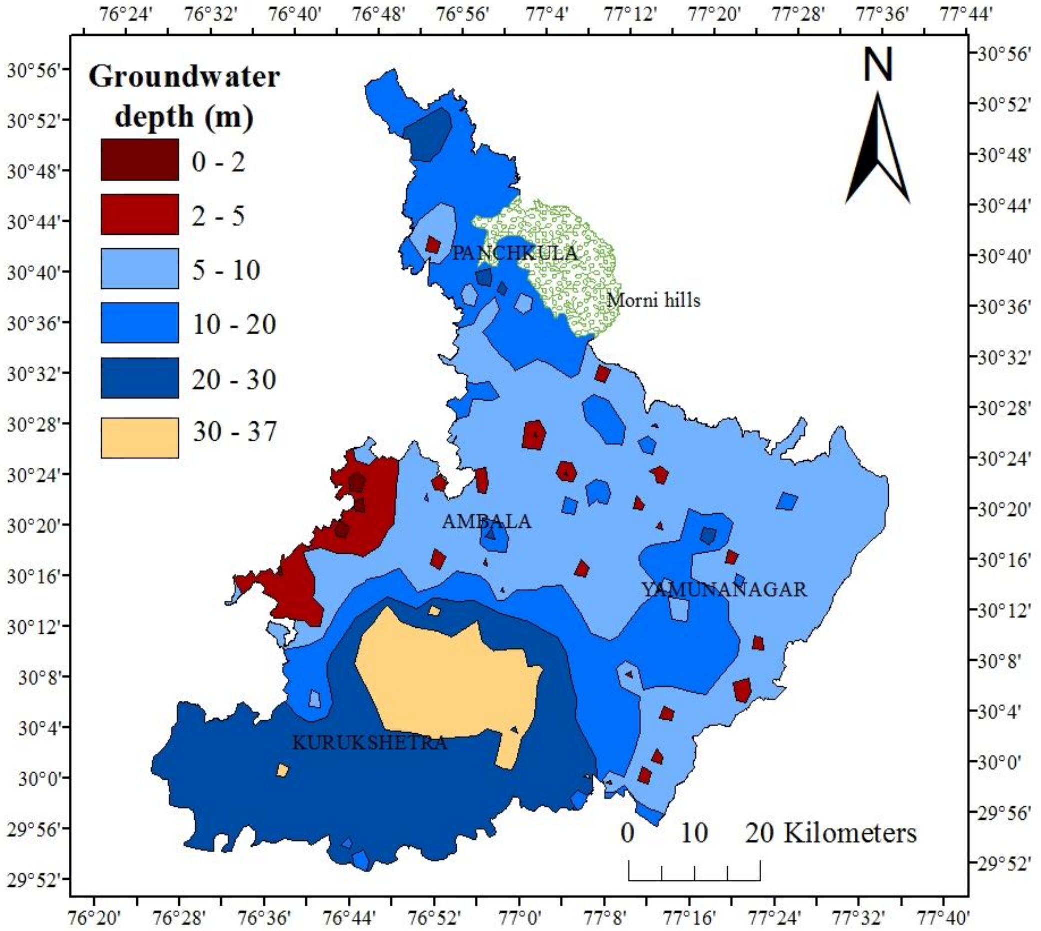


Fig. 4.4: Spatial distribution of groundwater depth in Northern Haryana in 2004

4.1.5 Blockwise spatial variations of groundwater depth during the year 2014

Blockwise average groundwater depth, its range and standard deviation for all four districts of the study area i.e. Ambala, Kurukshetra, Panchkula and Yamuna Nagar were calculated from the collected data and is presented in Table 4.5. . The spatial distribution map of groundwater depth was made using ArcGIS 10.3 software and is shown in Fig 4.5.

Table 4.5: Block-wise average water table depth (m), its range and standard deviation for the year 2014

District	Block	Average water table depth (m)	Range of water table depth (m)		Standard deviation
			Minimum	Maximum	
Ambala	Ambala-I	5.80	0.74	11.44	3.40
	Ambala-II	4.70	0.46	11.86	3.19
	Barara	14.22	4.5	34.15	11.27
	Naraingarh	14.35	6.25	21.94	6.09
	Saha	14.17	3.37	36.77	12.91
	Shahazadpur	11.17	3.2	23.69	5.69
Kurukshetra	Babain	36.38	34.5	39.82	1.86
	Ladwa	30.51	19.45	38.40	5.91
	Pehowa	31.87	26.63	38.32	3.15
	Shahbad	36.88	9.23	43.23	8.25
	Thanesar	29.47	25.02	39.80	3.86
Panchkula	Barwala	16.51	4.77	34.75	9.50
	Pinjore	18.46	4.4	36.49	10.49
	Raipur Rani	16.53	8	24.79	5.98
Yamuna Nagar	Bilaspur	7.80	4.83	15.35	3.13
	Chhachhrauli	7.21	3.0	14.15	3.12
	Jagadhri	14.95	6.14	20.05	4.65
	Mustafabad	13.97	6.8	27.90	7.46
	Radaur	16.56	4.6	30.17	10.89
	Sadhoura	8.92	6.05	17.70	4.02

During year 2014, in Ambala district, shallowest (0.46 m) and deepest (36.77 m) groundwater level was found in Ambala-II and Saha blocks respectively. In Kurukshetra district, shallowest (9.23 m) and deepest (43.23 m) groundwater level were both found in Shahbad block. In Panchkula district, shallowest (4.4 m) and deepest (36.49 m) groundwater level were both found in Pinjore block. In Yamuna Nagar district, shallowest (3.0 m) and deepest (30.17 m) groundwater level was found in Chhachhrauli and Radour blocks respectively. Overall in the study area, shallowest (0.46 m) and deepest (43.23 m) groundwater level was recorded in Ambala-II and Shahbad blocks, respectively.

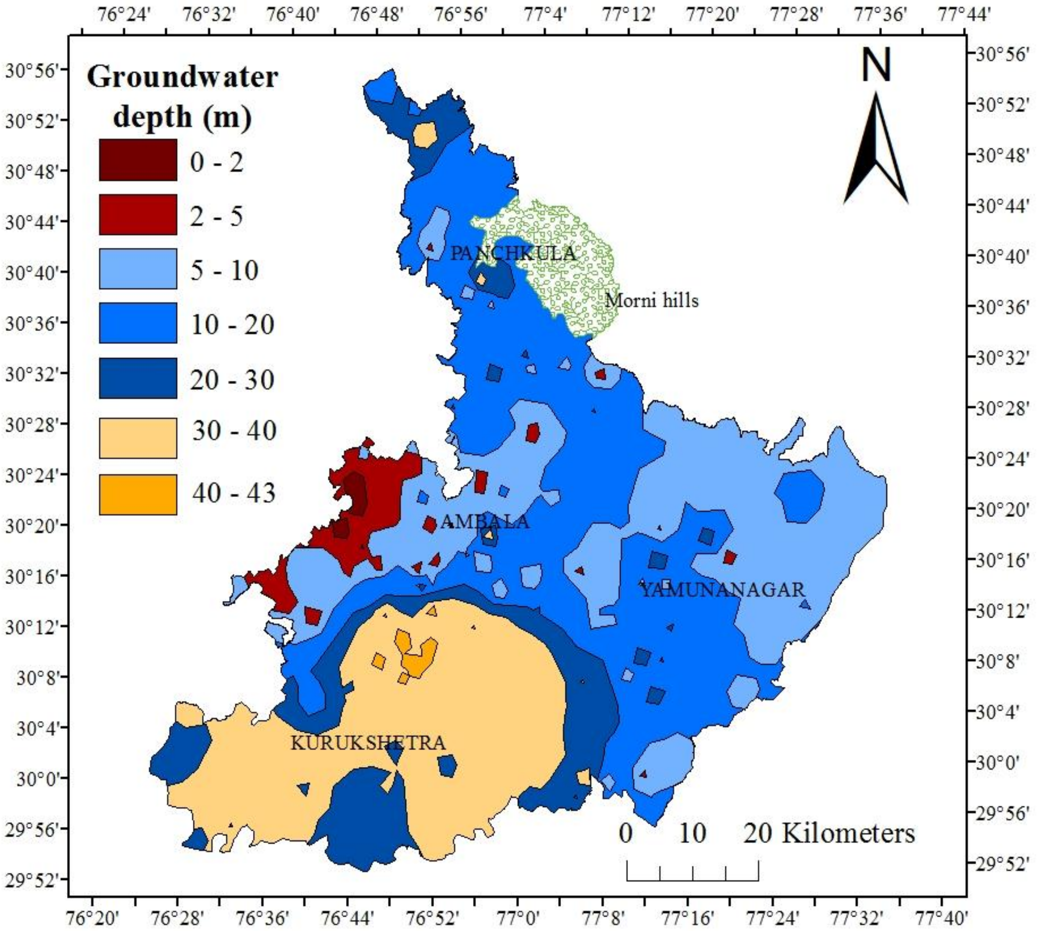


Fig. 4.5: Spatial distribution of groundwater depth in Northern Haryana in 2014

4.1.6 Blockwise spatial variations of groundwater depth during the year 2020

Blockwise average groundwater depth, its range and standard deviation for all four districts of the study area i.e. Ambala, Kurukshetra, Panchkula and Yamuna Nagar were calculated from the collected data and is presented in Table 4.6. The spatial distribution map of groundwater depth was made using ArcGIS 10.3 software and is shown in Fig 4.6.

Table 4.6: Block-wise average water table depth (m), its range and standard deviation for the year 2020

District	Block	Average water table depth (m)	Range of water table depth (m)		Standard deviation
			Minimum	Maximum	
Ambala	Ambala-I	6.48	1.39	14.82	4.07
	Ambala-II	7.20	1.42	22.63	6.21
	Barara	14.59	4.42	35.81	12.18
	Naraingarh	14.93	6.71	24.15	6.25

	Saha	14.87	3.64	37.12	13.02
	Shahazadpur	12.18	3.8	24.21	5.95
Kurukshetra	Babain	42.04	39.74	44.88	1.87
	Ladwa	35.90	21.88	43.34	6.81
	Pehowa	39.49	33.19	44.53	3.32
	Shahbad	45.23	8.8	56.16	10.03
	Thanesar	35.62	30.42	48.92	4.83
Panchkula	Barwala	16.83	5.56	36.75	10.29
	Pinjore	19.90	5.4	38.49	10.95
	Raipur Rani	17.63	8.61	26.79	6.39
Yamuna Nagar	Bilaspur	9.35	6.05	16.57	3.32
	Chhachhrauli	8.52	3.84	16.20	3.36
	Jagadhri	15.62	5.33	22.00	4.98
	Mustafabad	14.70	7.37	30.15	8.01
	Radaur	17.35	5.61	30.95	10.92
	Sadhoura	10.28	6.78	21.09	5.07

During year 2020, in Ambala district, shallowest (1.39 m) and deepest (37.12 m) groundwater level was found in Ambala-I and Saha blocks respectively. In Kurukshetra district, shallowest (8.8 m) and deepest (56.16 m) groundwater level were both found in Shahbad block. In Panchkula district, shallowest (5.4 m) and deepest (38.49 m) groundwater level were both found in Pinjore block. In Yamuna Nagar district, shallowest (3.84 m) and deepest (30.95 m) groundwater level was found in Chhachhrauli and Radour blocks respectively. Overall in the study area, shallowest (1.39 m) and deepest (56.16 m) groundwater level was recorded in Ambala-I and Shahbad blocks, respectively.

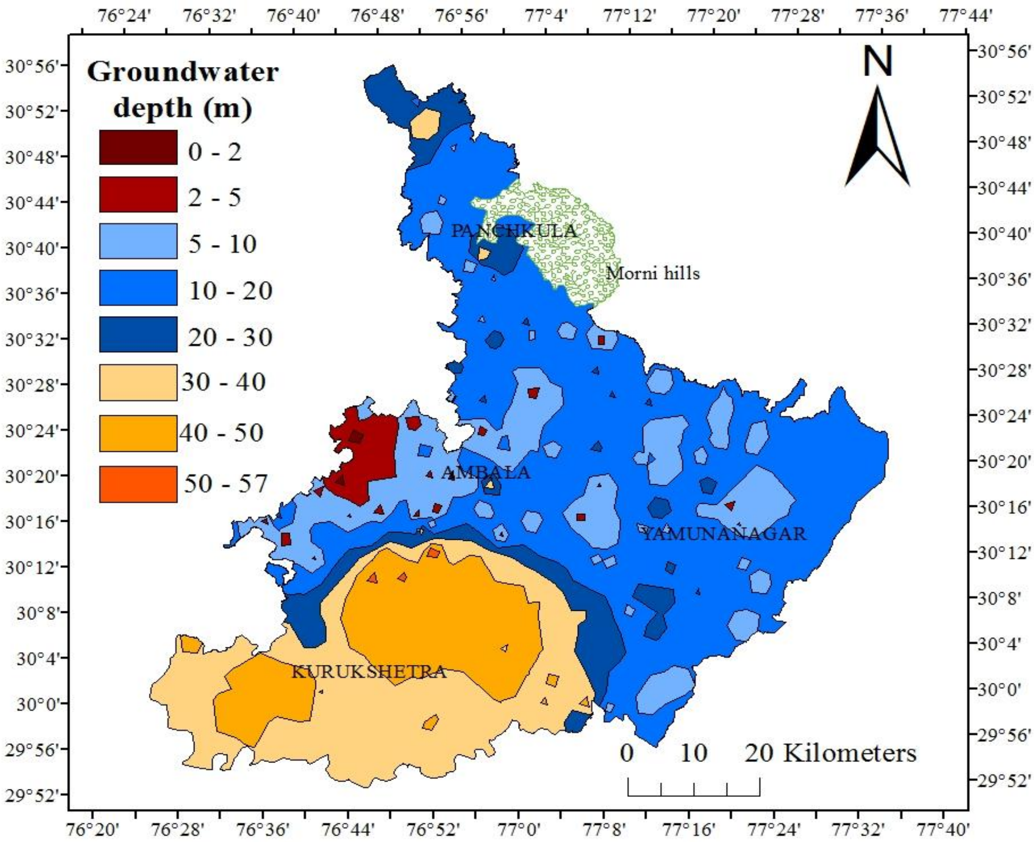


Fig. 4.6: Spatial distribution of groundwater depth in Northern Haryana in 2020

4.2 Area Under Different Groundwater Depths

Area of Northern Haryana under different groundwater depths (m) for the period 1974-2020 *i.e.*, 0-2, 2-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-60 was calculated by using the tools of ArcGIS 10.3 software and is presented in the Table 4.7.

Table 4.7: Area (km^2) under different groundwater depths (m) for the period of 1974-2020

Groundwater depth (m)	1974	1984	1994	2004	2014	2020
0-2	0.14	-	5.41	12.56	21.20	4.20
2-5	464.68	338.15	313.07	253.75	188.94	125.98
5-10	3222.19	2906.97	2731.30	2278.36	1426.17	814.39
10-20	2053.25	2417.87	2300.64	1483.10	2105.52	2651.05
20-30	5.94	73.05	394.42	1322.21	699.33	441.48
30-40	-	10.16	1.36	396.22	1275.32	1018.76
40-50	-	-	-	-	28.99	686.30
50-60	-	-	-	-	-	4.02
Total area	**5746.2**					

4.3 Spatial and Temporal Variations of Groundwater Fluctuations in Northern Haryana

Block wise average groundwater level fluctuation (m) was calculated at each 10, 20, 30, 40 and 47 year interval by taking 1974 as the reference year *i.e.*, for the years 1974-1984, 1974-1994, 1974-2004, 1974-2014 and 1974-2020 for all the four districts of the study area, as shown in Table 4.8. Average fluctuation of the blocks is calcuated by subtracting the average groundwater depth of the block for the required year from the average groundwater depth of the block in 1974. To further visualize the spatial variation of groundwater fluctuation at 10, 20, 30, 40, 56 year interval, fluctuation maps were prepared by using the groundwater level data at village level in ArcGIS 10.3 software and are shown in Figures 4.7 to 4.11.

Table 4.8: Block-wise groundwater fluctuation (m) of Northern Haryana for the period 1974-2020, by taking 1974 as the reference year

District	Block	1974-1984	1974-1994	1974-2004	1974-2014	1974-2020
Ambala	Ambala-I	-0.69	-0.12	-0.32	-0.21	-0.89
	Ambala-II	-0.39	0.15	0.26	0.34	-2.16
	Barara	-0.30	-0.52	-4.30	-8.52	-8.89
	Naraingarh	0.12	-2.42	-3.03	-7.13	-7.70
	Saha	0.10	-0.67	-4.44	-9.13	-9.82
	Shahazadpur	0.16	-0.32	-0.25	-3.79	-4.80
	Average	**-0.17**	**-0.65**	**-2.01**	**-4.74**	**-5.71**
Kurukshetra	Babain	-0.45	-1.49	-19.87	-24.70	-30.36
	Ladwa	1.42	-8.01	-9.79	-14.36	-19.75
	Pehowa	-2.85	-5.04	-14.72	-22.33	-29.95
	Shahbad	-2.12	-4.33	-15.60	-21.82	-30.16
	Thanesar	-1.96	-4.45	-12.91	-17.60	-23.76
	Average	**-1.19**	**-4.66**	**-14.58**	**-20.16**	**-26.80**
Panchkula	Barwala	-0.73	-1.38	-1.00	-5.74	-6.06
	Pinjore	-3.12	-2.58	-1.30	-5.32	-6.75
	Raipur Rani	-0.47	-1.39	-0.75	-6.23	-7.33
	Average	**-1.44**	**-1.78**	**-1.02**	**-5.76**	**-6.71**
Yamuna Nagar	Bilaspur	-1.12	-1.99	-0.86	-1.42	-2.97
	Chhachhrauli	-0.06	-0.94	1.23	0.27	-1.05
	Jagadhri	-1.34	-1.61	-2.78	-7.70	-8.36
	Mustafabad	-0.28	-0.66	-1.69	-7.11	-7.84
	Radaur	-0.25	-0.51	-5.80	-10.59	-11.38
	Sadhoura	-0.50	-0.85	1.74	-2.45	-3.81
	Average	**-0.59**	**-1.09**	**-1.36**	**-4.83**	**-5.90**

+ve value represent rise and –ve value represent fall in groundwater level

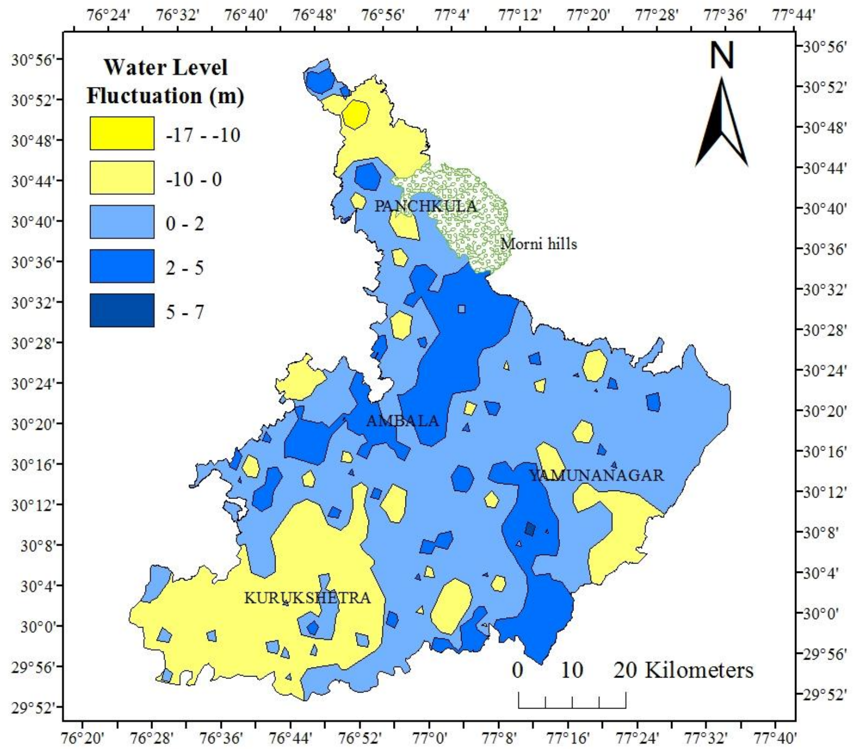


Fig. 4.7: Groundwater level fluctuation of Northern Haryana for the period 1974-1984

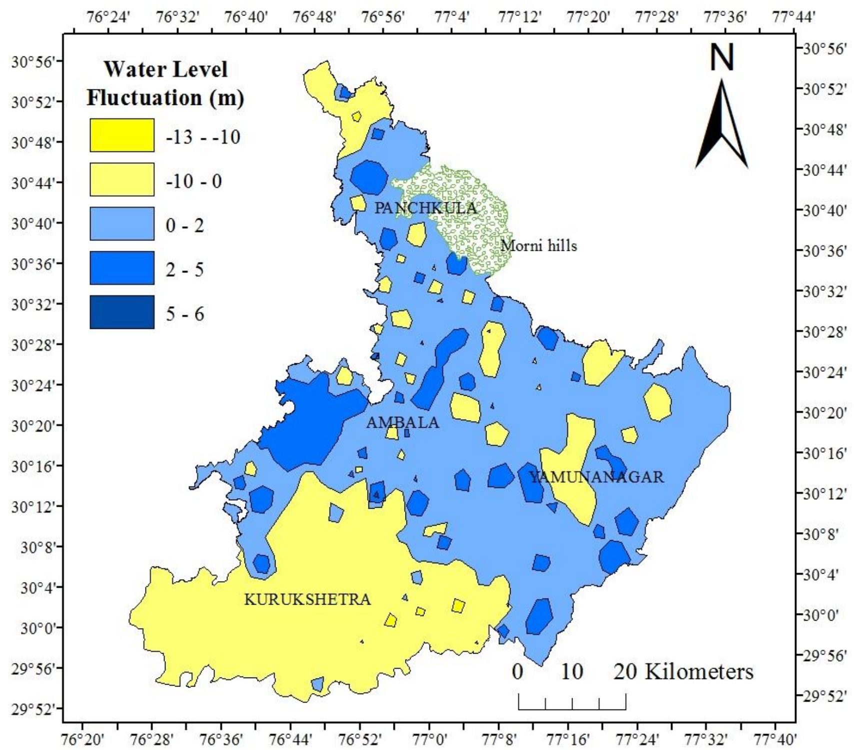


Fig. 4.8: Groundwater level fluctuation of Northern Haryana for the period 1974-1994

