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Praveen Kumar Rai *Editor*

River Conservation and Water Resource Management

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Contents

Chapter 9
Hydro-Geological Investigation and Groundwater Resource Estimation

Kuldeep Pareta

Abstract Water scarcity is an everlasting phenomenon in Udaipur despite the several man-made lakes. Due to indiscriminate usage, the stage of groundwater development in the Ayad River basin, Udaipur has reached 101.88%. The study is focussed on the hydrological, hydro-geological investigation, and estimates, projects the groundwater resource by innovating and extensive usage of secondary data collected from USGS, GSI, CGWB, SOI, NBSS&LUP, and WRD Rajasthan. Rainfall (1901–2021), LULC, soil, geology, geomorphology, drainage, river–lake link has been analysed based on satellite imagery, DEM, toposheet, and other secondary data. The area has a good aquifer inside the hard rock formations phyllite, schist, gneiss, and quartzite which is predominantly formed in weathered, fractured, and jointed rocks. The average depth of groundwater in various rock formations ranged from 3.9 m to 16.3 m. Based on behaviour of groundwater flow recharge and discharge zones has been identified. Rama and Iswal situated in NE of basin are the best recharge zone, while Amberi, Bedla, Badgaon, Sukher, Dhinkli, and Udaipur situated in the central of basin are discharge zones. The average annual groundwater resource (2011–2020) has been estimated based on GEC-1997 method, which is 127.81 MCM. Based on mini-max rainfall data and deficit / surplus reserves, a mathematical relationship has been established, and the same has been used to project the availability of groundwater. Large RHS, water conservation, reuse-recycle measures have been recommended for sustainable management of groundwater reserves. Awareness campaigns and training on these measures may be helpful to stop the decline in water levels and justified use.

Keywords Hydrology · Hydrogeology · Groundwater resource · Ayad River · Remote sensing and GIS

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9.1 Introduction

Water resources have been essential for human survival on the planet and the functioning of nature since the beginning of time (Rai et al. 2017, 2018, 2019; Priscoli 2000; Singh et al. 2021). The main source of life on earth is water, it is abundantly supplied by nature. However, it is challenging to obtain this resource in sufficient amounts, and its quality and quantity are dwindling quickly (Sirhan et al. 2011). One of the major challenges of the twenty-first century is still seeing good quality, sufficient quantities of water in urban and peri-urban areas to meet the needs of communities and ecosystems with unregulated urbanization fueled by internal migration and population expansion (Anomohanran 2015). Many people rely on groundwater exploration and exploitation to provide adequate, good-quality water, and that has increased extensively because of awareness and technology (Lawrence et al. 2012). Although groundwater is a resource that may be annually replenished, but its availability is not constant with time and space (CGWB 2006). With time, the rapid pace of urbanization and the expanding population have greatly strained surface water resources and deteriorated the quality of groundwater (Carpenter et al. 1998; Sharma et al. 2018; Rai et al. 2021, 2022; Mishra et al. 2021).

In India, the requirement for groundwater has grown significantly over the past several years to fulfil domestic and industrial needs as well as to improve agricultural productivity (Karanth 2008). About 85% of rural drinking water comes from groundwater sources (IDFC 2013). According to Sharma et al. (NIH) 2008, the total annual water resources of India is 1960 Km^3, out-of-that utilizable water resource is 1140 Km^3 (690 Km^3 from surface water and 450 Km^3 from groundwater). The present utilization is 750 Km^3 (500 Km^3 from surface water and 250 Km^3 from groundwater). The predicted demand for 2025 is 1050 Km^3, which means that by that time, all the water resources would have to be used. The semi-arid state of Rajasthan is particularly vulnerable (Rajasthan Water Assessment 2013). It has 10% of India's area but only about 1% of the water resources. Due to limited surface water resources in Rajasthan, groundwater has become an important source for supplying domestic, agricultural, and industrial water needs (Rajput et al. 2020). Udaipur city is a growing urban area, which now is the sixth largest city in Rajasthan and known as the city of lakes in India. During the last decade, the groundwater has already dried up in Udaipur city particularly the valley fills near Ayad River around Kanpur, most shallow tube wells and wells run dry throughout the summer (CGWB 2013).