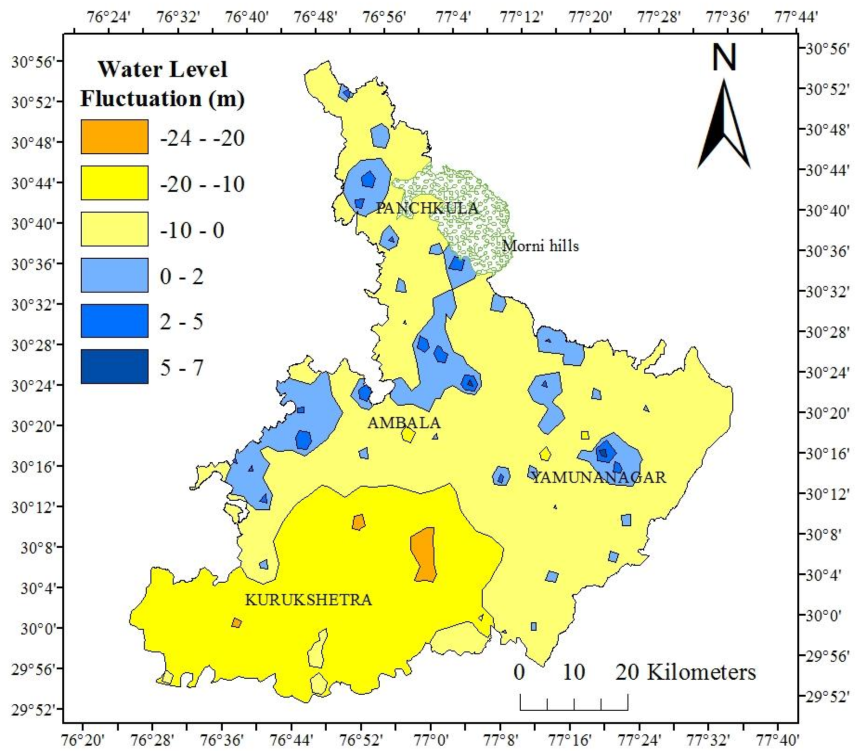


Fig. 4.9: Groundwater level fluctuation of Northern Haryana for the period 1974-2004

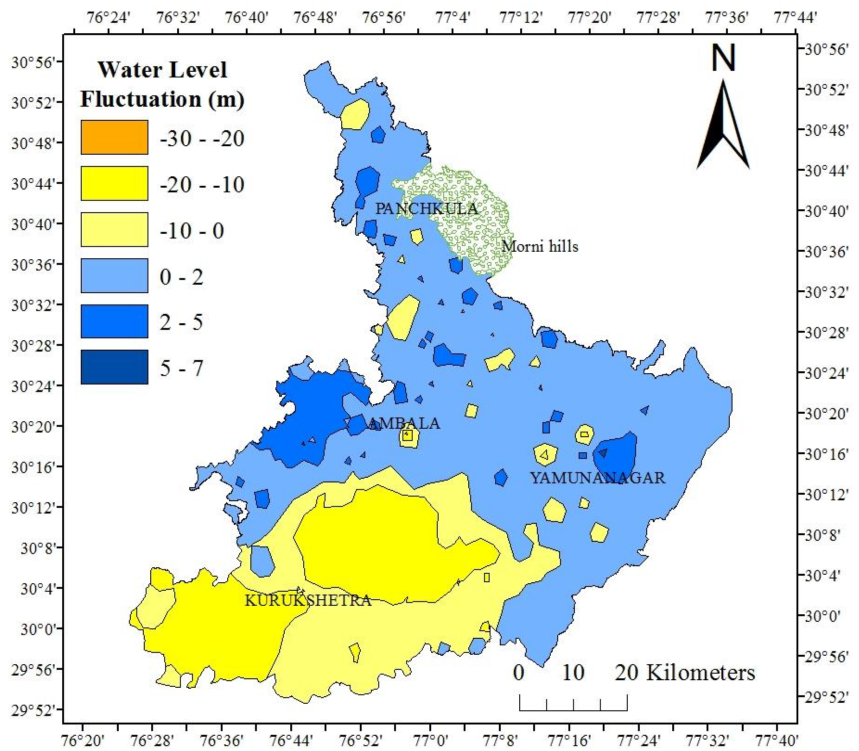


Fig. 4.10: Groundwater level fluctuation of Northern Haryana for the period 1974-2014

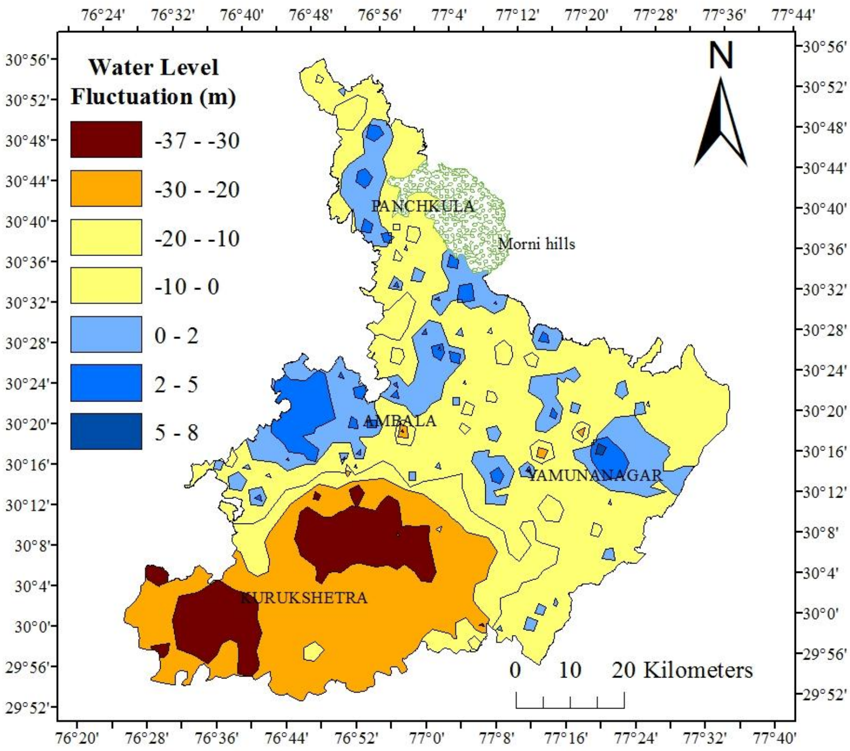


Fig. 4.11: Groundwater level fluctuation of Northern Haryana for the period 1974-2020

The percentage of area under different fluctuation range for the period 1974-2020 was calculated and is shown in Table 4.9.

Table 4.9: Percent area under different fluctuation range from the year 1974-2020

Range of fluctuation (m)	Average fluctuation (m)	Per year fluctuation (m/year)	Area (km^{2})	Percent area
-37 to -30	-33.5	0.71	468.15	8.14
-30 to -20	-25	0.53	1209.60	21.05
-20 to -10	-15	0.32	509.95	8.87
-10 to 0	-5	0.11	2518.52	43.82
0 to 2	1	0.02	821.54	14.29
2 to 5	3.5	0.07	215.87	3.75
5 to 8	7.5	0.16	2.54	0.04
Total			**5746.2**	**100**

4.4 Groundwater Level Fluctuation at Successive 10 Years Interval

Groundwater level fluctuation was calculated at each 10 year interval i.e 1974-1984, 1984-1994, 1994-2004, 2004-2014 and 2014-2020 to study the variation at successive intervals and is presented in Table 4.10.

Table 4.10: Block-wise groundwater level fluctuation (m) at successive 10 year interval

District	Block	1974-1984	1984-1994	1994-2004	2004_2014	2014-2020
Ambala	Ambala-I	-0.69	0.57	-0.19	0.11	-0.68
	Ambala-II	-0.39	0.55	0.11	0.08	-2.50
	Barara	-0.30	-0.22	-3.78	-4.22	-0.37
	Naraingarh	0.12	-2.53	-0.61	-4.10	-0.58
	Saha	0.10	-0.77	-3.76	-4.69	-0.70
	Shahazadpur	0.16	-0.47	0.06	-3.54	-1.01
	Average	**-0.16667**	**-0.47833**	**-1.36167**	**-2.72667**	**-0.97333**
Kurukshetra	Babain	-0.45	-1.04	-18.38	-4.83	-5.66
	Ladwa	1.42	-9.42	-1.79	-4.57	-5.38
	Pehowa	-2.85	-2.19	-9.69	-7.61	-7.62
	Shahbad	-2.12	-2.22	-11.26	-6.22	-8.35
	Thanesar	-1.96	-2.49	-8.45	-4.70	-6.16
	Average	**-1.192**	**-3.472**	**-9.914**	**-5.586**	**-6.634**
Panchkula	Barwala	-0.73	-0.64	0.37	-4.73	-0.32
	Pinjore	-3.12	0.54	1.29	-4.02	-1.44
	Raipur Rani	-0.47	-0.93	0.64	-5.48	-1.10
	Average	**-1.44**	**-0.34333**	**0.766667**	**-4.74333**	**-0.95333**
Yamuna Nagar	Bilaspur	-1.12	-0.87	1.13	-0.56	-1.54
	Chhachhrauli	-0.06	-0.88	2.17	-0.97	-1.31
	Jagadhri	-1.34	-0.27	-1.18	-4.92	-0.66
	Mustafabad	-0.28	-0.39	-1.03	-5.42	-0.73
	Radaur	-0.25	-0.26	-5.29	-4.78	-0.79
	Sadhoura	-0.50	-0.35	2.59	-4.19	-1.36
	Average	**-0.59167**	**-0.50333**	**-0.26833**	**-3.47333**	**-1.065**

+ve value represent rise and –ve value represent fall in groundwater level

4.5 District-wise average groundwater depth trend

District-wise line graphs were prepared to detect the trend of groundwater depth in Northern Haryana for the period 1974-2020 and are shown in Fig. 4.12 to 4.15.

4.5.1 Ambala district: In Ambala district, an increasing trend of groundwater depth was observed. The trend line shows value of R^2 = 0.9009, which shows a significant increasing trend.

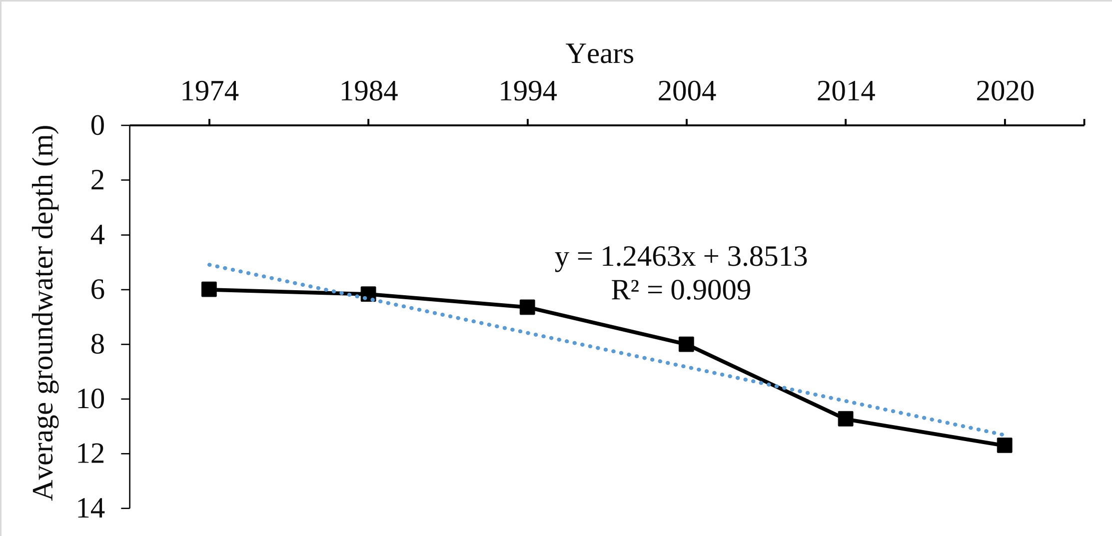


Fig. 4.12: Average groundwater depth of Ambala district for the period 1974-2020

4.5.2 Kurukshetra district: In Kurukshetra district, an increasing trend of groundwater depth was observed with value of R^2 of the trend line 0.9548 (very close to 1), which shows a significant increasing trend.

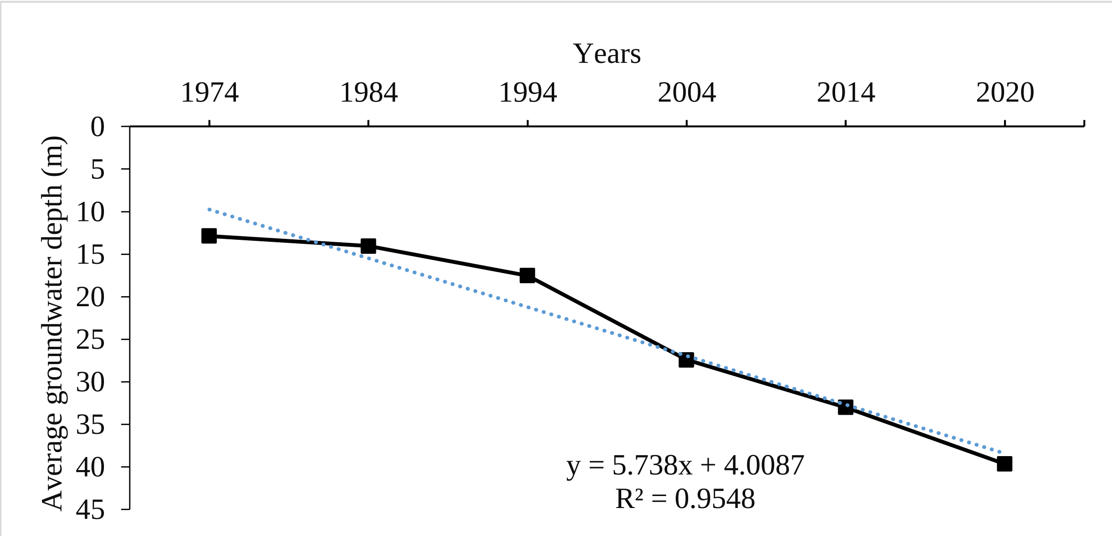


Fig. 4.13: Average groundwater depth of Kurukshetra district for the period 1974-2020

4.5.3 Panchkula district: In Panchkula district, the groundwater depth increased slightly till 1994 and decreased from 1994 to 2004. However, it increased significantly from 2004 to 2020. On the basis of trend line increasing trend of groundwater depth was observed as the value of $R^2 = 0.7869$.

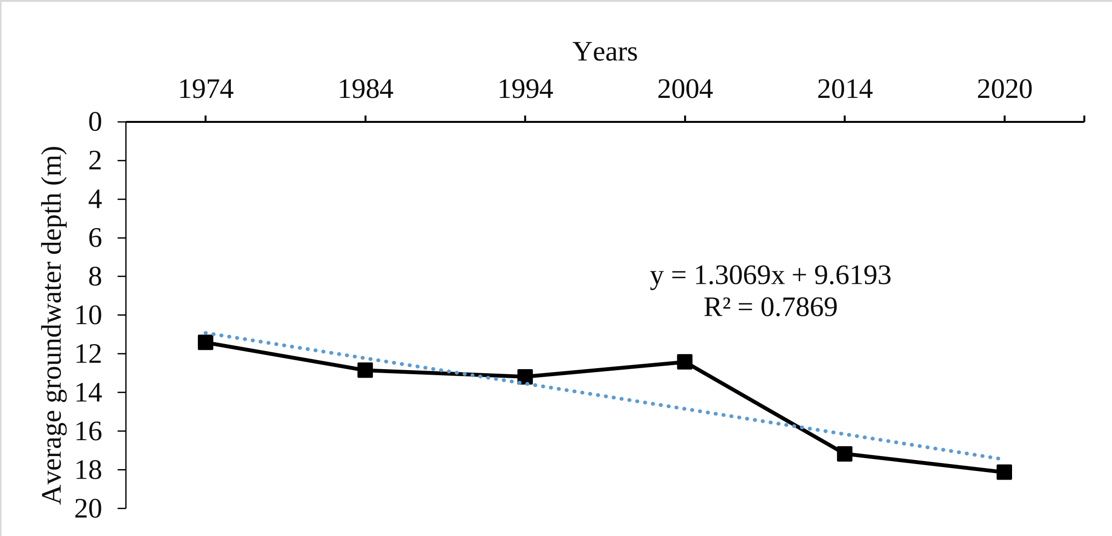


Fig. 4.14: Average groundwater depth of Panchkula district for the period 1974-2020

4.5.4 Yamuna Nagar district: Yamuna Nagar district shows very slight change in groundwater depth from 1974 to 2004 and significant increasing groundwater depth trend after 2004. The trend line shows increasing groundwater depth trend with $R^2 = 0.862$.

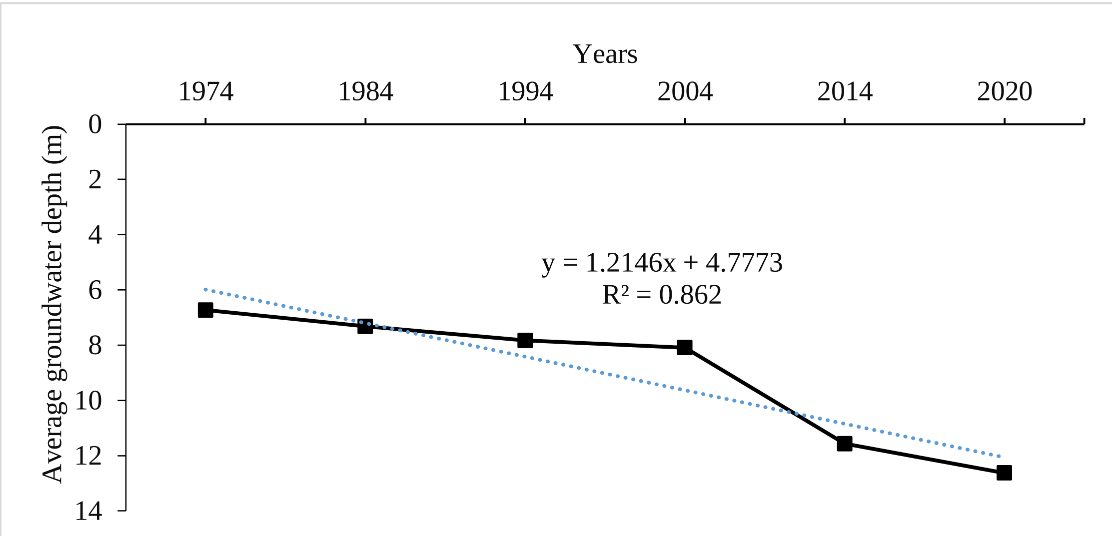


Fig. 4.15: Average groundwater depth of Yamuna Nagar district for the period 1974-2020

4.6 Minimum, Maximum and Average Depth of Groundwater

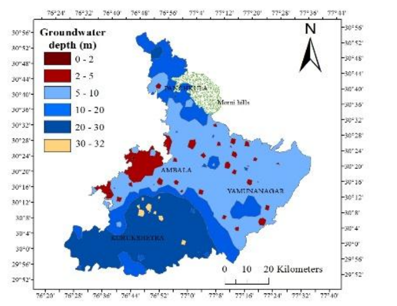
Minimum, maximum and average groundwater depth was calculated from 235 observation wells installed in the study area for the period 1974-2020 and is presented in Table 4.11.

Table 4.11: Minimum, maximum and average groundwater depth (m) of the study area for the period 1974-2020

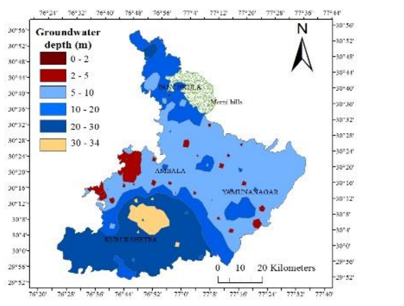
Year	Groundwater depth (m)		
	Average	**Minimum**	**Maximum**
1974	8.95	0.02	24.95
1979	9.42	0	27.28
1984	9.89	0.05	34.55
1989	10.53	0.68	31.95
1994	11.17	0.67	31.7
1999	13.73	1.15	30.73
2004	14.94	0.91	36.45
2009	17.4	1.19	39.33
2014	18.81	1.46	43.23
2020	21.83	1.39	56.16

4.7 Seasonal Effect on Groundwater Depth

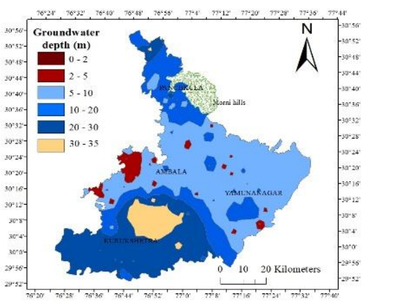
The groundwater depth data is generally recorded twice a year *i.e.*, pre-monsoon (in the month of June) and post-monsoon (in the month of October) because the recharge of groundwater is mainly dependent on rainfall and majority of rainfall in the study area occur during monsoon season. Therefore, to study the seasonal effect spatial distribution maps of pre-monsoon and post-monsoon data for each year from 2001-2020 and are presented in Figures 4.16 and 4.17 respectively.



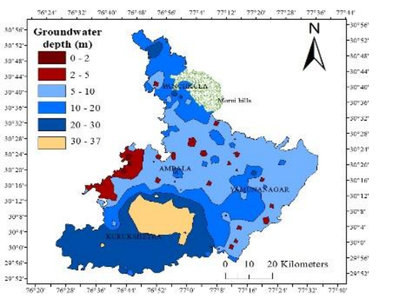
2001



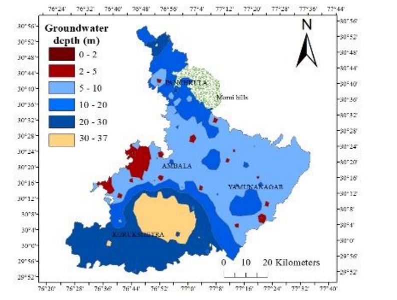
2002



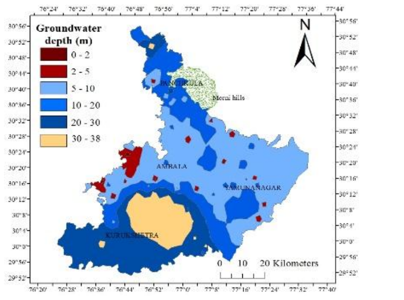
2003



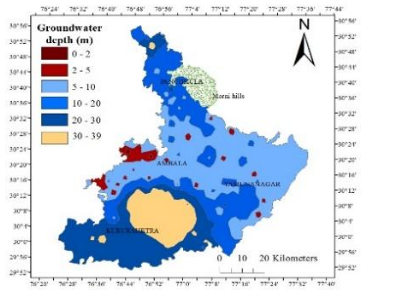
2004



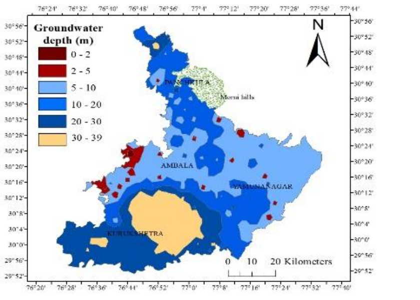
2005



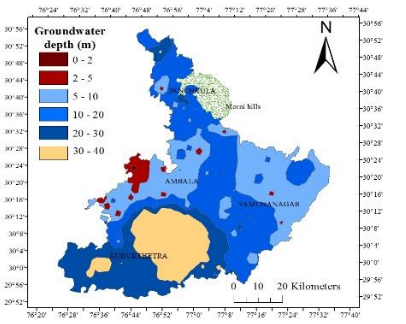
2006



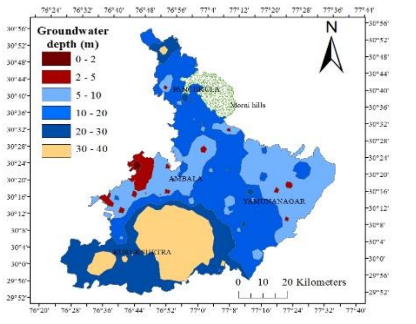
2007



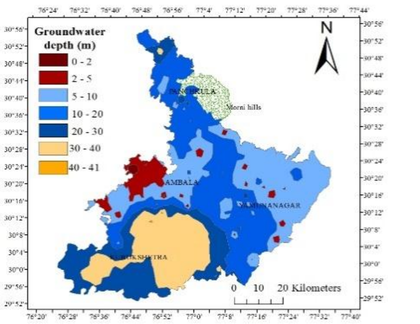
2008



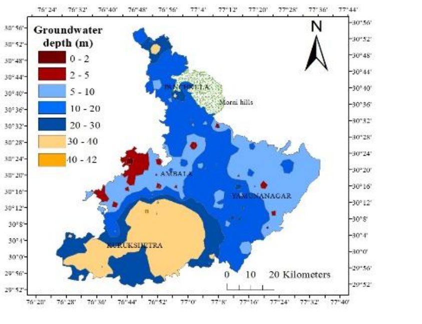
2009



2010



2011



2012

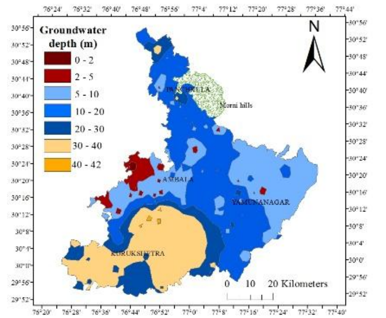
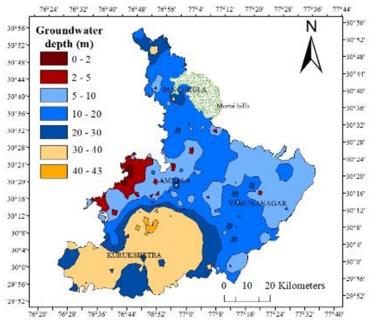
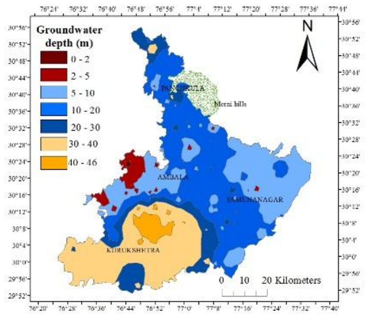
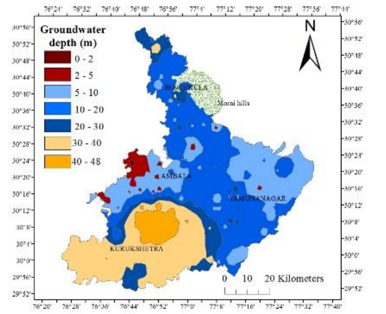
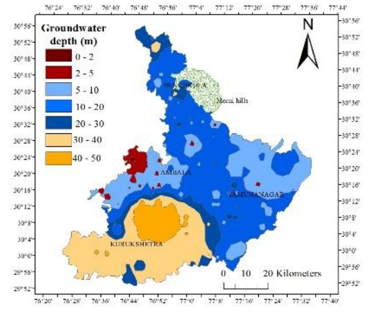
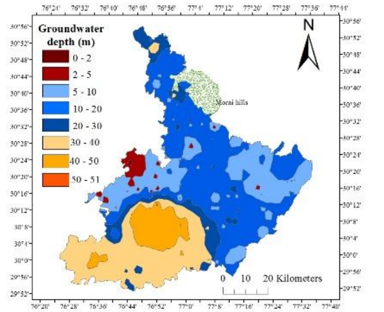
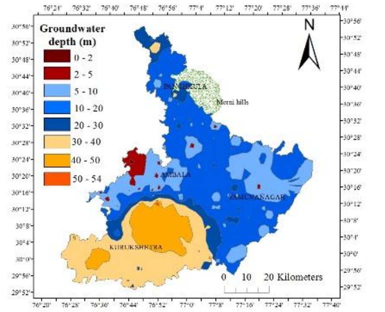
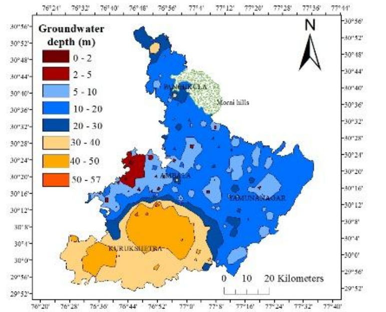
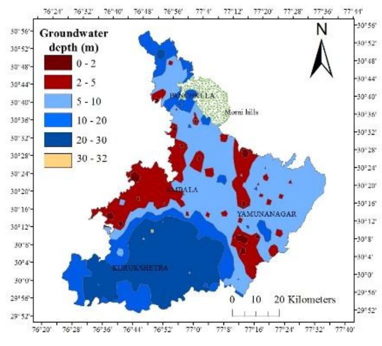
			
2013	2014	2015	2016
			
2017	2018	2019	2020

Fig 4.16: Pre-monsoon annual groundwater depth maps of Northern Haryana for the period 2001-2020



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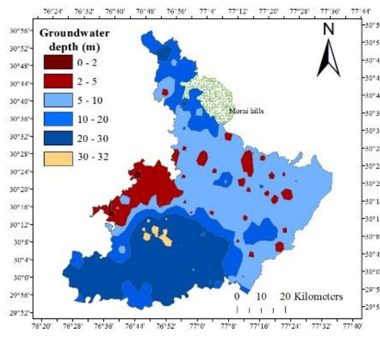

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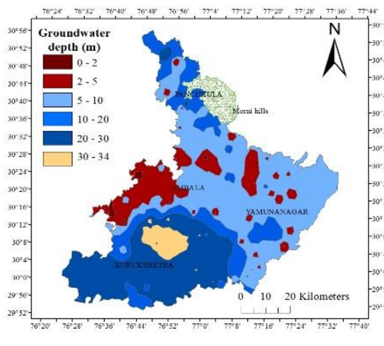

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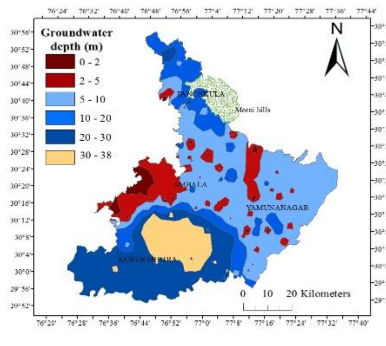

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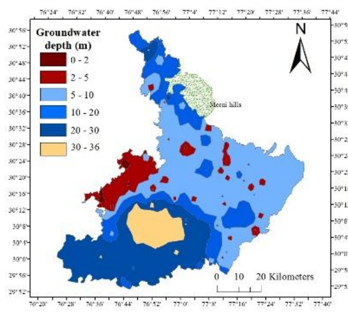

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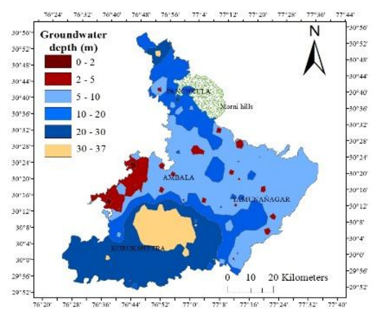

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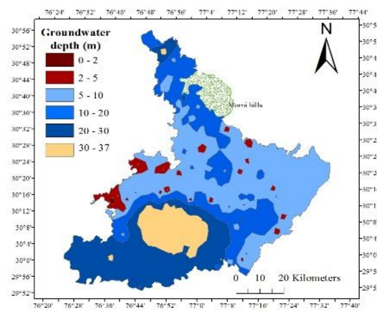

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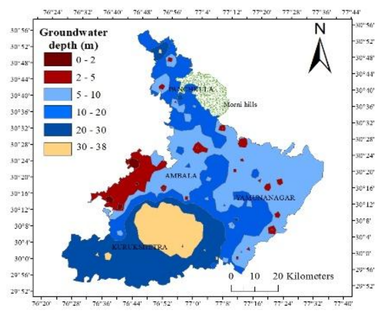

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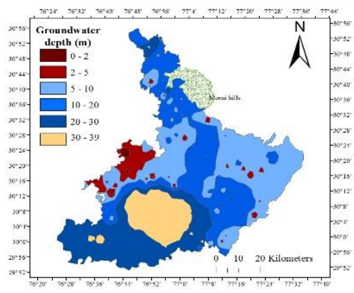

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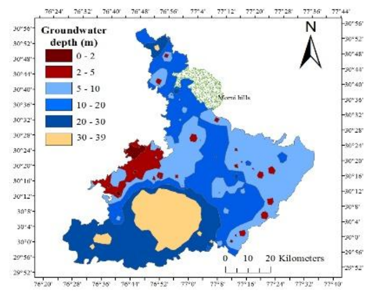

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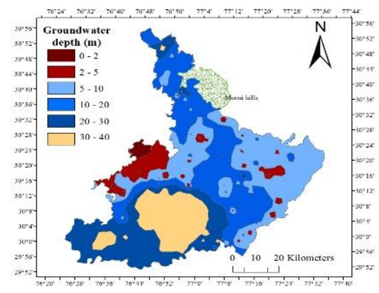

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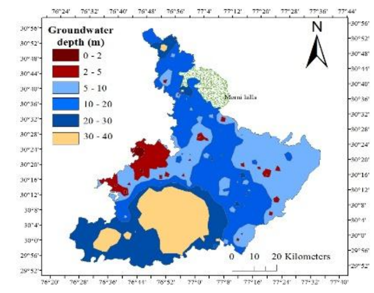

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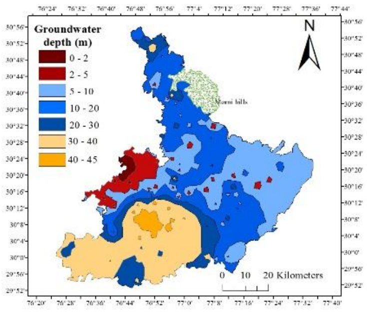	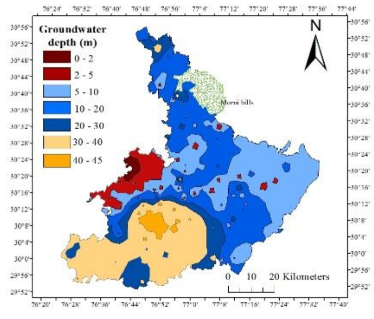	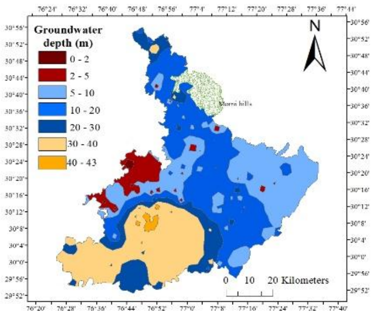	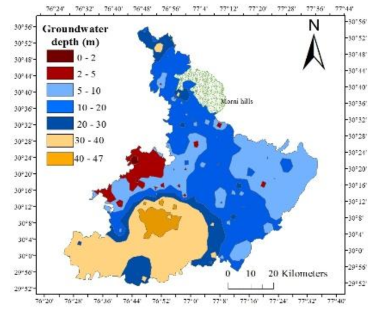
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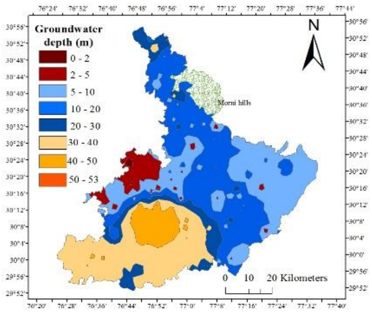	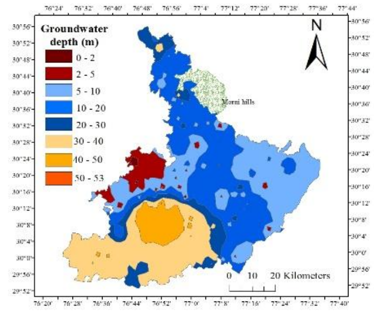	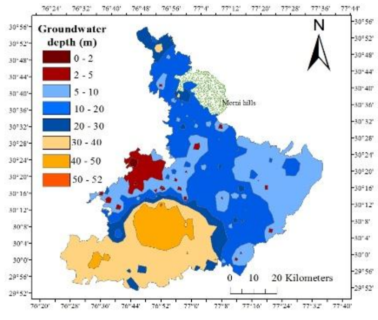	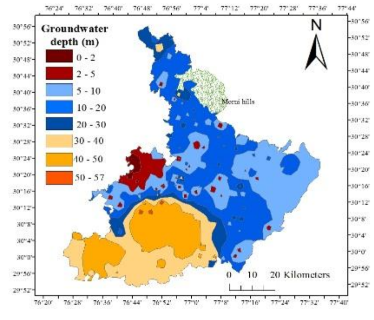
2017	2018	2019	2020

Fig 4.17: Post-monsoon annual groundwater depth maps of Northern Haryana for the period 2001-2020

4.8 Effect of Rainfall on Groundwater Depth Trend

Rainfall is the major source for recharge of the aquifer, so to study the effect of variations in incident rainfall amounts, graph was plotted between average annual rainfall and time period to observe the rainfall trend over the study period in the study area and is shown in Fig. 4.18. The average annual rainfall of study area for the period 1974-2020 was calculated by Weighted Mean Average of average annual rainfall of all four districts of the study area and is shown in Appendix I. To analyze the effect of rainfall trend on groundwater depth trend another graph was plotted between minimum, maximum and average groundwater depth and average annual rainfall with respect to time and is shown in Fig 4.19.

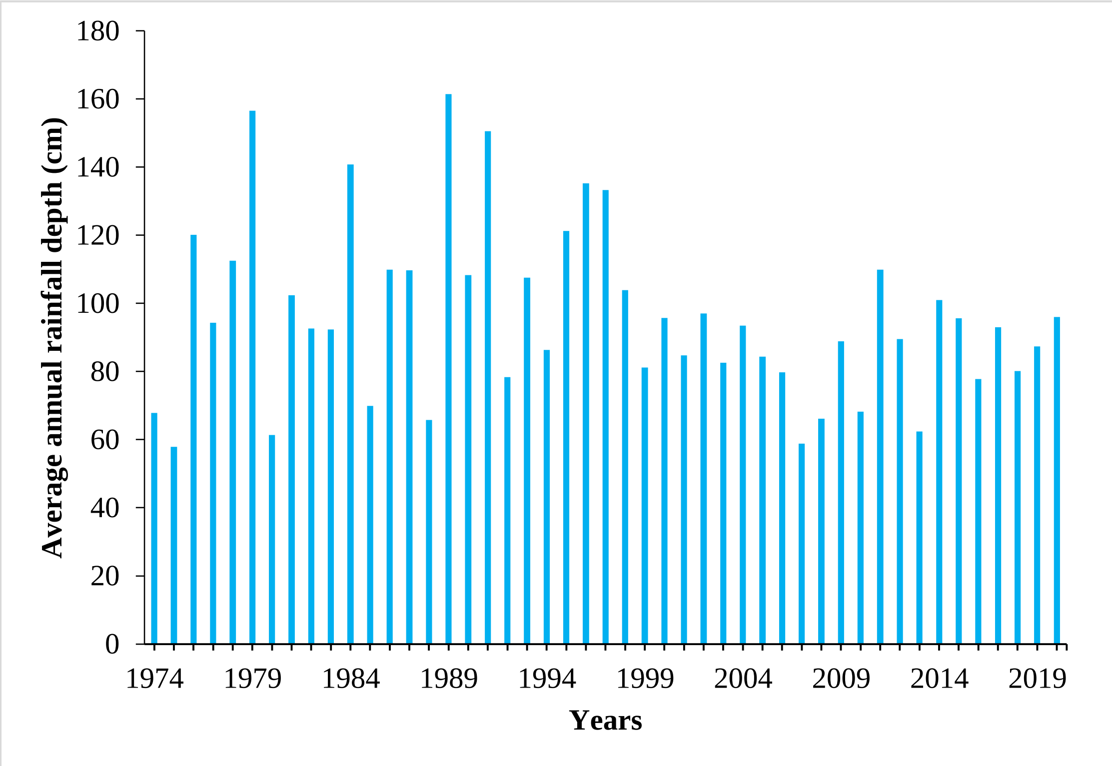

Fig. 4.18: Average annual rainfall (cm) of Northern Haryana for the period 1974-2020

The average annual rainfall depth graph with respect to time period shows that the rainfall shows no particular trend and is fluctuating during the study period i.e from 1974-2020, with maximum and minimum annual rainfall of 161.4 cm and 57.8 cm observed in the year 1989 and 1975 respectively. The mean annual rainfall of the area was observed to be 96.32 cm for the period 1974-2020.