The available literature was used in this work to review the methodologies for hydrological, hydro-geological investigation and groundwater resource estimation, and to discuss the best way to estimate the groundwater resource of Ayad River basin, Udaipur. Several studies have suggested various approaches for groundwater resource estimation in Udaipur and Ayad River basins. Such as Dani (2009) investigated the GW exploration using electrical resistivity method in Ahar (Ayad) River basin, Udaipur. He has analysed the electrical resistivity data and explored the potential groundwater in the study area. Pareta (2013) has attempted to work on sustainable GW management using RS/GIS. He calculated the annual GW increment, annual GW draft, total GW balance, and identified the dark zones where GW draft is more than the dynamic potential. Samar and Vaishnav (2014) analysed the GW level pattern of Ahar (Ayad) River basin by using statistical method. They have investigated the hard-rock aquifers of Ahar River basin at 50 sites. Pareta and Pareta (2015) have worked on Berach River basin and estimated the GW balance and reserves using geospatial technology. They have used GEC-97 method and calculated the GW potential for the year 2014. According to them, net annual GW availability was 786.56 mcm, GW draft was 379.29 mcm, and total GW potential was 1165.85 mcm. Machiwal et al. (2017) have attempted to work on Ahar (Ayad) River catchment and determined aquifer parameters in hard-rock by conducting 19 pumping tests. They have analysed pre- and post-monsoon GW levels data at 50 sites and found that the distribution of the aquifer parameters and recharge indicated that the northern portion of the catchment with high ground elevations (575–700 m msl), high specific yield (Sy: 0.08–0.25) and transmissivity (T: 600 m^2 / day) values acted as recharge zone. Sinha et al. (2018) have worked on delineation of GW potential zones in Udaipur district using RS/GIS-based multi-criteria decision-making technique and selected eight criteria to identify the GW potential zones. Pradeep et al. (2018) have attempted to work on estimation of GW recharge through soil moisture balance method at CTAE farm, Udaipur. The average recharge has been observed that 32.9 mm, i.e., 6.9% of the average annual rainfall. Rathore et al. (2018) has worked on shrinking of water resource in Udaipur by using SOI toposheets, multi-temporal satellite imageries from 1972 to 2014, and mapped the water resource in the Udaipur district, and they have found that the lakes/ponds/reservoirs are continuously shrinking. Shyam et al. (2022) have worked to assess the GW reserves of Udaipur district using geospatial techniques. They have estimated the annual dynamic GW reserves (637.42 mcm), and total GW draft (639.67 mcm). The deficit GW reserves are 2.25 mcm/annum from an average rainfall of 627 mm; hence the stage of groundwater development is 100.67% and categorized as over-exploited.

The main objective of the present study is to analyse the biophysical—geomorphic, hydrological, and hydro-geological characteristics as well as groundwater resource estimation, projection, and sustainability management of groundwater reserves. Additionally, this study is also insinuating the innovative and extensive use of secondary source data in hydrological and hydro-geological investigation.

9.2 About the Study Area

The Ayad River basin extends from 24° 50′ 16” N to 24° 27′ 46” N and 73° 31′ 44” E to 73° 59′ 44” E and covers an area of 1206.75 Km^2. Administratively, the Ayad River basin fall into 4 tehsils (Girwa—58.48%, Mavli—19.85%, Vallabh Nagar—6.97%, Gogunda—5.94%) of Udaipur district and 1 tehsil (Nathdwara—8.76%) of Rajsamand district. The Ayad River is also known as Ahar River, which originates from the hills of Gogunda in the north-west of Udaipur and travels through for 68.45 km before joining the Vallabh Nagar lake in the eastern part of Udaipur