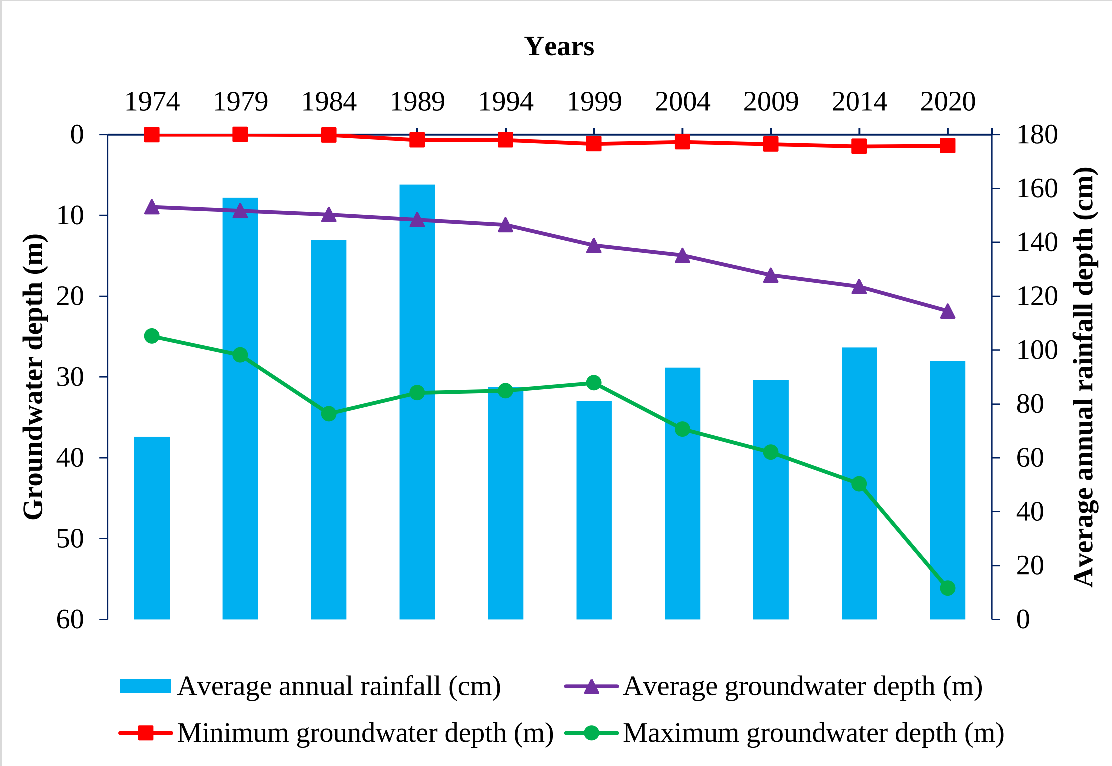

Fig. 4.19: Minimum, maximum and average groundwater depth (m) and average annual rainfall (cm) of Northern Haryana for the period 1974-2020

4.9 Statistical Analysis

To analyze the groundwater depth trend and to detect abrupt change points in the groundwater depth data parametric and non-parametric statistical tests were applied respectively using MS-Excel and XL-STAT softwares.

4.8.1 Parametric tests: Mann-Kendall Test and Sen's Slope estimator were applied on the groundwater depth data to analyze the trends and the results so obtained were spatially distributed for the entire study area and map was prepared using ArcGIS 10.3 software for better analysis and is shown in Fig. 4.20 and 4.21 respectively.

The Mann-Kendall test showed that the groundwater table is rising in western part of the study area (*i.e.*, western parts of Ambala district) and in some patches in north-eastern part. Whereas, majority of the study area, the groundwater level is significantly decreasing.

The Sen's slope estimator showed that the groundwater table is rising in western part of the study area (*i.e.*, western parts of Ambala district). Water table is decreasing significantly in south-western part and central parts of Kurukshetra while in Yamuna Nagar and Panchkula it is falling at a lower rate. The majority of study area showed falling trends.

Both Mann Kendall Test and Sen's Slope estimator showed results which are in good agreement with each other.

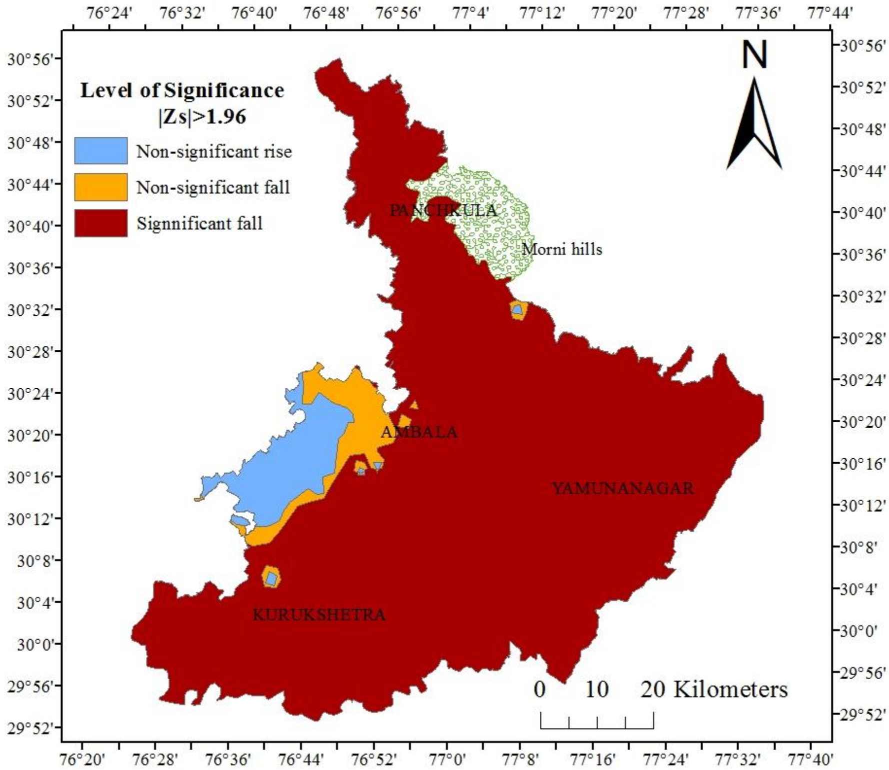

Fig. 4.20: Mann-Kendall's Statistic (Z_S) value for the period 1974-2020

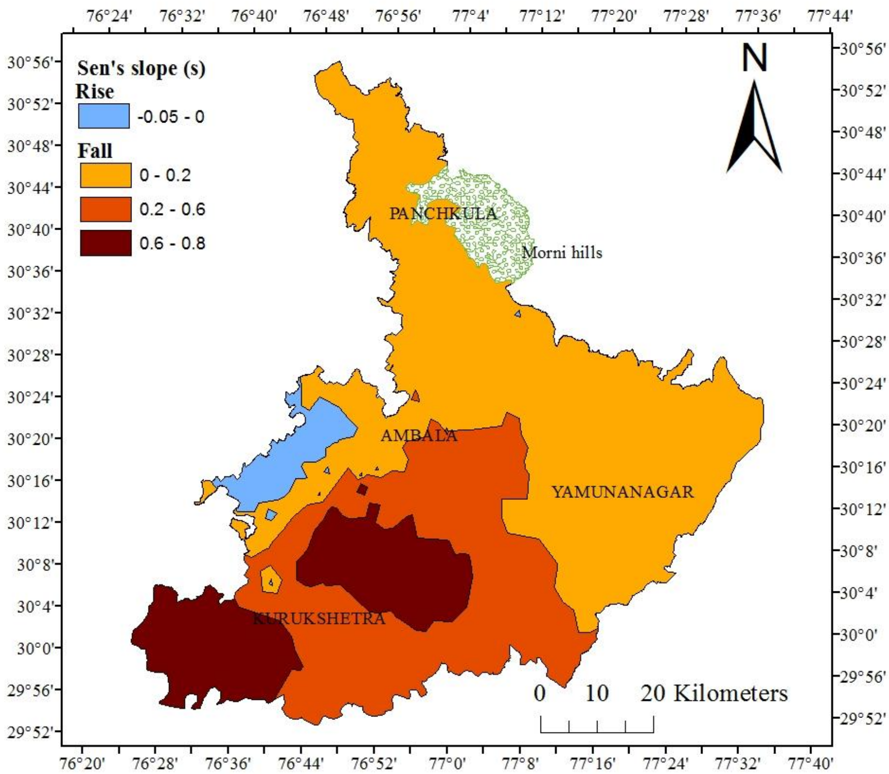

Fig. 4.21: Sen's slope estimator statistic (S) value for the period 1974-2020

4.8.2 Non-parametric Tests

The non- parametric test, Linear Regression was conducted to detect the trends in groundwater level and Pettitt, Buishand and Standard Normal Homogenity test were conducted to detect the abrupt change points in the groundwater level trends. The results of linear reression were spatially distributed for the entire study area and map was prepared using ArcGIS 10.3 software for better analysis and is shown in Fig. 4.22. The Linear regression showed that the groundwater depth is rising in eastern and western part of the study area, while rest of the area showed falling trend. The results of blocks which showed significant abrupt change points by using Pettitt test, Buishand test and Standard Normal Homogenity test are presented in Table 4.12.

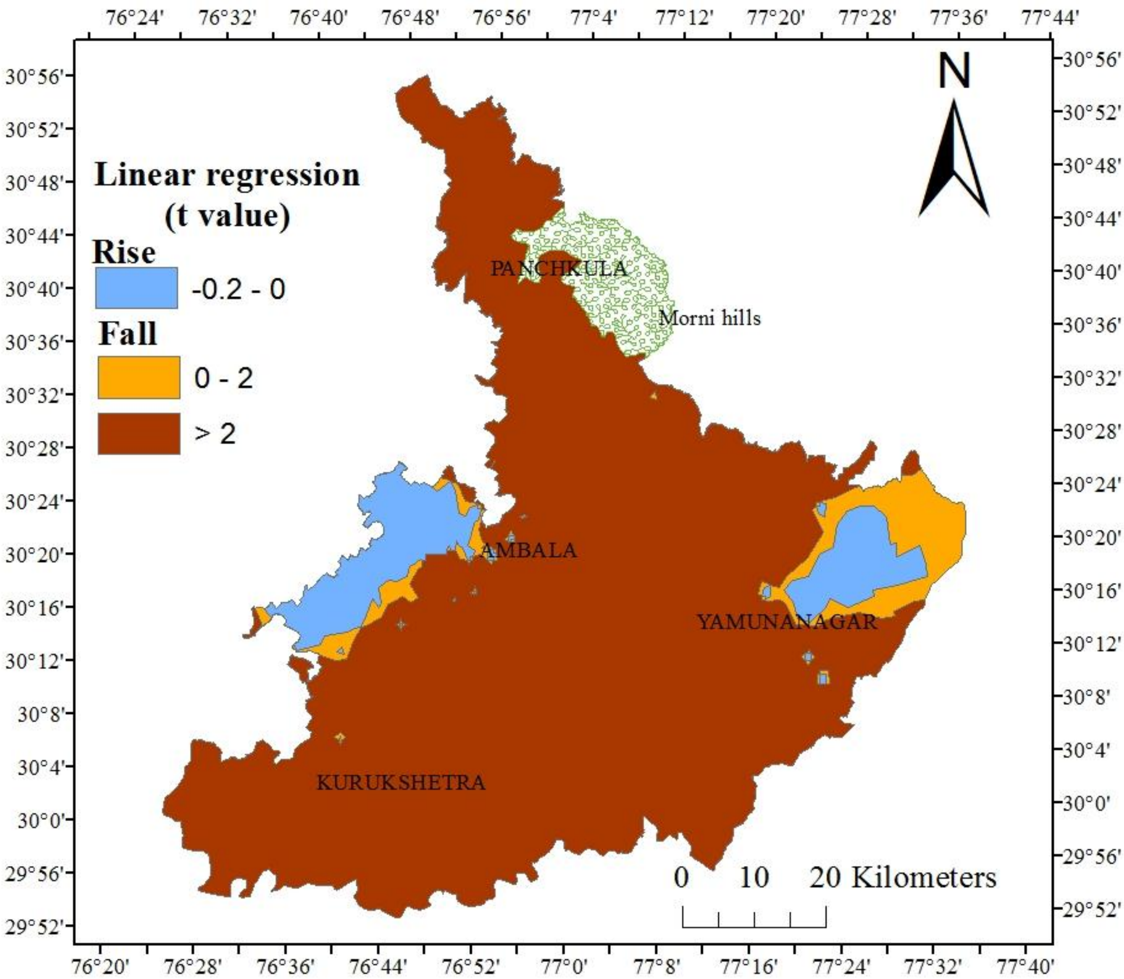

Fig. 4.22: Linear regression t value for the period 1974-2020

Table 4.12 : Pettitt test, Buishand test and Standard Normal Homogenity test

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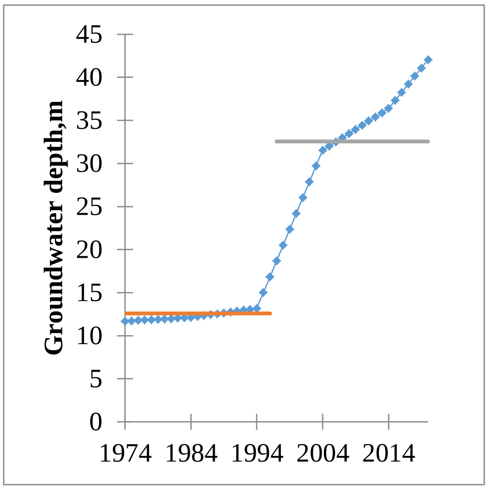
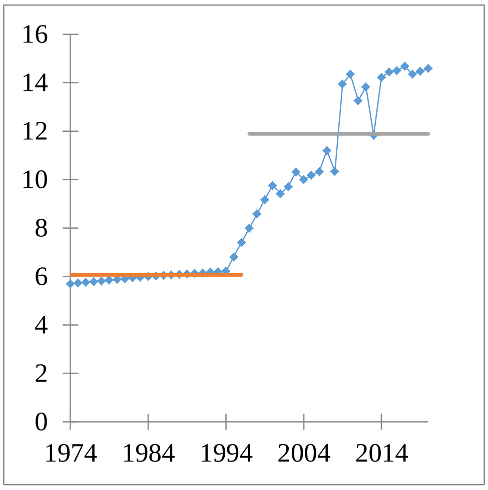
<tr><td>Pettitt's test</td><td>
</td><td>
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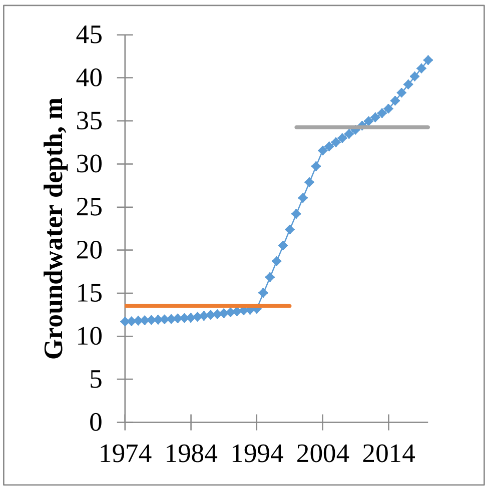
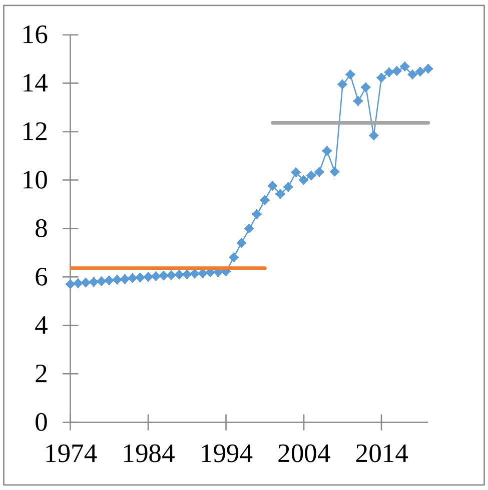
<tr><td>SNHT test</td><td>
</td><td>
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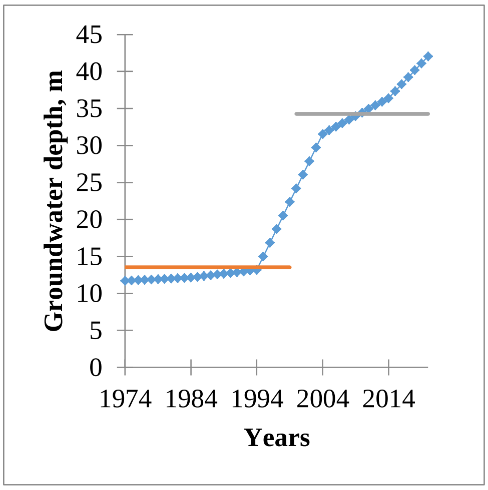
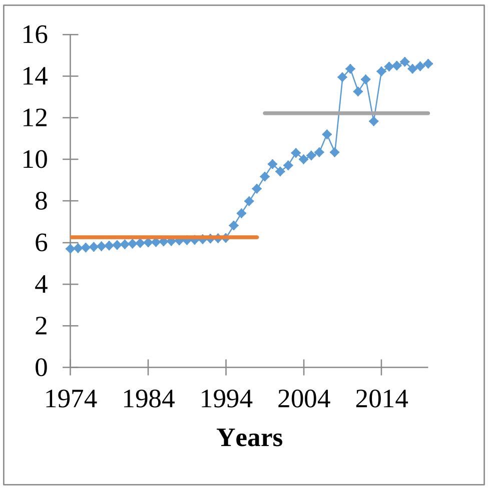
<tr><td>Buishand test</td><td>
</td><td>
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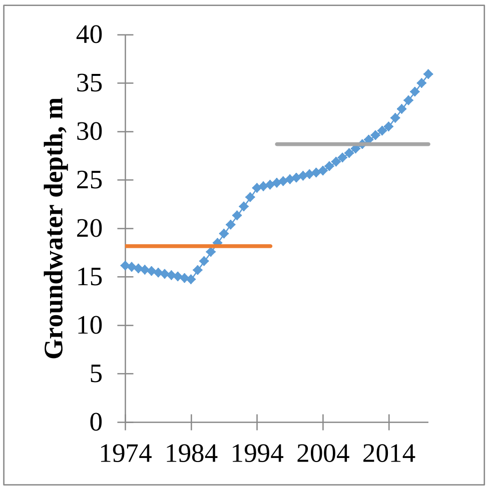
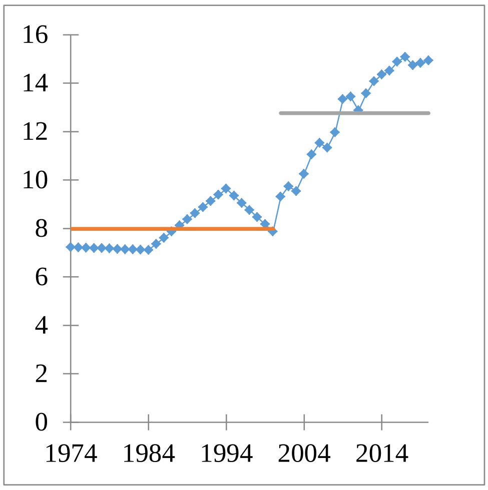
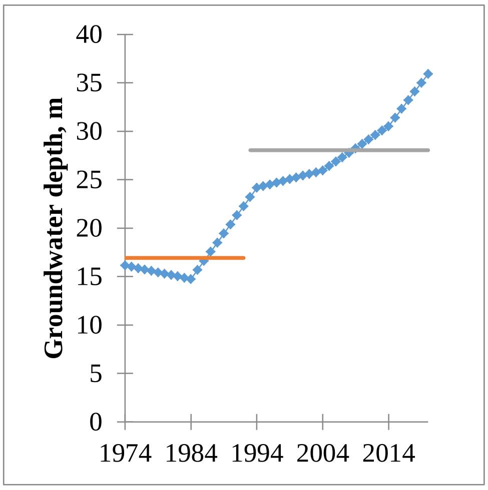
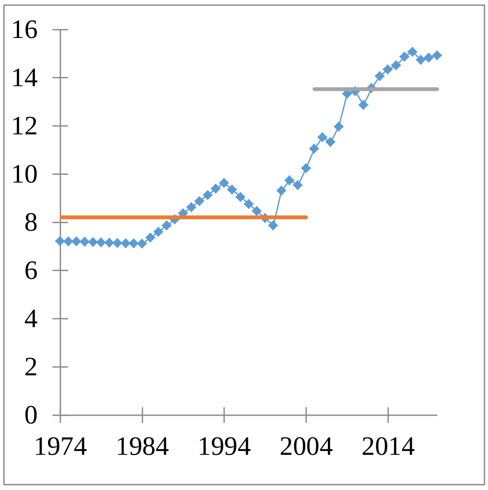
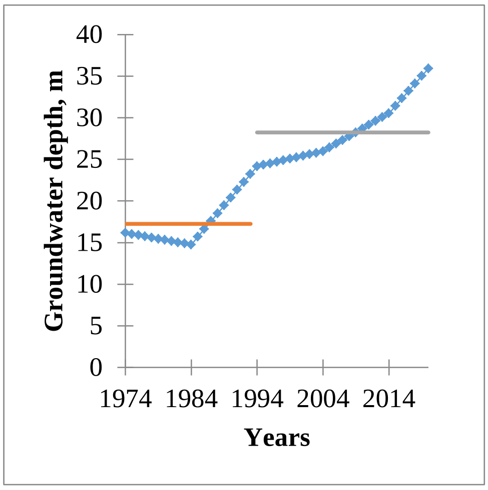
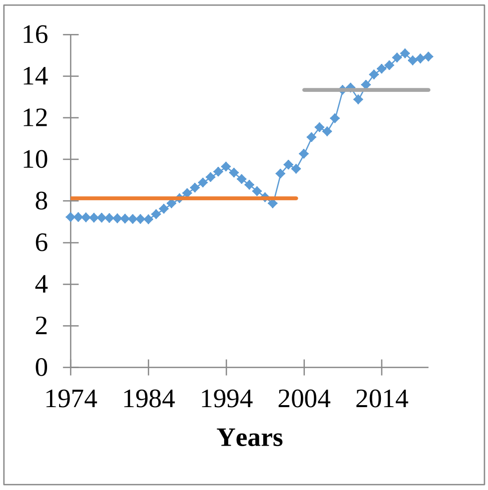
Pettitt's test		
SNHT test		
Buishand test		

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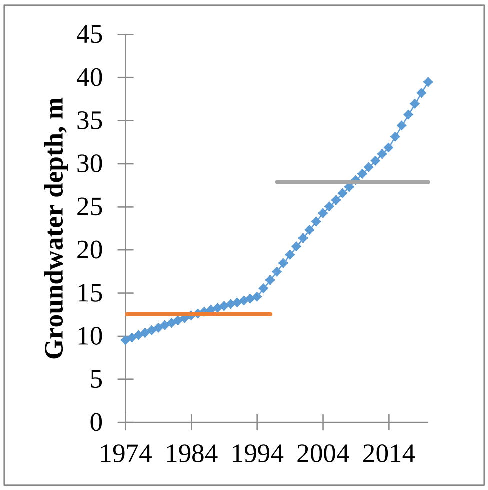
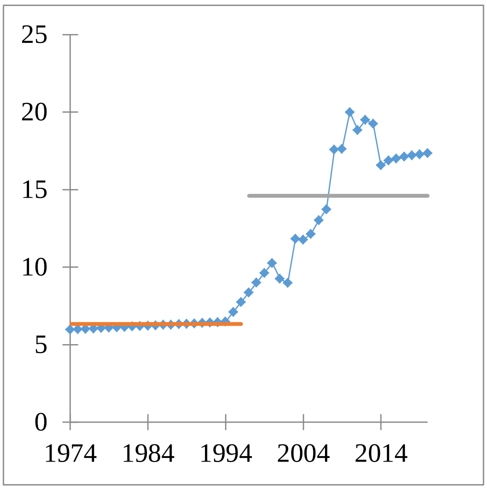
<tr><td>Pettitt's test</td><td>
</td><td>
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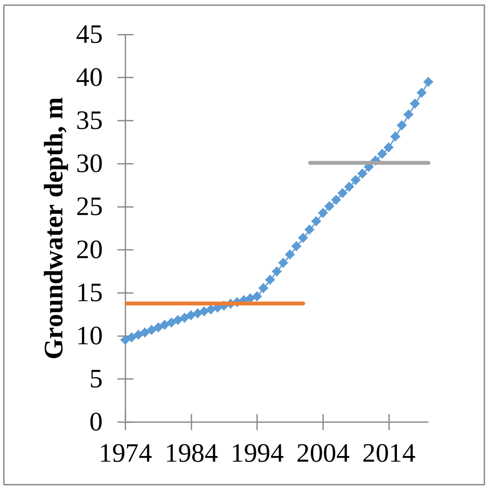
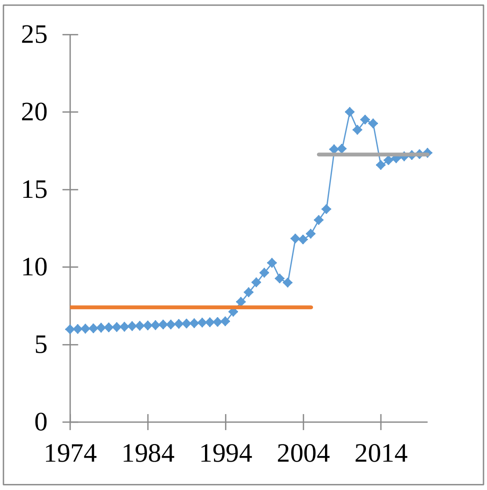
<tr><td>SNHT test</td><td>
</td><td>
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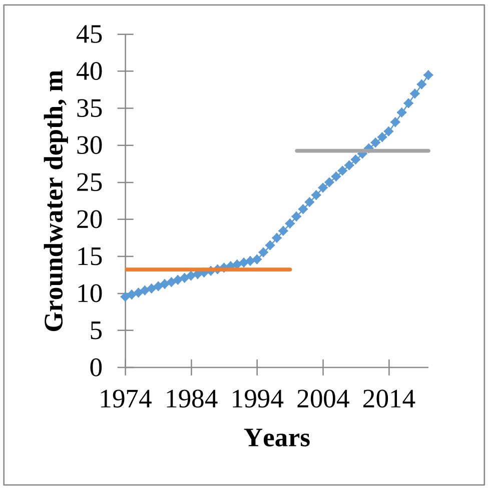
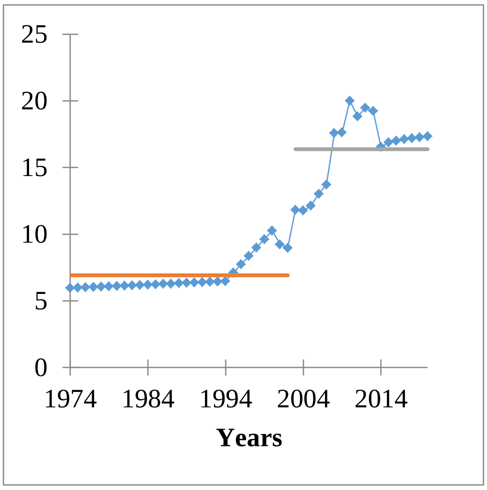
<tr><td>Buishand test</td><td>
</td><td>
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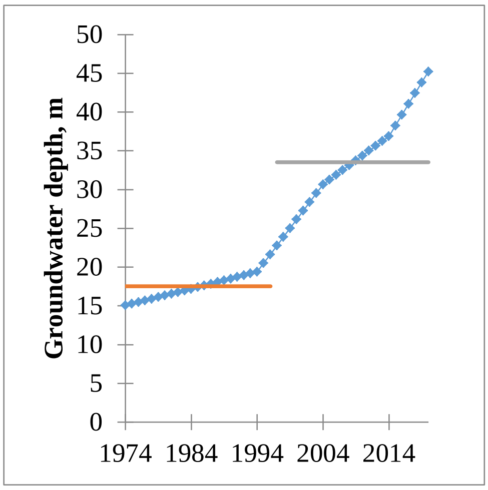
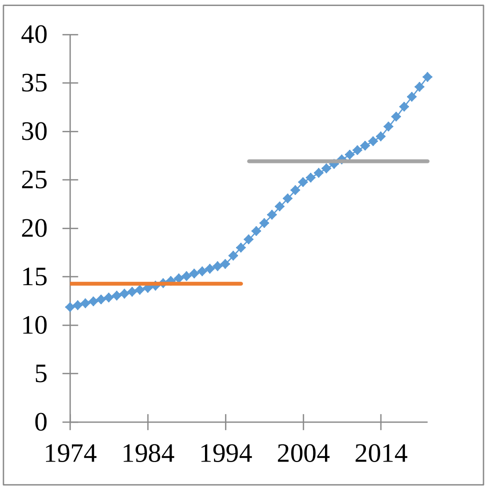
<tr><td>Pettitt's test</td><td>
</td><td>
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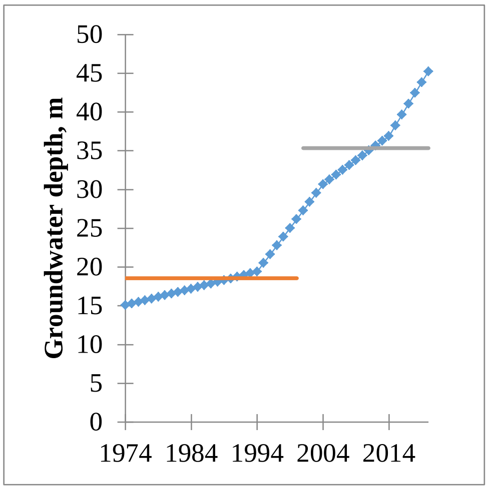
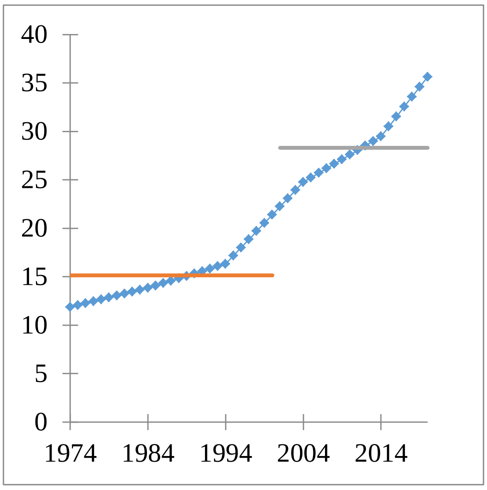
<tr><td>SNHT test</td><td>
</td><td>
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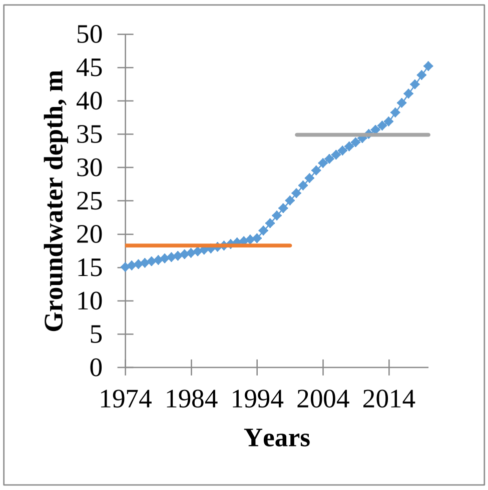
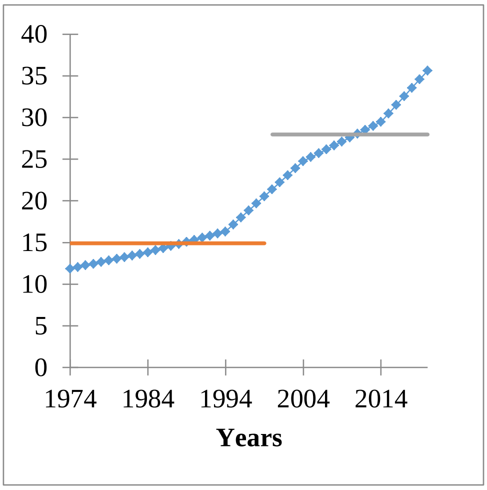
<tr><td>Buishand test</td><td>
</td><td>
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The Pettitt test, Buishand test and Standard Normal Homogenity test was applied to each block of the study area and the blocks which showed significant abrupt change points according to these tests are shown in Table 4.12, whereas the rest of the blocks showed no significant abrupt change points. In Table 4.12, the red and grey horizontal line indicate abrupt change points, and the corresponding values at X and Y axis denote the change point year and groundwater depth (m) respectively. The Pettitt test, Buishand test and Standard Normal Homogenity test show results which are in good agreement with each other.

CHAPTER V

DISCUSSIONS

In this chapter the results of the present study "Trend Analysis of Groundwater Levels in Northern Haryana, India" are discussed and the correlation of various climatic and anthropogenic factors with groundwater depth is discussed.

5.1 Groundwater Depth Fluctuation of Northern Haryana

5.1.1 Spatial and temporal variation of groundwater depth

The spatial distribution maps of groundwater depth at 10 year interval for the study period 1974-2020 were prepared as shown in Figures 4.1 to 4.6. On comparing maps of the years 1974, 1984, 1994, 2004, 2014 and 2020, it is observed that the majority of study area showed decline in groundwater levels with maximum decline in Kurukshetra followed by Panchkula, Yamuna Nagar and Ambala. However, western parts of Ambala district (Ambala I and Ambala II blocks) showed rising trend of groundwater level. The minimum and maximum groundwater depths in north Haryana ranged from 0 m to 1.46 m and 24.95 m to 56.16 m, respectively during the period of 1974-2020 (Table 4.11).

5.1.2 Change in area under different groundwater depths

Analysis of area under different groundwater depth (Table 4.7) revealed that the area under shallower depth *i.e.*, 2-5 m has reduced from 8% in 1974 to 2.1% in 2020 and the area under 5-10 m groundwater depth reduced from 56.07% in 1974 to 14% in 2020. However the area under 10-20 m groundwater depth increased from 35.72% in 1974 to 46.1% in 2020. The area under deeper groundwater depths *i.e.*, 30-40 m and 40-50 m was 17 and 11.9%, respectively in the year 2020, where as in 1974 there was no area under these depths. In 1974 the maximum area lied under 5-10 m depth (56.07%), whereas in 2020 the maximum area lied under 10-20 m groundwater depth (46.1%). This shows the shifting of groundwater depth from shallower to deeper. During the study period the groundwater has been over-exploited mainly for irrigation needs, which demands adoption of low water requiring crops like millets in place of paddy, to ensure sustainability of groundwater. To observe the variation in area under different depths of the study area, graph between area under different depths and time period was plotted, as shown in Fig. 5.1.

5.1.3 Spatial variation of groundwater fluctuations

Figures 4.7 to 4.11 represent the spatial variation of groundwater depth fluctuation for 10, 20, 30, 40 and 47 year interval by taking 1974 as the reference year *i.e.*, for the years 1974-1984, 1974-1994, 1974-2004, 1974-2014 and 1974-2020.

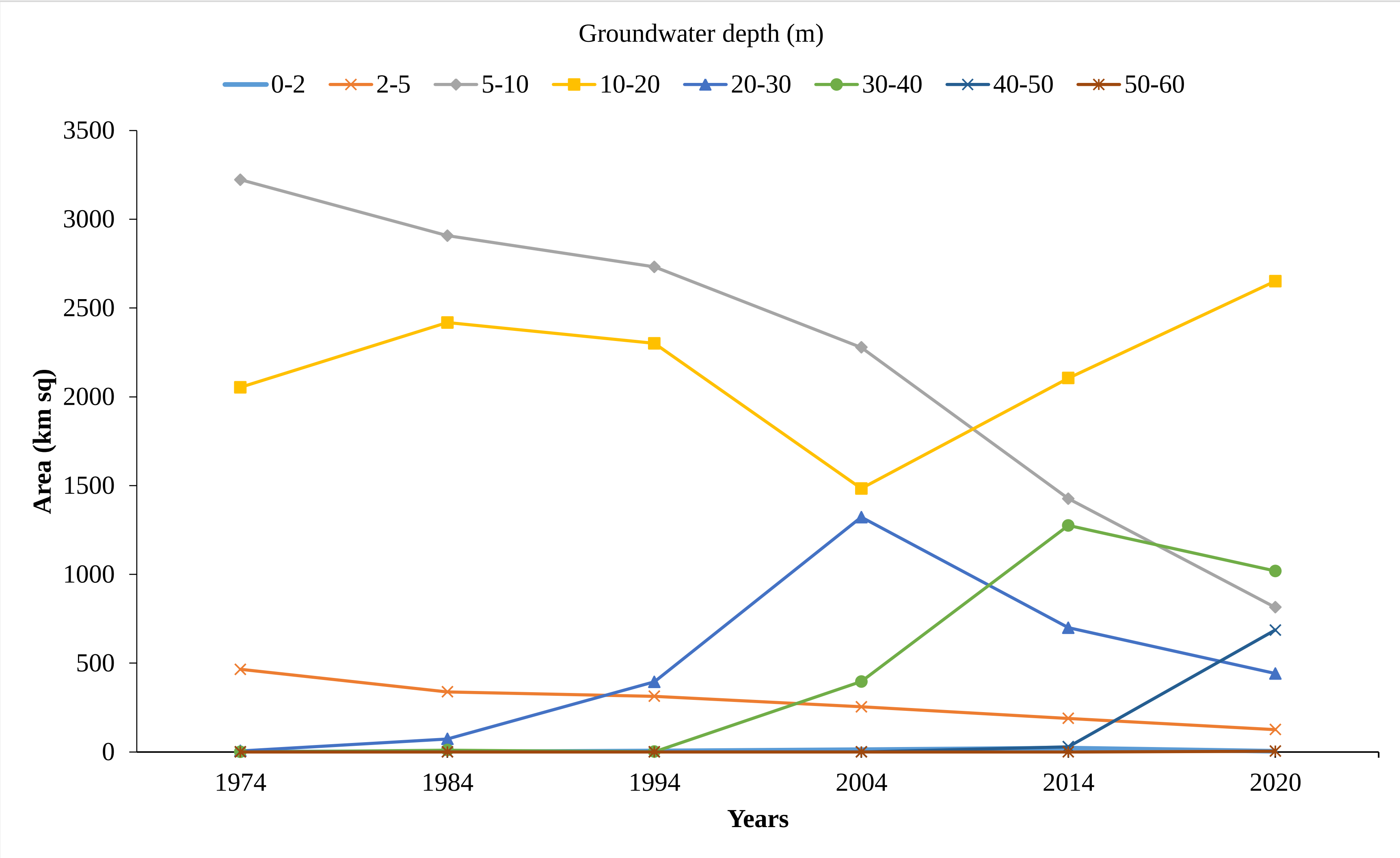

Fig. 5.1: Area under different groundwater depths (m) in Northern Haryana for the period 1974-2020

To further analyze the fluctuation, block wise graphs were plotted between groundwater fluctuation depth and time period and are shown in Figures 5.2 to 5.5. District wise fluctuation graph is shown in Fig. 5.6.

In Ambala district, maximum positive fluctuation was observed in Ambala II block (34 cm, +ve representing rise in water table) during the period 1974-2014, while maximum negative fluctuation was observed in Saha block (- 982 cm, -ve representing fall in water table) during 1974-2020. Positive fluctuation was only observed in Ambala II block till 2014, but after that even in that block, negative fluctuation was seen.

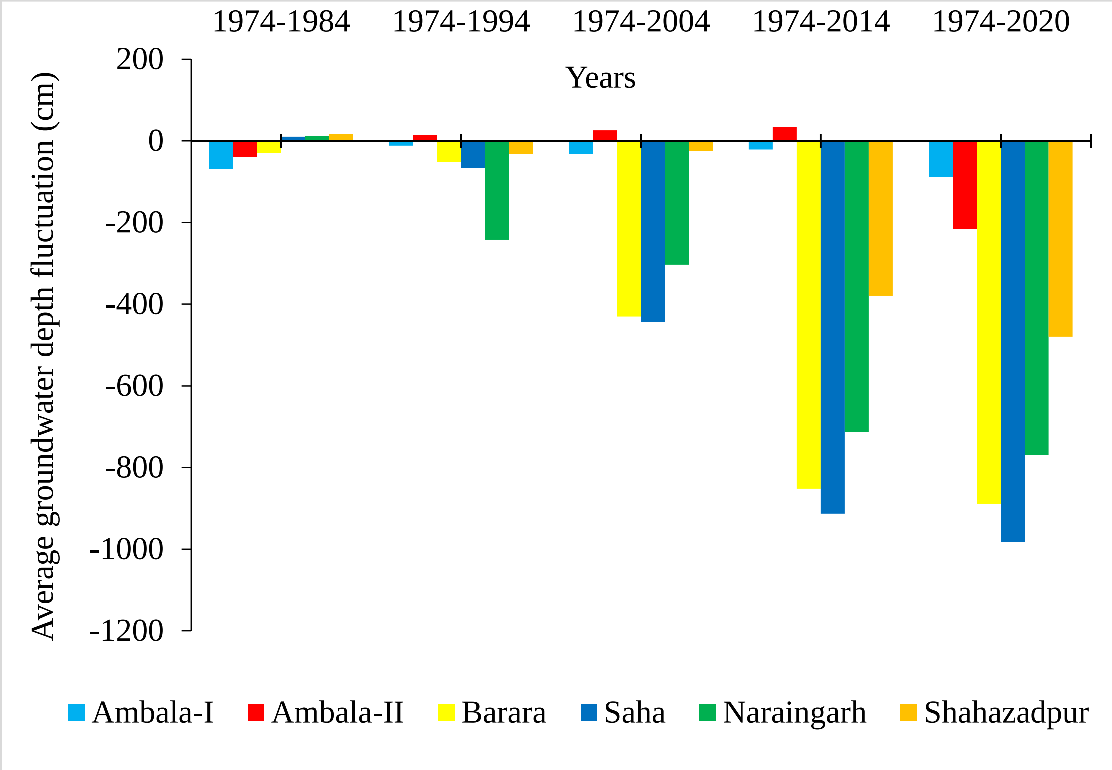

Fig. 5.2: Block-wise average groundwater depth fluctuation for Ambala district

In Kurukshetra district, the maximum negative fluctuation was observed in Babain block (- 3036 cm) during 1974-2020. Maximum positive fluctuation was observed in Ladwa block (142 cm) during 1974-1984, but after that Ladwa block also showed negative fluctuation. Overall maximum fluctuation was observed in Babain block while minimum fluctuation in Ladwa block.

In Panchkula district, negative fluctuation was seen in all blocks. Maximum (- 733 cm) as well as minimum (- 47 cm) fluctuation was seen in Raipur Rani block during 1974-2020 and 1974-1984 respectively.

For Yamuna Nagar block, maximum positive fluctuation was seen in Sadhoura block (174 cm) during 1974-2004 while maximum negative fluctuation was seen in Radour block (-1138 cm) during 1974-2020.