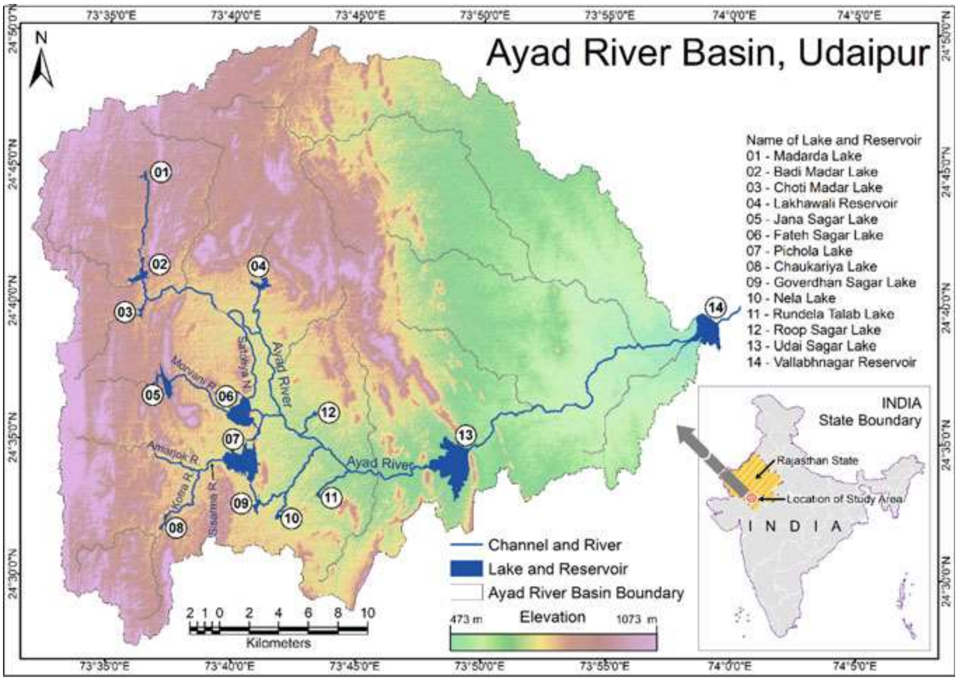


Fig. 9.1 Location map of Ayad River Basin, Udaipur

(Fig. 9.1). The Ayad River is the major river flowing through Udaipur, and it is seasonal in nature and is on the peak of its youth during monsoons. The Ayad River is a tributary of the Berach River. Journey of Ayad River to Bey-of-Bengal is: Ayad River = > Berach River = > Banas River = > Chambal River = > Yamuna River = > Ganges River = > Bay-of-Bengal.

9.3 Data Used and Their Sources

The present study is based on secondary data such as rainfall, topography, digital elevation data, land use land cover, soil, landform, geology, geomorphology, aquifer data, groundwater level, and groundwater draft which have been compiled from different sources, e.g., Water Resource Department (WRD) Rajasthan, Survey of India (SoI), United States Geological Survey (USGS), National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) Udaipur, Geological Survey of India (GSI), Ground Water Department Rajasthan, Central Ground Water Board (CGWB). The list of data used and their sources are given in Table 9.1.

The abominated data can be accessed from the project website: http://udaipur.dhi-india.com.

Table 9.1 List of data used and sources

S. No	Data type	Period	Sources
1	Survey of India (SoI) Toposheet at 1:50,000 Scale	2006	Toposheet No.: 45H/09, 10, 11, 13, and 14 Source: http://www.soinakshe.uk.gov.in
2	Landsa-7 ETM + , and Landsat-9 OLI-2 Satellite Imageries with 30 m Spatial Resolution	2011, 2021	USGS Earth Explorer Source: http://earthexplorer.usgs.gov
3	Topography/Digital Elevation Data (DEM) Data with 30 m Spatial Resolution	2014	Shuttle Radar Topography Mission (SRTM), USGS Earth Explorer Source: http://earthexplorer.usgs.gov
4	Soil Texture Data at 1:250,000 Scale	2016	National Bureau of Soil Survey and Land Use Planning, Regional Centre, Udaipur Source: http://www.bhoomigeoportal-nbsslup.in/
5	Geological Data at 1:50,000 Scale	1999–2001	Geological Survey of India (GSI) Source: http://www.portal.gsi.gov.in
6	Daily Precipitation Data	1901–2021	Water Resource Department, Govt. of Rajasthan Source: https://water.rajasthan.gov.in
7	Daily Evapotranspiration (ET) with $0.25^{O} \times 0.25^{O}$ Spatial Resolution	2000–2021	Giovanni, NASA. (GLDAS_CLSM025_DA1_D v2.2) Source: https://giovanni.gsfc.nasa.gov
8	Monthly River Discharge Data for Gambhiri and Berach River	1964–1990	Water Resource Department, Govt. of Rajasthan Source: https://water.rajasthan.gov.in
9	Depth to Water Level (DTWL) Data (Pre-Post Monsoon)	2011–2020	Ground Water Department, Jodhpur (Rajasthan) Source: https://phedwater.rajasthan.gov.in
10	Aquifer Potential Zone Map of Udaipur District	2013	Ground Water Department, Rajasthan Source: https://phedwater.rajasthan.gov.in