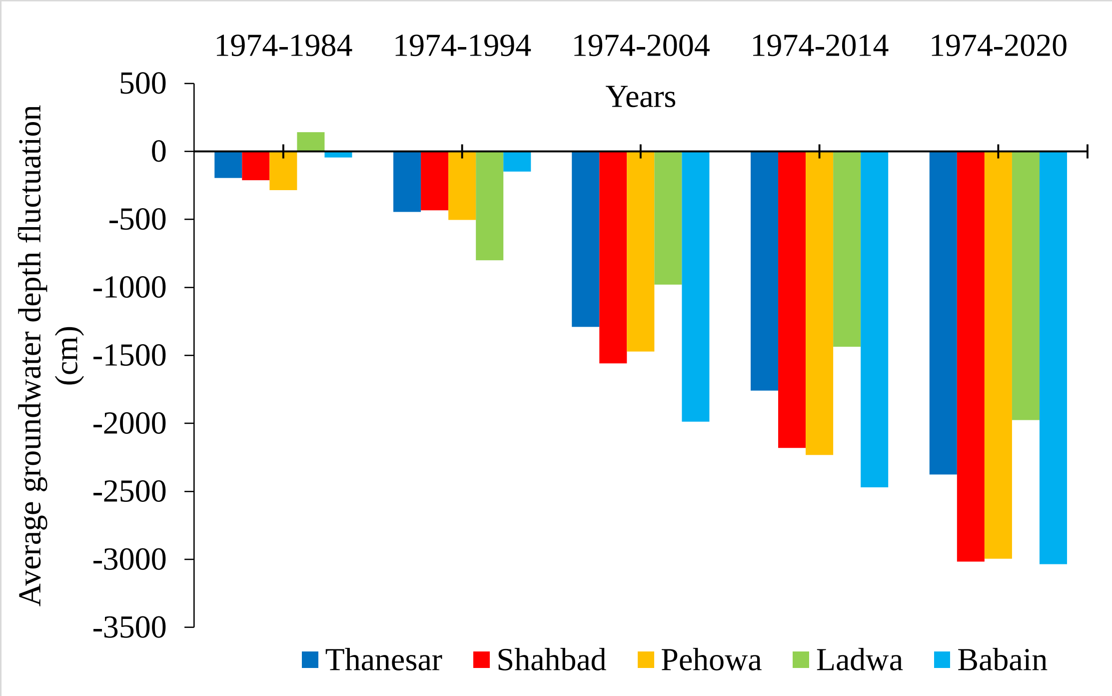

Fig. 5.3: Block-wise average groundwater depth fluctuation for Kurukshetra district

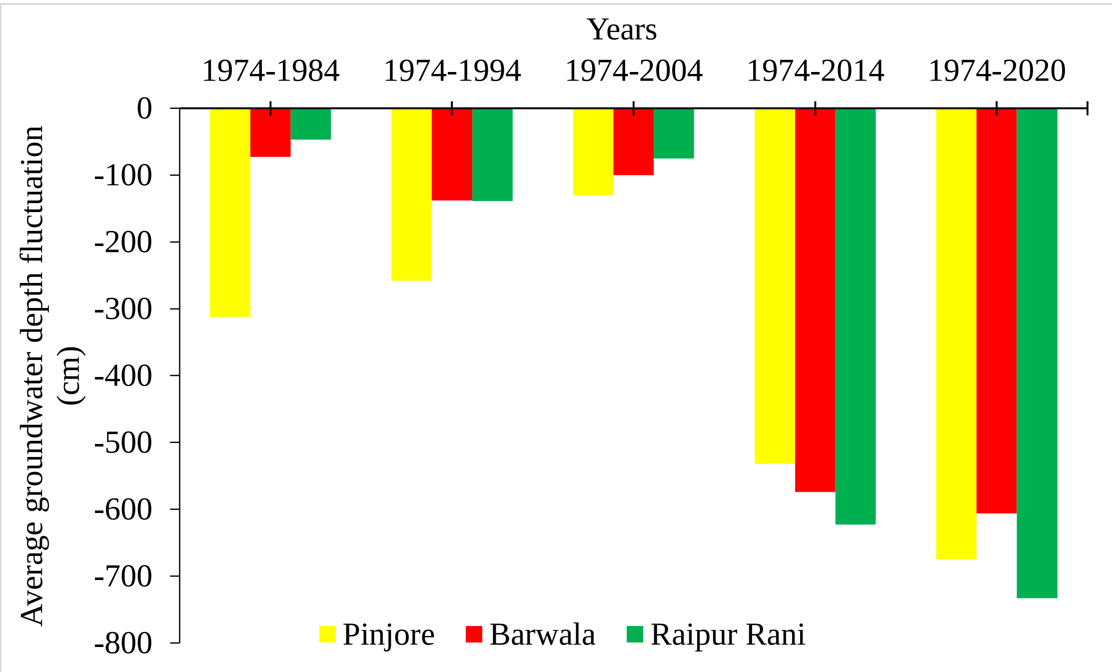

Fig. 5.4: Block-wise average groundwater depth fluctuation for Panchkula district

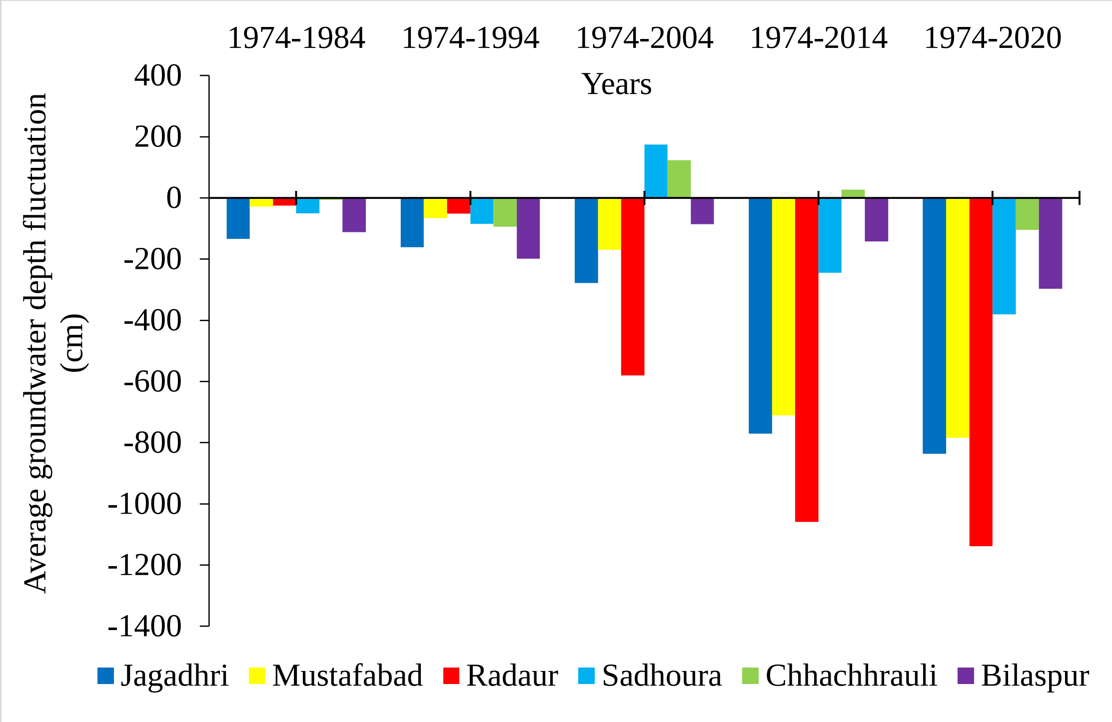

Fig. 5.5: Block-wise average groundwater depth fluctuation for Yamuna Nagar district

All the four districts showed negative fluctuation (-ve representing fall in water table). For the period 1974-2020, the average fluctuation ranged from -2680 cm (Kurukshetra) to -571 cm (Ambala), which was calculated on the basis of 235 observation wells located in the study area. Maximum fluctuation was seen in Kurukshetra district (-2680 cm) in the period 1974-2020, whereas minimum fluctuation was seen in Ambala district (-16.7 cm) in the period 1974-1984.

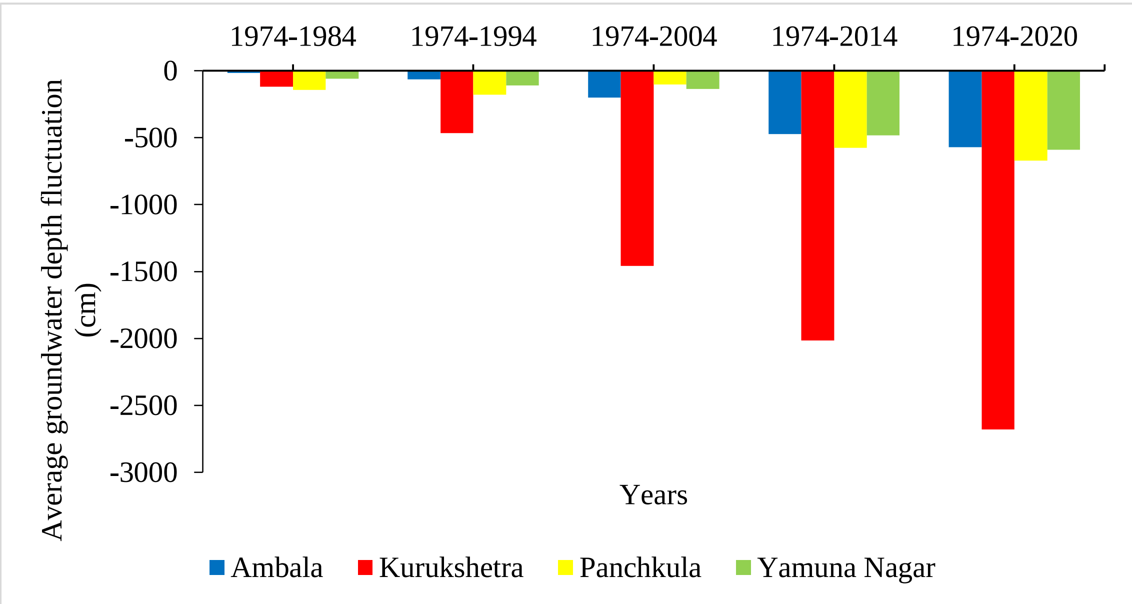

Fig. 5.6: District-wise average groundwater depth fluctuation for Northern Haryana

5.1.4 Overall trend of groundwater level

The groundwater table in North Haryana declined at an average rate of 27.4 cm per year. Highest declining trend was observed for Kurukshetra with an average rate of 57.02 cm per year, followed by Panchkula (14.27 cm per year), Yamuna Nagar (12.55 cm per year) and Ambala (12.14 cm per year). The highest decline in Kurukshetra is because of increasing intensive rice cultivation by groundwater irrigation (Singh *et al*., 2015). Average fluctuation graph of Northern Haryana is shown in Fig. 5.7. The average fluctuation graph of Northern Haryana for the period 1974-2020, revealed declining trend of groundwater levels. Table 4.9 shows the percentage of area lying under different groundwater depth fluctuation for the period 1997-2020. It reveals that the maximum area (43.82%) lies in the range of -10 to 0 m, whereas the minimum area (0.04) lies in the range of 5 to 8 m fluctuation.

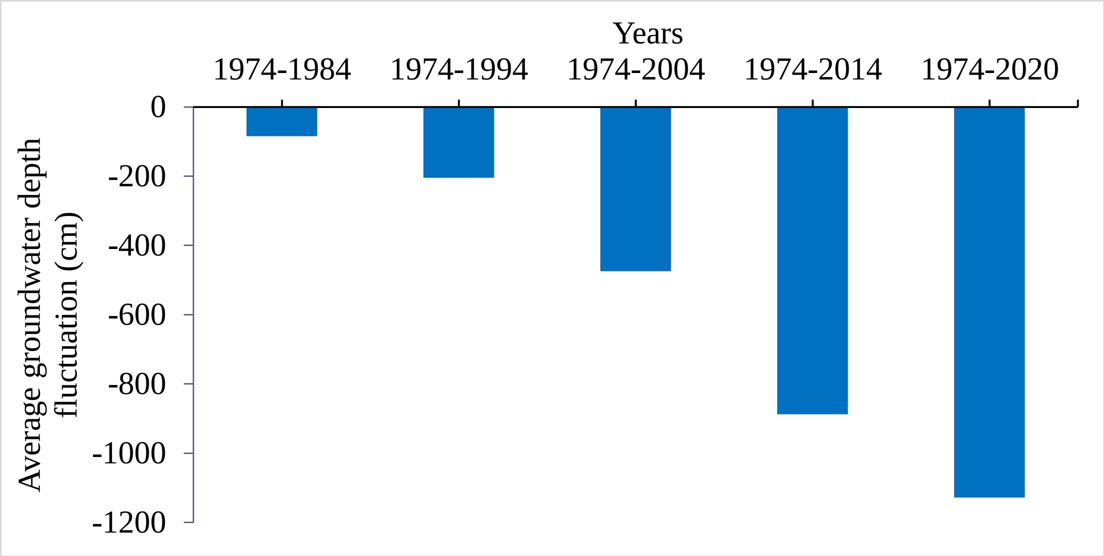

Fig. 5.7: Average groundwater depth fluctuation for Northern Haryana

5.2 Major Natural and Anthropogenic Factors Affecting Groundwater Depth in Northern Haryana

Spatial and temporal analysis of groundwater levels is important for planning of groundwater use in a sustainable manner. Some anthropogenic factors (number of tube wells, irrigation practices and cropping patterns), forest area and climatic factor (rainfall) were analyzed to study their dependence on groundwater level trends. Their correlation with respect to groundwater levels was also computed.

5.2.1 Impact of annual rainfall on groundwater level

To analyze the effect of rainfall trend on groundwater depth, a graph was plotted between average groundwater depth and average annual rainfall with respect to time and is shown in Fig 5.8, which shows that despite very much fluctuation observed in rainfall over the years, the groundwater depth is seen to be increasing continuously. So we can say that, rainfall trend do not have any impact on the groundwater depth trend over the study period, because the increasing groundwater depth trend is because of the increasing extraction and over-exploitation of groundwater resources. Although rainfall is the major source of groundwater recharge (Prakash, 2005), the present day extraction needs are fulfilled by the water stored in the aquifers over hundreds of years and not by the yearly recharge by rainfall. Also, the yearly recharge by monsoon rains is insufficient to balance the current extraction patterns. However, rainfall has seasonal effects on the groundwater depth as shown in Fig. 4.16 and Fig. 4.17. Chen *et al.*, (2004) also found that the weakest correlation exist between groundwater level and climatic parametrs. Panda *et al.*, (2012) and Whittemore *et al.*, (2016) also proved weak correlation between groundwater level and climatic parameters in Gujarat and USA, respetively. Singh *et al.*, (2016) found that groundwater level show poor response to incident rainfall in the Kurukshetra district of Haryana. However, Sivarajan *et al.*, (2019) reported groundwater decline show coherent variability with evapotranspiration and temperature in the Ahmednagar district of Maharashtra. So, increase in temperature can result in increased crop water requirements leading to stress on groundwater resources.

To balance the ever increasing extraction of groundwater, there is need for artificial recharge methods and plans to reduce the groundwater consumption.

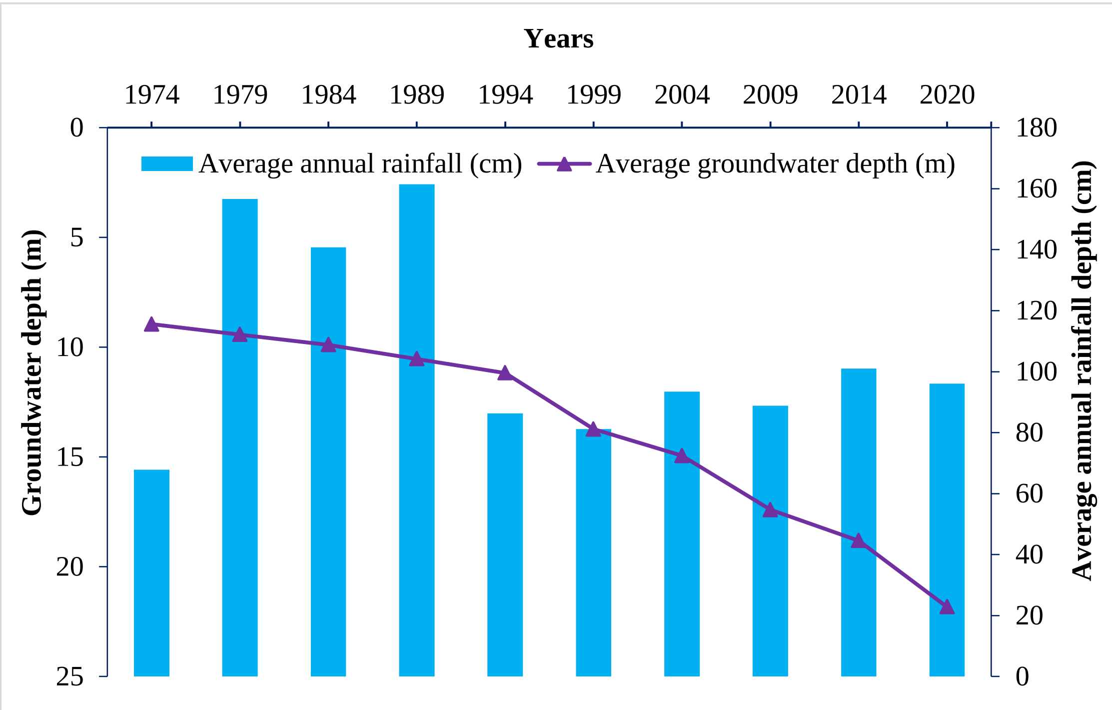

Fig. 5.8: Average groundwater level (m) with average annual rainfall (cm) for the period 1974-2020

5.2.2 Impact of number of tube wells on groundwater level

As the number of tubewells in the Northern Haryana is continuously increasing, it is the prime driver of groundwater level changes in the area. Rodell *et al.,* (2009) revealed that depletion of groundwater resources in India is mainly due to tubewell irrigation. The total number of tubewells in the area increased from 35,779 to 1,00,237 during 1974 to 2020 in the study area (Fig. 5.9). The rise in number of tubewells can be due to the following factors:

- **Poor service delivery from public water supply systems** has prompted many farmers, and rural and urban households, to turn to their own private supply for irrigation and for drinking water.
- **New feasible pump technologies** meant that even farmers and households with very modest incomes could afford to sink and operate their own tubewell.
- **The flexibility and timeliness of groundwater supply** presented an attractive alternative to the technically and institutionally less responsive provision of surface water through public systems.
- **Government electricity subsidies** have shielded farmers from the full cost of pumping, creating a modality of groundwater use that has proved very difficult to change. (Pahuja *et al.,* 2010)

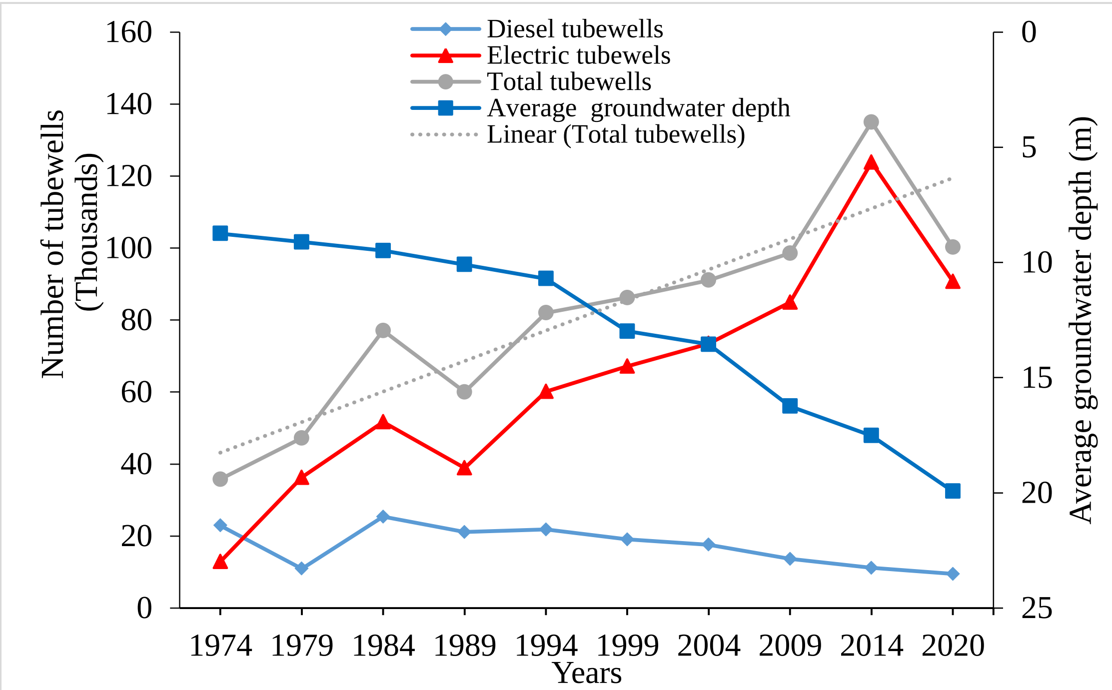

Fig. 5.9: Average groundwater depth (m) with number of tube-wells for the period 1974-2020

5.2.3 Impact of cropping patterns on groundwater level

Northern Haryana's principal crops constitute rice, sugarcane and wheat which are all high water requiring crops and their production and area under cultivation has tremendously increased in past few decades leading to depletion of groundwater resources. The area under rice and wheat cultivation has increased from 110.2 to 293.3 thousand ha (2.65 times) and 180.2 to 309.3 thousand ha (1.7 times), respectively from 1974 to 2020. The area under sugarcane cultivation increased till 2004 to about 71 thousand ha from 22.3 thousand ha in 1974, however after 2004 it is continuously decreasing and in 2020 it was 48.8 thousand ha The area under maize cultivation decreased from 64.6 to 2.5 thousand ha from 1974 to 2004, but after 2004 there has been a slight rise in it (5.1 thousand ha in 2020) due to efforts by the government to promote low water consuming crops, like giving compensatory amount to maize farmers. The depth to water table trend with cropping pattern is shown in Fig. 5.10.

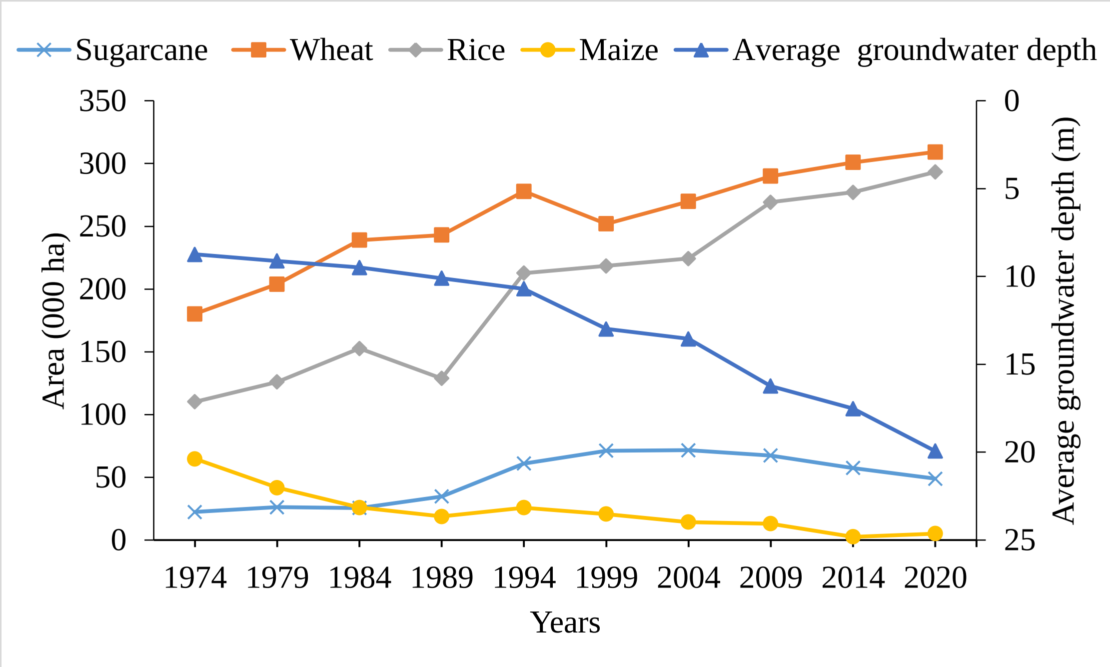

Fig. 5.10: Average groundwater depth with area under different principal crops for the period 1974-2020

5.2.4 Impact of irrigated area, cropped area and area under different sources of irrigation on groundwater depth

The net irrigated area and gross irrigated area increased from 201 to 411 thousand ha and 302 to 728 thousand ha respectively from 1974 to 2020 in Northern Hayana (Fig. 5.11). The total cropped area in the region also increased from 356 to 755 thousand ha (Fig. 5.12). The area under tubewell irrigation increased from 213 to 384 thousand ha whereas the area irrigated by canals decreased from 87 to 33 thousand ha The area irrigated by wells and tanks was found to be negligible in the study area (Fig. 5.13). This increase in irrigated area, cropped area and tubewell irrigated area, inversely affects the groundwater depth as shown in Fig. 5.11 to 5.13.

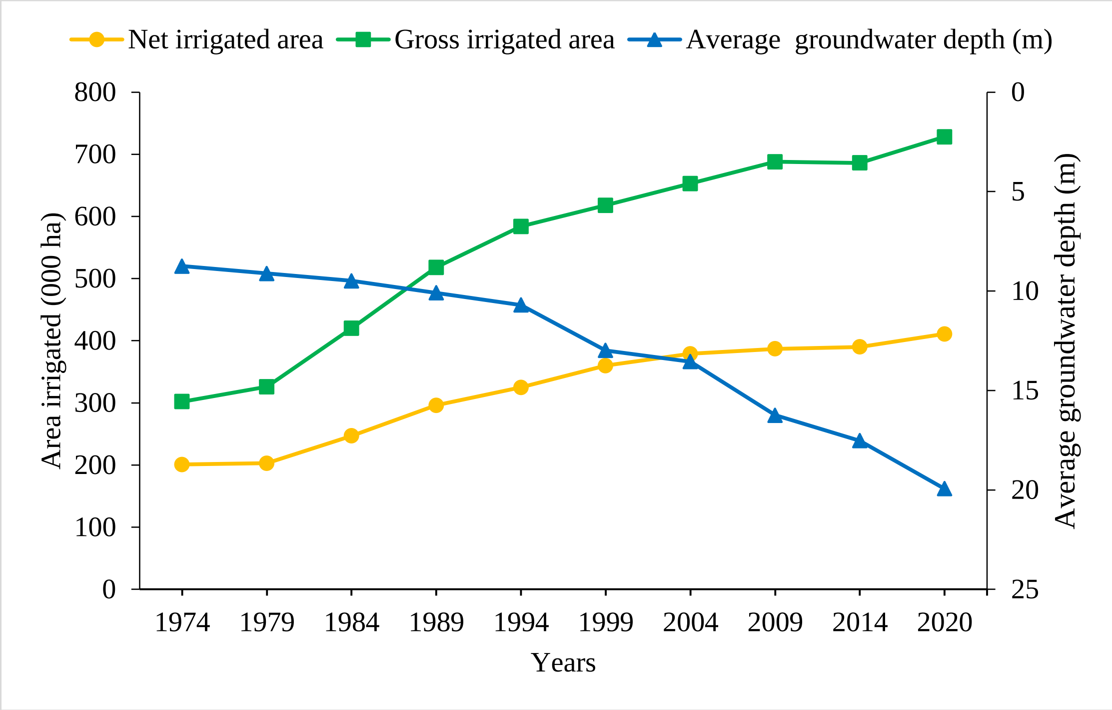

Fig. 5.11: Average groundwater depth with irrigated area for the period 1974-2020

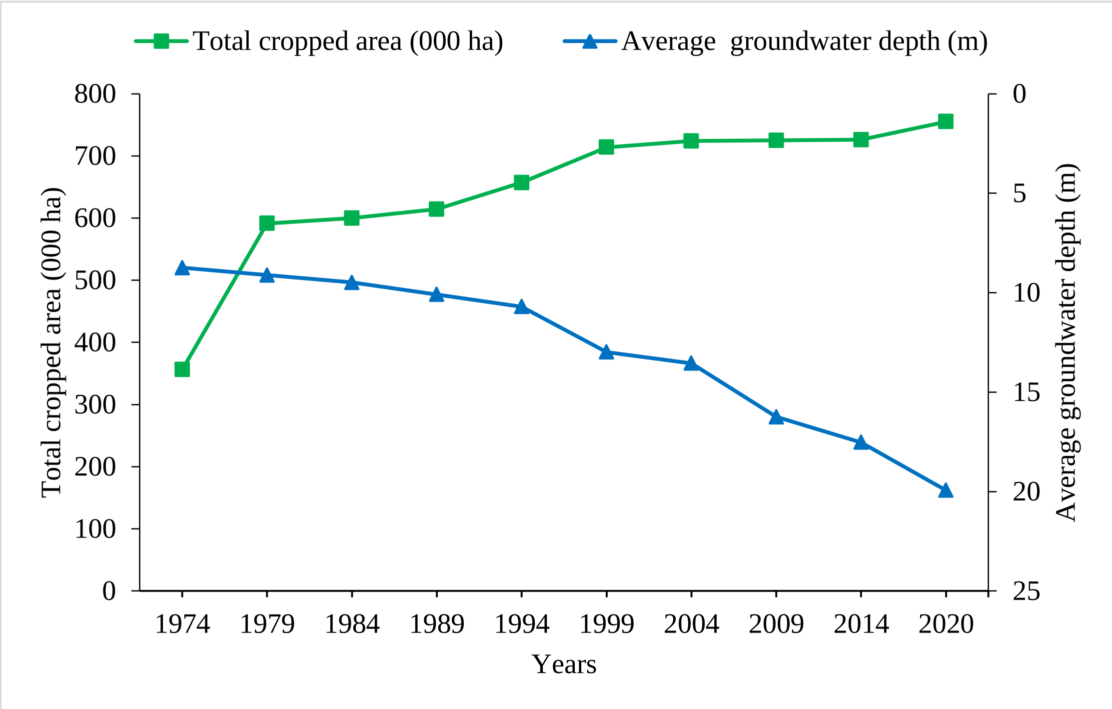

Fig. 5.12: Average groundwater depth with total cropped area for the period 1974-2020

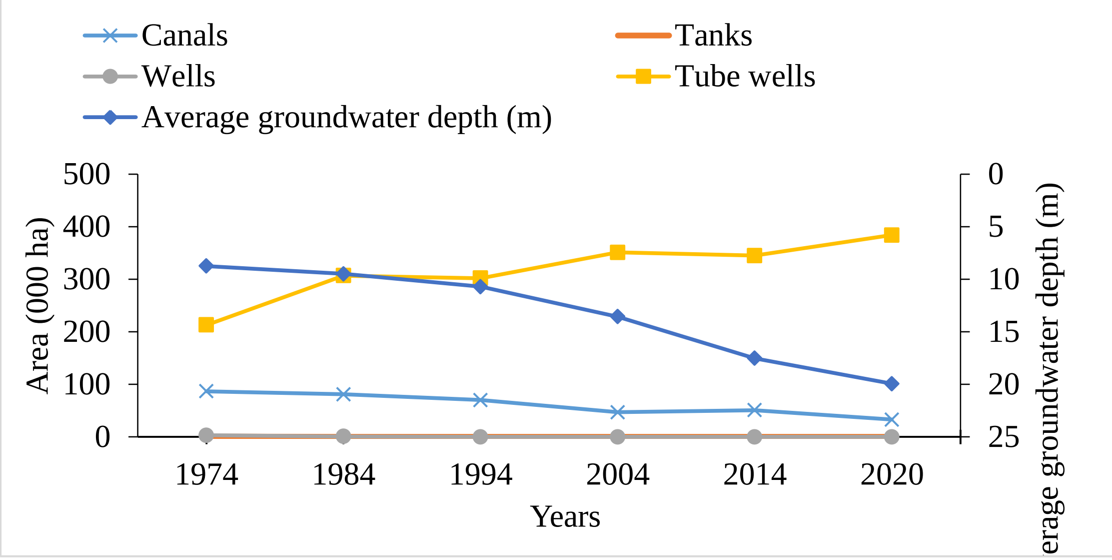

Fig. 5.13: Average groundwater depth with area under different sources of irrigation for the period 1974-2020

5.2.5 Impact of forest area on groundwater depth

The total forest area in the study area decreased from 38 to 17 thousand ha from 1974-2020. The forest cover includes of Reserve forest area (in Shivalik ranges of Panchkula and Yamuna Nagar districts) and some part in Ambala district. The majority of forest in the area belong to sub-tropical dry deciduous category. Pine forests are found in protected forests of Morni Hills of Panchkula district, whereas Sal forests are found in the Reserved forests in Shivaliks of Yamuna Nagar district. Poplar tree plantations are very common in north Haryana. The forest cover has reduced significantly over the years due to expansion of agricultural land and rapid urbanization but now great emphasis is being given by the state government to agro-forestry and farm-forestry to increase the forest cover of the state.

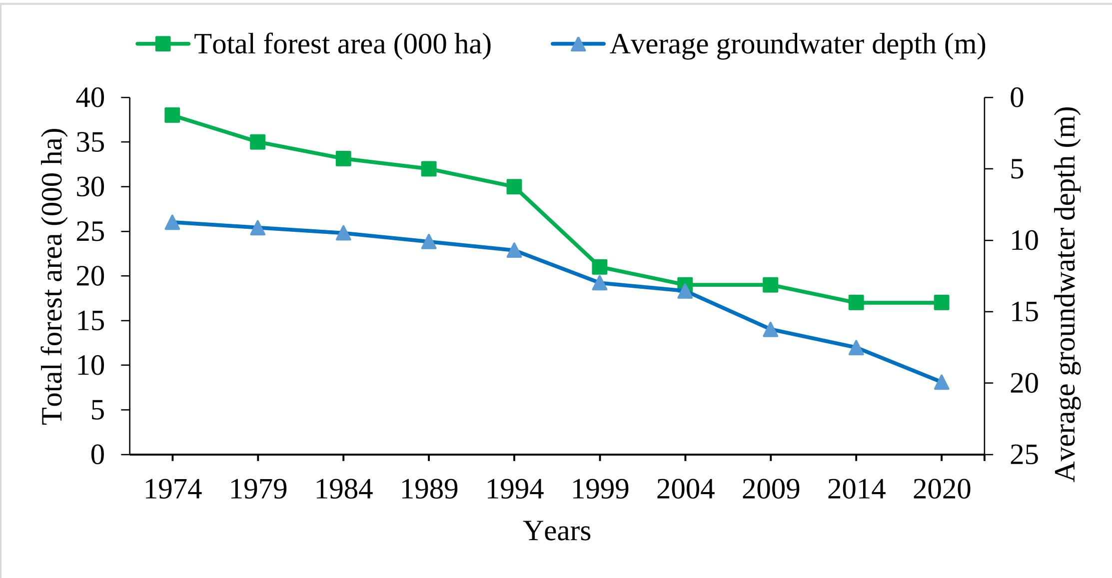

Fig. 5.14: Average groundwater depth with total forest area for the period 1974-2020

5.3 Present Scenario

In the year 2020, the total annual extraction of groundwater was greater than the annual extractable groundwater recharge for Ambala, Kurukshetra and Yamuna Nagar, which denotes that there is urgent need to plan the sustainable usage of the resource. While for Panchkula, the annual extraction is less than the annual extractable groundwater recharge. Also, the yearly annual groundwater is insufficient to meet the annual demands in Ambala, Kurukshetra and Yamuna Nagar. The annual stage of groundwater extraction for Ambala, Panchkula, Yamuna Nagar and Kurukshetra was 124.13%, 62.21%, 149.25% and 245.96%, respectively, which indicate the former three districts to be 'over-exploited' whereas Panchkula to be in 'safe' category as per the categorization of CGWB (Anonymous 2021a).

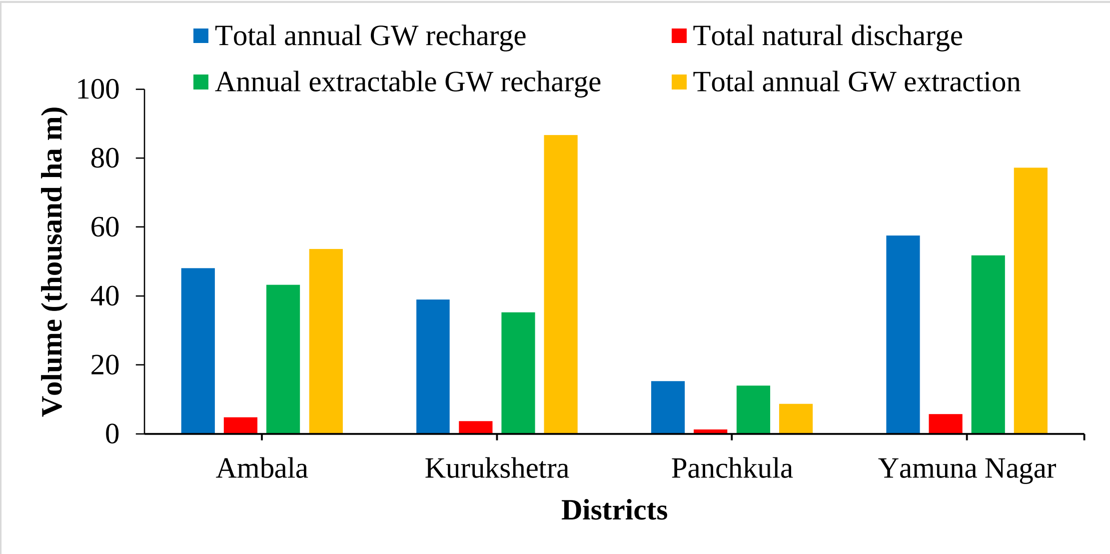

Fig. 5.15: Groundwater status for the year 2020 (Anonymous 2021a)

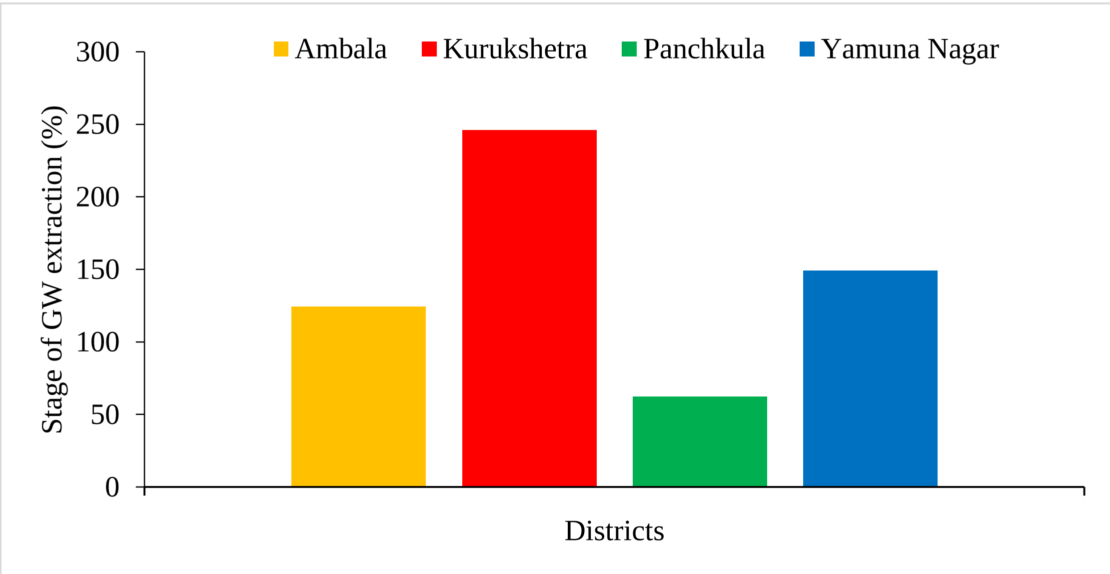

Fig. 5.16: Groundwater extraction stage for the year 2020 (Anonymous 2021a)

Table 5.1: Categorization of groundwater based on quantity (Anonymous 2021a)

Stage of Groundwater extraction	Category
≤70%	Safe
70% to 90%	Semi-critical
90% to 100%	Critical
>100%	Over-exploited

5.4 Correlation between Groundwater Depth and Various Factors Affecting It

The impact of various anthropogenic and climatic parameters is discussed in section 5.2. To further study the correlation between groundwater depth and the parameters, correlation matrix was tabulated by OPSTAT software and shown in Table 5.1.

The correlation matrix reveal that the highest positive impact on groundwater depth is by area under rice cultivation (r = 0.94) followed by area under wheat cultivation (r = 0.86). The net irrigated area and gross irrigated area also have very significant positive impact on groundwater depth with value of r equal to 0.884 and 0.871 respectively. The number of tubewells also significantly affect the groundwater depth, with value of r = 0.829, which implies very significant positive correlation. The groundwater depth is negatively correlated with area under maize cultivation (r = 0.783) and forest cover (r = 0.736), which implies that increasing area under maize cultivation and forest area will eventually lead to decrease in water table depth. However the correlation matrix shows no significant correlation between rainfall and groundwater depth. The results of correlation matrix are in good agreement with our results, discussed in the previous sections.

Table 5.2: Correlation matrix of average groundwater depth and various climatic and anthropogenic parameters

	Total forest area	Total cropped area	Net irrigated area	Gross irrigated area	Total number of tubewells	Average annual rainfall	Area under sugarcane	Area under wheat	Area under rice	Area under maize	Average groundwater depth
Total forest area	1										
Total cropped area	-0.670^{*}	1									
Net irrigated area	-0.644^{*}	0.869^{**}	1								
Gross irrigated area	-0.617^{NS}	0.884^{**}	0.997^{**}	1							
Total number of tubewells	-0.693^{*}	0.814^{**}	0.864^{**}	0.869^{**}	1						
Average annual rainfall	0.458^{NS}	-0.048^{NS}	-0.429^{NS}	-0.389^{NS}	-0.288^{NS}	1					
Area under sugarcane	-0.639^{*}	0.760^{*}	0.848^{**}	0.839^{**}	0.686^{*}	-0.530^{NS}	1				
Area under wheat	-0.599^{NS}	0.884^{**}	0.933^{**}	0.954^{**}	0.906^{**}	-0.267^{NS}	0.710^{*}	1			
Area under rice	-0.803^{**}	0.827^{**}	0.936^{**}	0.934^{**}	0.903^{**}	-0.500^{NS}	0.764^{*}	0.933^{**}	1		
Area under maize	0.513^{NS}	-0.936^{**}	-0.884^{**}	-0.903^{**}	-0.880^{**}	-0.010^{NS}	-0.645^{*}	-0.928^{**}	-0.814^{**}	1	
Average groundwater depth	-0.736^{*}	0.742^{*}	0.884^{**}	0.871^{**}	0.829^{**}	-0.409^{NS}	0.582^{NS}	0.860^{**}	0.940^{**}	-0.783^{**}	1

*NS: Non-significant correlation, * Significant correlation, ** Very significant correlation*

5.5 Statistical Analysis

The parametric tests, Mann-Kendall and Sen's slope estimator showed declining water table in majority of the study area, while rising water table in western parts of Ambala district and in some patches in north-eastern part. The Sen's slope estimator showed water table is decreasing significantly in south-western part and central parts of Kurukshetra while in Yamuna Nagar and Panchkula it is falling at a lower rate. Parametric test linear regression revealed that the groundwater depth is rising in eastern and western part of the study area, while rest of the area showed falling trend (Figures 4.21 and 4.22). The rising trend in western part and eastern of the area could be due to the dense canal network in that area as shown in Fig. 5.17, whereas in Kurukshetra there is decline of water level due to intensive rice cultivation, in spite of presence of canal network.