9.4 Methodology

SRTM DEM of 30 m spatial resolution has been used to derive the general topographic characteristics (such as slope, landforms) of the area, and it has been updated by using Survey of India topographical map of 1:50,000 scale. Landsat satellite imageries have been used in this study, which is very useful for the preparation of LULC maps, and the updation of soil, geology, and geomorphology data. Rainfall data from 1901 to 2021 (121 years in total) has been collected from WRD Rajasthan which has further analysed with mean, standard deviation (SD), coefficient of variation (CV), and Mann–Kendall's test was performed for rainfall trend analysis. Residual mass curve has been prepared to analyse the annual groundwater increment condition. Drainage network of the area has been extracted from SRTM DEM. Thereafter, based on drainage network, drainage density has been generated and correlated with topography, lithology, precipitation, and vegetation coverage. Author has also analysed river and lake link in the Ayad River basin.

Depth-to-water-level (DTWL) data of 45 water monitoring stations from 2011 to 2020 (pre- and post-monsoon) has been acquired from Central Ground Water Board (CGWB), which are well distributed in Ayad River basin. Thus, these datasets have been analysed and extracted from the groundwater flow and water level fluctuation. Subsequently, the best recharge zone as well as discharge zone has been identified. Author has estimated the groundwater resource by using groundwater level fluctuation and specific yield method, and rainfall infiltration factor method recommended by GEC-1997. Annual groundwater draft, overall stage of groundwater development, projected groundwater reserves have also analysed. Flow diagram of the overall methodology is shown in Fig. 9.2.

9.5 Results and Discussion

9.5.1 Biophysical and Geomorphic Characteristics

9.5.1.1 Land Use Land Cover Analysis

Various traditional classification schemes incorporate one or two parameters to classify the image (e.g. spectral differentiation, texture) and the focus is the physical property of the image (Mishra and Rai, 2016). These approaches are efficient with low to moderate spatial resolution satellite images. Visual image processing was used to prepare land use land cover (LULC) maps of the Ayad River basin for the year 2011 and 2021. Landsat-7 ETM + (Enhanced Thematic Mapper Plus) satellite imagery of 20th November 2011 with 30 m spatial resolution, and Landsat-9 OLI-2 (Operational Land Imager-2) satellite imagery of 9th November 2021 with 30 m spatial resolution have been used for preparation of LULC maps. The Landsat data processing done for Ayad River basin for 2011 and 2021 has been divided into two steps:

Land Use Land Cover Classification: (i) acquisition of Landsat imageries and generation of seamless image mosaic for 2011and 2021, (ii) geo-rectification using GCPs and subsequent resampling of the images into a common coordinate system and pixel size of 30 m, (iii) image subset creation for highlighting area of interest,