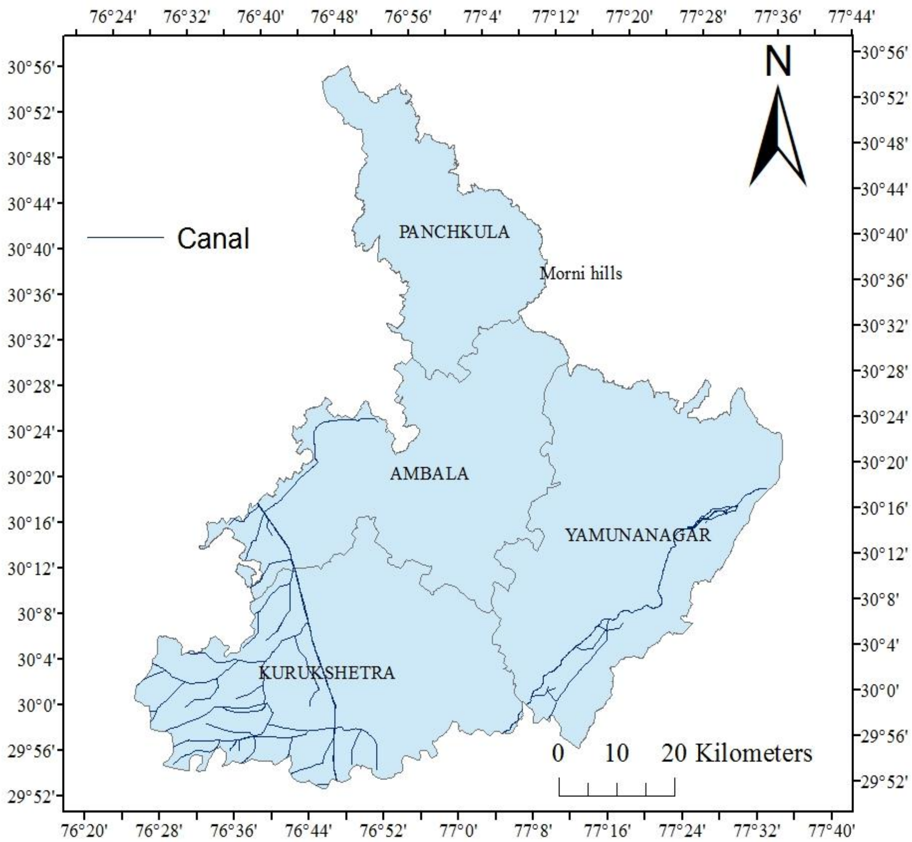

Fig. 5.17: Canal network in northern Haryana

The number of sample points out of total 235 sample points, lying under different Mann-Kendall statistic (Z_S), Sen' slope statistic (S) and Linear regression (t) categories are presented in Table 5.3, 5.4 and 5.5 respectively.

Table 5.3: Number of sample points lying under different Z_S categories

Category of Z_s	Number of sample points	Trend of groundwater level
$Z_S \geq 1.96$	206	Significant fall
$0 \leq Z_S < 1.96$	10	Non-significant fall
$Z_S = 0$	0	No trend
$-1.96 \leq Z_S < 0$	19	Non-significant rise
$Z_S < (-1.96)$	0	Significant rise

Table 5.4: Number of sample points lying under different S categories

Category of S	Number of sample points	Trend of groundwater level
-0.05 – 0	19	Rise
0 – 0.2	109	Fall
0.2 – 0.6	59	Fall
0.6 – 0.8	48	Fall

Table 5.5: Number of sample points lying under different t categories

Category of t	Number of sample points	Trend of groundwater level
-0.2 – 0	0	Rise
0 – 2	39	Fall
>2	196	Fall

The significance of rise or fall increase with increase in magnitude of the statistical parameter for Table 5.4 and 5.5.

The results of parametric tests (Pettitt test, Buishand test and Standard Normal Homogenity test) used for abrupt change point detection revealed that out of 20 blocks of the study area, only 8 blocks i.e. Babain, Barara, Ladwa, Narayangarh, Pehowa, Radour, Shahbad and Thanesar showed significant abrupt change points (Table 4.12), and are shown along with their abrupt change point years in Table 5.6. It is observed from Table 5.6 that most of the abrupt change point years were observed to be 1988 and 2010.

Table 5.6: Block-wise abrupt change point years

District	Block	Abrupt change point years
Ambala	Barara	1994, 2010, 2012
	Narayangarh	1988, 2000, 2010, 2012
Kurukshetra	Babain	1994, 2006
	Ladwa	1988, 2010
	Pehowa	1988, 2010
	Shahpur	1988, 2010
	Thanesar	1988, 2010
Yamuna Nagar	Radour	1994, 1996, 2010, 2014

5.6 Remedial Measures for Groundwater Fluctuations

In northern Haryana, there has been tremendous increase in the area under high water demanding crops like rice and decline in area of millets (maize), which have led to the decline in the water levels of the region. Consequently, to satisfy the growing water demands for irrigation, which could not be fulfilled by the surface irrigation sources, the groundwater resources of the area are over-exploited, and the number of tubewells have been increased manifold. The area under forest also reduced due to expansion of agricultural land. To overcome these problems, some remedial measures are presented as follows:

Reducing demand: By reducing non-beneficial evapotranspiration from the fields, with the use of mulching and drip irrigation, crop water requirements can be decreased Measures such as laser land levelling and soil moisture-based irrigation timer could also lower the demand.

Prohibition of early transplanting of paddy: By pushing back the transplanting time from mid-May to mid-June to align the peak irrigation need for paddy with monsoonal rains.

Groundwater recharge enhancement: Physical engineering measures can be implemented to retard and retain the runoff from seasonal precipitation and to provide conditions more conducive to infiltration, with the objective of increasing the amount of precipitation stored in aquifers, as most of the water during monsoon does not infiltrates in the ground and flows directly to streams and rivers.

Restrictions to control groundwater abstraction: These may include restricting the depth of irrigation water wells (for example by only using dug wells for irrigation) or establishing and enforcing minimum distance between irrigation water wells.

Crop diversification: High water demand for irrigation can be reduced by diversifying the cropping pattern *i.e.* instead of only wheat and rice, more and more farmers should be encouraged to grow less water requiring crops like maize or horticultural crops. This can be made possible by the government efforts like providing compensatory money to grow millets, providing higher support prices for other crops.

Adoption of precision irrigation methods: Adoption of water saving methods of irrigation like drip and sprinkler which can help in ensuring sustainability of groundwater resources. In addition to it, agronomic practices like furrow irrigation can reduce water requirements. The farmers should be made aware of and encouraged to adopt such practices and avail the benefits of subsidies that government provides.

Establishing a village level participatory methodology: It focusses on establishing a village level participatory methodology and tools to aid in enhancing groundwater supplies and reducing demand through direct participation of farmers and other affected stakeholders. The key to successful groundwater management is that communities have considered groundwater as a "common pool resource" rather than an individual's property. Community engagement can play a critical role in the country's groundwater management. Maheshwari and Mehta (2019) carried out an innovative approach for village level groundwater management under the project MARVI (Managing Aquifer Recharge and Sustaining Groundwater Use through Village-level Intervention), in the Meghraj watershed in Gujarat and the Dharta watershed in Rajasthan, which was proved to be very successful.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Haryana is called the *food-bowl* of the country and is primarily known for its rice and wheat cultivation. There has been tremendous increase in agricultural production and irrigation over the past few decades as a result of Green Revolution to provide food security to the country. The percentage of cultivated land area that is irrigated in Haryana is about 80%. Groundwater irrigation is becoming increasingly important in Haryana's agricultural industry. A number of factors have encouraged the remarkable expansion of groundwater use such as poor service delivery from public water supply systems has prompted many farmers, and rural and urban households, to turn to their own private supply for irrigation and for drinking water. New feasible pump technologies through which even farmers and households with very modest incomes could afford their own tube wells. As for north Haryana 16 out of 24 blocks are over-exploited as per the norms of Central Groundwater Board. In light of these facts the present study "Trend Analysis of Groundwater Levels in Northern Haryana, India" has been conducted with the following objectives:

1. Spatial and temporal mapping of groundwater levels and its trend analysis.
2. To enumerate the magnitudes of changes by using parametric and nonparametric tests.

The research was conducted to analyse the trends of groundwater level depth and its relationship with climatic and anthropogenic factors from the year 1974 to 2020, on the basis of secondary data procured from different departments of the Government. The results obtained from the spatial variation and fluctuation maps of the groundwater depths made are summarized as follows:

- The average groundwater table in north Haryana declined from 8.95 m in the year 1974 to 21.83 m in the year 2020, and hence showing an average decline rate of 27.4 cm per year.
- The minimum and maximum groundwater depths in north Haryana ranged from 0 m to 1.46 m and 24.95 m to 56.16 m, respectively during the period of 1974-2020.
- The worst affected district in north Haryana has been identified as Kurukshetra with an average groundwater table decline rate of 57.02 cm per year, followed by Panchkula (14.27 cm per year), Yamuna Nagar (12.55 cm per year) and Ambala (12.14 cm per year).

- No district in north Haryana showed rising trend of groundwater table on an average. However, in some western parts of Ambala the water table showed rising trend.
- The area under 0-10 m groundwater depth reduced from 64.01% in 1974 to 16.43% in 2020. However, the area under 10-20 m groundwater depth increased from 35.72% in 1974 to 46.1% in 2020. The area under groundwater depths of 20-30 m, 30-40 m and 40-50 m was 7.6%, 17% and 11.9% respectively in the year 2020, whereas, in 1974 there was no area under these depths.
- In 1974 the maximum area was under 0-10 m depth (64.01%), whereas, in 2020 the maximum area was under 10-20 m groundwater depth (46.1%).
- During the period of 1974-2020, the groundwater has been over-exploited mainly for irrigation needs, which demands adoption of low water requiring crops like millets in place of paddy, to ensure sustainability of groundwater.
- Maximum and minimum annual rainfall of 1614.2 mm and 578.5 mm was observed in the year 1989 and 1975, respectively. The average annual rainfall of the area was observed to be 960.32 mm for the period 1974-2020.
- The area under rice and wheat cultivation increased from 110.2 to 293.3 thousand ha (2.65 times) and 180.2 to 309.3 thousand ha (1.7 times), respectively, whereas area under maize cultivation decreased from 64.6 to 5.1 thousand ha, from 1974 to 2020.
- The net irrigated area increased from 201 to 411 thousand ha, the gross irrigated area increased from 302 to 728 thousand ha from 1974 to 2020, and the total cropped area increased from 356 to 755 thousand ha from 1974 to 2020.
- The area under tubewell irrigation increased from 213 to 384 thousand ha, whereas, the area irrigated by canals decreased from 87 to 33 thousand ha. The area irrigated by wells and tanks was negligible in the study area.
- The parametric tests, Mann-Kendall and Sen's slope estimator showed declining water table in majority of the study area, while rising water table in western parts of Ambala district and in some patches in north-eastern part. The Sen's slope estimator showed water table is decreasing significantly in south-western part and central parts of Kurukshetra while in Yamuna Nagar and Panchkula it is falling at a lower rate. Parametric test linear regression revealed that the groundwater depth is rising in eastern and western part of the study area, while rest of the area showed falling trend.
- Pettitt test, Buishand test and Standard Normal Homogenity test used for abrupt change point detection revealed that all the blocks showed increasing trends of

groundwater depth, and only 8 blocks of the study area showed significant abrupt change points, and most of the abrupt change point years were observed to be 1988 and 2010.

- The correlation matrix revealed highest positive impact on groundwater depth is by area under rice cultivation (r = 0.94) followed by area under wheat cultivation (r=0.86), net irrigated area (r=0.884), gross irrigated area (r=0.871) and number of tubewells (r = 0.829). The groundwater depth is negatively correlated with area under maize cultivation (r = 0.783) and forest cover (r = 0.736), which implies that increasing area under maize cultivation and forest area will eventually lead to decrease in water table depth. However the correlation matrix shows no significant correlation between rainfall and groundwater depth.

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Appendix I

District-wise average annual rainfall (mm) of Northern Haryana for the period of 1974-2020

Year	Ambala	Kurukshetra	Panchkula	Yamuna Nagar
1974-75	678	*	*	*
1975-76	578.5	*	*	*
1976-77	1201.1	*	*	*
1977-78	943.5	*	*	*
1978-79	1125.4	*	*	*
1979-80	1566	*	*	*
1980-81	613.2	*	*	*
1981-82	1023.7	*	*	*
1982-83	926	*	*	*
1983-84	923.6	*	*	*
1984-85	1407.5	*	*	*
1985-86	699	*	*	*
1986-87	1098.9	*	*	*
1987-88	1097.4	*	*	*
1988-89	657.7	*	*	*
1989-90	1614.2	*	*	*
1990-91	1082.6	*	*	*
1991-92	1561.4	*	*	1455.8
1992-93	788.4	*	*	778.5
1993-94	1036.1	*	*	1110.2
1994-95	880.4	*	*	848.4
1995-96	1136.9	*	*	1280.1
1996-97	1235.5	*	*	1456
1997-98	1274.4	614.5	1622.1	1858.3

1998-99	1045	612.8	935.3	1455.8
1999-00	1076	567.6	827	778.5
2000-01	1145	678	804.2	1110.2
2001-02	1098	576	866	848.4
2002-03	1125	459.7	957	1280.1
2003-04	978.1	417	940.5	985
2004-05	1085	441.5	1755.8	810.4
2005-06	1043.5	551	935.3	870.9
2006-07	1104	292	827	948
2007-08	725	248.5	804.2	649.7
2008-09	907.8	320	866	633.9
2009-10	1240	366	957	992.9
2010-11	769.5	290.5	691.2	938
2011-12	1172	671.5	1142	1383.6
2012-13	1215	395	952.4	1015.4
2013-14	660	262.5	739	845.3
2014-15	1313	402	588	1479.5
2015-16	1138.5	1138.5	484	875.5
2016-17	751.1	312	390	1403
2017-18	1200.5	618.8	531	1160.7
2018-19	814.2	711.3	406.8	1069.2
2019-20	915.4	657.2	1076.1	922.5

*Rainfall data not available for the initial years in which the districts were not formed.

Appendix II

Area under principal crops in Northern Haryana for the period of 1974-2020 (thousand ha.)

Year	Sugarcane	Wheat	Rice	Maize	Total cropped area	Total forest cover
1974	22.3	180.2	110.2	64.6	356	38
1979	26.1	203.8	126.0	41.7	591.5	35
1984	25.5	239.0	152.6	25.9	600.0	33
1989	34.6	243.1	128.8	18.8	614.3	32
1994	60.9	277.9	212.7	25.7	657	30
1999	71.1	252	218.4	20.7	714	21
2004	71.5	269.9	224.3	14.2	724	19
2009	67.3	290	269.2	13.05	725	19
2014	57.4	301	277.1	2.5	726	17
2020	48.8	309.3	293.3	5.1	755	17

Appendix III

Number of tube well pumping sets in Northern Haryana for the period of 1974-2020

Year	Diesel operated	Electric operated	Total
1974	22,904	12,875	35,779
1979	10,947	36,277	47,224
1984	25,358	51,715	77,073
1989	21,107	38,925	60,032
1994	21,823	60,160	81,983
1999	19,058	67,151	86,209
2004	17,599	73,448	91,047
2009	13,633	84,942	98,575
2014	11,135	123,849	134,984
2020	9484	90753	100,237

Net irrigated area, Gross irrigated area and Total forest cover (thousand ha) of Northern Haryana for the period of 1974-2020

Year	Net irrigated area	Gross irrigated area
1974	201	302
1979	203	326
1984	247	420
1989	296	518
1994	325	584
1999	360	618
2004	379	653
2009	387	688
2014	390	686
2020	411	728

District wise net area irrigated by different irrigation sources

Year	District	Government canal	Tank	Wells	Tube wells
1974	A	5	0.5	1	50
	K	82	0.5	2	163
	P	*	*	*	*
	Y	*	*	*	*
	Total	**87**	**1**	**3**	**213**
1984	A	3	0.5	1	91
	K	78	-	-	216
	P	*	*	*	*
	Y	*	*	*	*
	Total	**81**	**0.5**	**1**	**307**
1994	A	-	0.5	-	85
	K	4	-	-	125
	P	*	*	*	*
	Y	3		-	92
	Total	**7**	**0.5**	**0**	**302**
2004	A	16	-	-	111
	K	27	-	-	123
	P	1	-	-	7
	Y	3	-	-	110
	Total	**47**	**0**	**0**	**351**
2014	A	3	-	-	105
	K	45	-	-	102
	P		-	-	23
	Y	3	-	-	115
	Total	**51**	**0**	**0**	**345**
2020	A	3	-	-	145
	K	28	-	-	111
	P		-	-	19
	Y	2	-	-	109
	Total	**33**	**0**	**0**	**384**

A, K, P and Y represent Ambala, Kurukshetra, Panchkula and Yamuna Nagar respectively

Appendix IV

District wise annual groundwater extraction in Northern Haryana for the period of 2004-2020 (per ha.)

District	Annual GW extraction				
	2005	**2009**	**2013**	**2017**	**2020**
Ambala	0.251	0.327	0.3808	0.3389	0.3555
Kurukshetra	0.398	0.443	0.8616	0.4335	0.5147
Panchkula	0.18	0.234	0.23	0.1641	0.1719
Yamuna Nagar	0.36	0.456	0.4806	0.5269	0.5392

District wise details of groundwater recharge in Northern Haryana for the year 2020

District	Total annual GW recharge(from rainfall and other sources)(ha-m)	Total natural discharge(ha-m)	Annual extractable GW recharge (ha-m)
Ambala	48026.5	4802.65	43223.85
Kurukshetra	38918.56	3677.52	35241.04
Panchkula	15252.36	1249.36	14003
Yamuna Nagar	57510.26	5751.03	51759.23

District wise Stage of groundwater extraction (%) in Northern Haryana for the year 2020

District	Stage of groundwater extraction (%)
Ambala	124.13
Kurukshetra	245.96
Panchkula	62.21
Yamuna Nagar	149.25

ABSTRACT

Title of Thesis	**Trend Analysis of Groundwater Levels in Northern Haryana, India**
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Groundwater use in the past few decades, has increased tremendously to meet the growing demands of irrigation which has caused its over-exploitation to unsustainable levels. It provides agricultural social security due to assured irrigation and requirement of small investments, and is the main source of irrigation water. This study was conducted to find out the fluctuations in groundwater levels and its trends in northern Haryana for the period 1974-2020. Arc GIS was used to find the spatial distribution and fluctuation of groundwater depth and to delineate the area under different categories of depth. Parametric tests Mann-Kendall test and Sen's slope estimator and non-parametric test linear regression were used to detect the trends in the data series whereas, non-parametric tests Pettitt test, Buishand test and Standard Normal Homogenity test were used to identify the abrupt change points in groundwater level. The results revealed that the groundwater depth is increasing for majority of the study area except in western parts of Ambala. The average groundwater table in north Haryana declined from 8.95 m in the year 1974 to 21.83 m in the year 2020, and hence showing an average decline rate of 27.4 cm per year. The worst affected district in north Haryana has been identified as Kurukshetra with an average groundwater table decline rate of 57.02 cm per year, followed by Panchkula (14.27 cm per year), Yamuna Nagar (12.55 cm per year) and Ambala (12.14 cm per year). The maximum area (43.82%) for the period 1974-2020 lied in the groundwater depth fluctuation range -10 m to 0 m while minimum area lied in the range of 5 m to 8 m fluctuation (0.04%). The groundwater depth was found to have maximum positive correlation with area under rice followed by area under wheat cultivation, net irrigated area, gross irrigated area and number of tubewells. Whereas it was found to be negatively correlated with area under maize cultivation and forest cover. However it shows no significant correlation with rainfall. Crop diversification, participatory groundwater management, artificial groundwater recharge and precision irrigation methods would help in better management of the resource in a sustainable manner.

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(i) Academic qualifications

Degree	University/Board	Year of Passing	Marks	Subjects
M. Tech.	CCS HAU, Hisar, Haryana	2022	78.4%	Major: Soil and Water Engineering Minor: Soil Science
B. Tech.	MPUAT, Udaipur, Rajasthan	2020	76.6%	Agricultural Engineering
12th	CBSE	2016	88%	Physics, Chemistry, Mathematics, English, Physical Education
10th	CBSE	2014	10 CGPA	Mathematics, Science, Hindi, English, Social Science

(j) Co-curricular activities : Painting, Sketching and Yoga

(k) List of Publications :

Gupta, A., Singh, A.K., Kumar, S. (2021). Integrated and participatory watershed management in ravine regions of India, *Soil and water conservation and management*, ISBN: 978-93-90647-86-6, 1: 115-120.

I, hereby, declare that all the information given in the resume is true to the best of my knowledge.

Date:

Place: Hisar (Abha Gupta)

UNDERTAKING OF THE COPYRIGHT

I, **Abha Gupta,** Admn No. **2020AE13M** undertake that I give copyright of my thesis entitled "**Trend Analysis of Groundwater Levels in Northern Haryana, India"** to Chaudhary Charan Singh Haryana Agricultural University, Hisar.

I also undertake that the patent, if any, arising out of the research work conducted during the programme shall be filed by me only with due permission of the competent authority of Chaudhary Charan Singh Haryana Agricultural University, Hisar.

Signature of the student