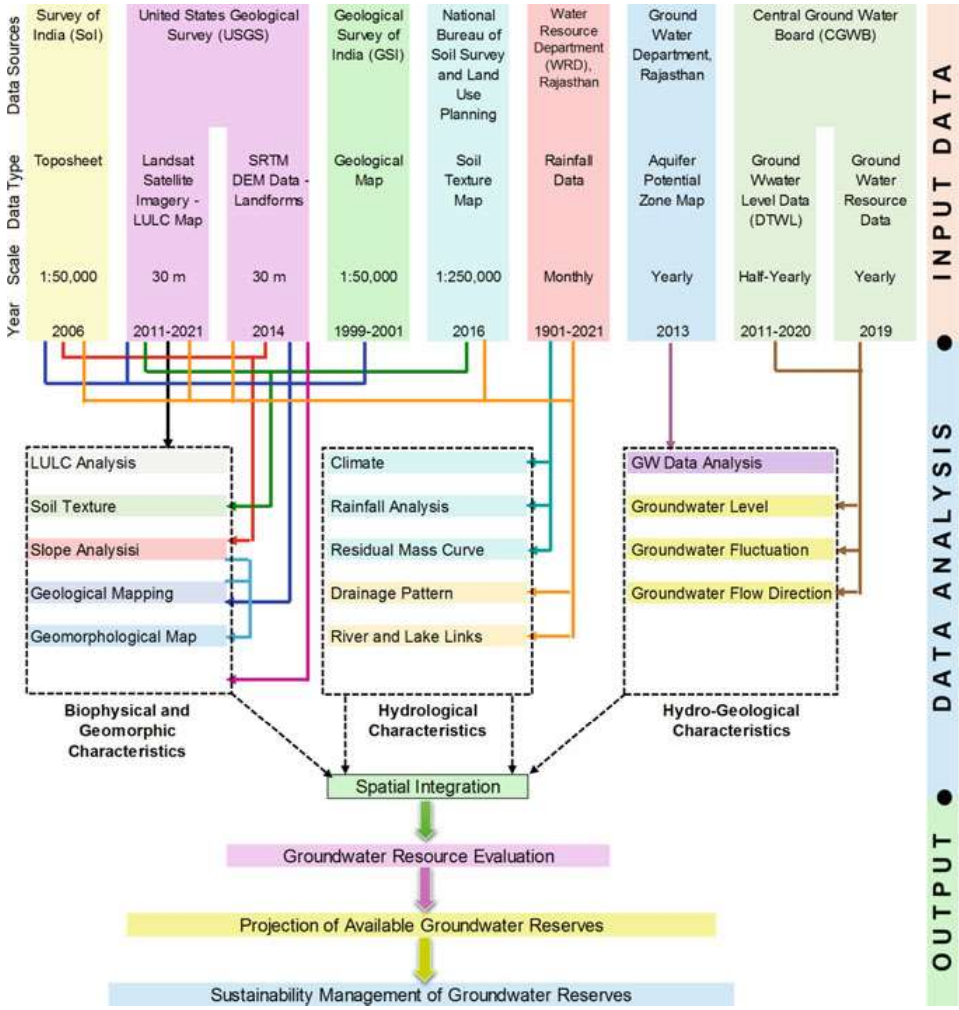


Fig. 9.2 Overall methodology of the present study

(iv) LULC classification (level 2) using visual image interpretation, and (v) accuracy assessment for the LULC thus generated.

Change Detection and Conversion Matrix: (i) post-classification method of image change detection was implemented, (ii) images of two vintages (2011 and 2021) were classified to LULC classification scheme, (iii) detection of LULC changes between the year 2011 and 2021 in the Ayad River basin both in quantitative and qualitative terms using techniques of RS and GIS, and (iv) conversion matrix was created to better understand the changes in LULC in terms of direction of change (which land use encroached on which).

LULC data for the year 2011 and 2021 have been prepared, and LULC statistics have been presented in Table 9.2. The LULC maps of Ayad River basin for 2011 and 2021 are shown in Fig. 9.3.

Table 9.2 Land use land cover (LULC) statistics of Ayad River basin for the Year 2011 and 2021

S. No	LULC classification (Level-1)	Area in 2011		Area in 2021		Changes (from 2011 to 2021)	
		Km^2	%	Km^2	%	Km^2	%
1	Built-up area (urban)	61.71	5.11	75.17	6.23	+13.46	+01.12
2	Built-up area (rural)	10.40	0.86	15.85	1.31	+05.45	+00.45
3	Agricultural crop land	210.38	17.43	185.47	15.37	−24.91	−02.06
4	Agricultural fallow land	563.96	46.73	598.50	49.60	+34.53	+02.86
5	Vegetation	91.05	7.55	87.81	7.28	−03.24	−00.27
6	Scrub land/barren land	95.79	7.94	83.53	6.92	−12.26	−01.02
7	Forest area	142.34	11.80	127.47	10.56	−14.88	−01.23
8	Water bodies	18.07	1.50	20.52	1.70	+02.45	+00.20
9	River/Drain/Canal	13.04	1.08	12.44	1.03	−00.60	−00.05
	Total	1206.75	100.00	1206.75	100.00		

9.5.1.2 Soil Texture

For detailed analysis of soil material and texture in the basin, a published soil map of Ayad River basin has been collected from National Bureau of Soil Survey & Land Use Planning (NBSS&LUP). The soil map has geometrically registered to the base data to match Landsat-9 OLI-2 satellite imagery. The geo-referenced soil map has been used to assist in visual classification of satellite imagery for obtaining soil categories. Survey of India (SoI) toposheets (1: 50,000), Landsat-9 OLI-2 satellite imagery, SRTM (DEM) data have been used for updation of soil categories. The final vector data layer has been stored in a geo-database which has amenable to spatial analysis. More than one-third (34.49%) of Ayad River basin is covered by less permeable black clayey soil, other than this soil, brown loamy soil covered 33.02% of area, brown gravelly loam soil covered 20.8% of area, red gravelly loam hilly soil covered 9.77% of area, while red loamy soil covered only 1.92% area of Ayad River basin. With reference to soil depth, approx. 47% of area was covered by deep / moderately deep soil (>50 cm), 29%, and 23% of area was covered by extremely shallow soil (<10 cm), and very shallow soil (10–25 cm), respectively, while only 1% of the area covered by shallow soil (25–50 cm). Soil texture classes with soil depth of Ayad River basin is shown in Fig. 9.4.

9.5.1.3 Geology

Satellite remote sensing imagery-based geological map can usually provide information such as (i) distribution of the rock type and lithological groups in the area; (ii)

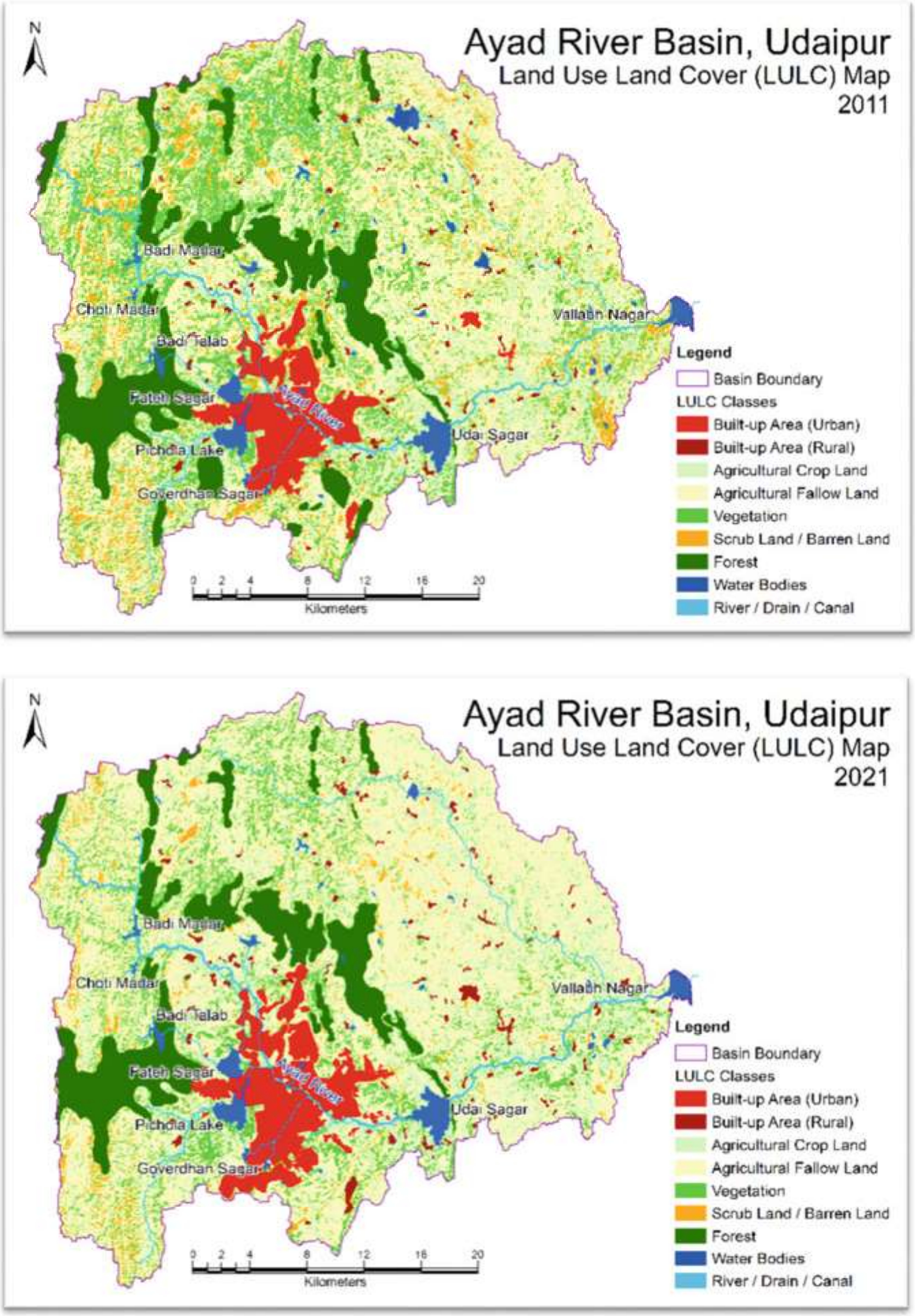


Fig. 9.3 LULC maps of Ayad River Basin for year 2011 and 2021

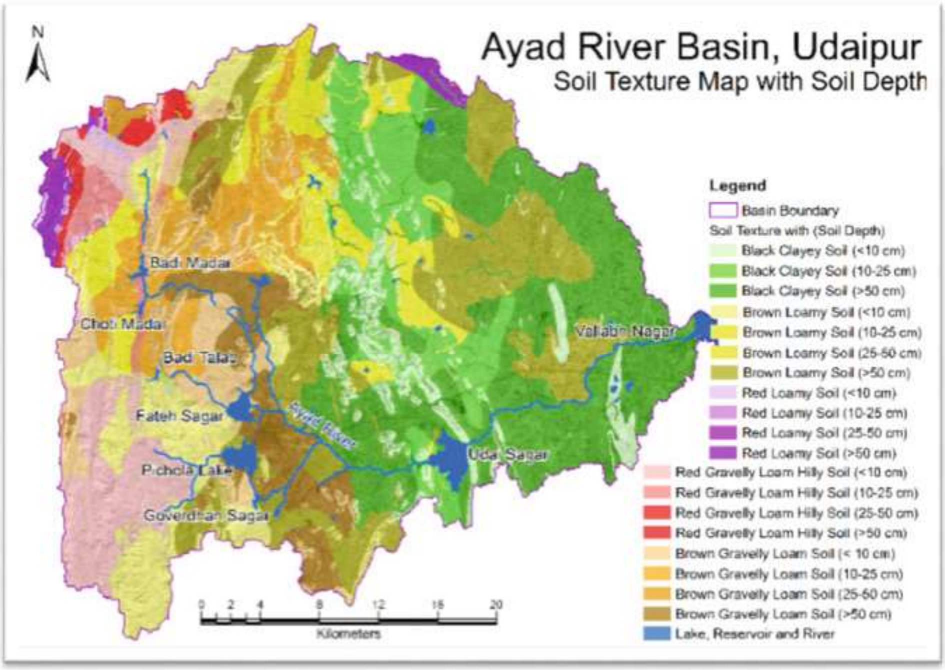


Fig. 9.4 Soil texture map of Ayad River Basin, Udaipur

an indication of the dips of the strata, which are classified as gentle, moderate, and steep; (iii) faults and unconformities can also be picked up on satellite imagery with fair certainty. A general geological of the area has been mapped by the Geological Survey of India (GSI). Several geologists have contributed to the study area, among them are Heron 1953; Raja Rao et al. 1971; Gupta et al. 1968; Sahu et al. 1995; Sinha-Roy et al. 1998; Gupta et al. 1981; Wiedenbeck et al. 1996; Aggarwal et al. 2011, etc. They havedescribed various geological aspects of the study area. They have recorded the principal rock formations as described in Table 9.3. A geological map of the Ayad River basin has been prepared by using published geological map of Geological Survey of India (GSI) at 1:250,000 scale, Landsat-9 OLI-2 satellite imagery (30 m spatial resolution), SRTM DEM data (30 m spatial resolution), and Survey of India (SoI) topographical map at 1:50,000 scale with limited field check. A geological map of the Ayad River basin is shown in Fig. 9.5.

Rock types ranging in age from Archaean to Upper Proterozoic are present in the Ayad River basin, Udaipur. The Precambrian metasediments belong to three geological cycles, designated as Bhilwara, Aravalli, and Delhi supergroups (Raja Rao et al. 1971). The Bhilwara supergroup is represented by the Mangalwar Complex of Archaean age. The Mangalwar Complex is named after Mangalwar village which is located about 55 km southwest of Chittorgarh (Gupta et al. 1981). The rocks of the Aravalli supergroup are represented by several groups, which are given in Table 9.3. The Aravalli supergroup is separated from the Bhilwara supergroup by the quartzitic horizon of Gurali formation of Debari group (Sahu et al. 1995). We analysed

Table 9.3 Geological succession of the Ayad River basin

Age	Supergroup	Group	Formation	Lithology
Palaeo Proterozoic - Meso Proterozoic	Delhi	Gogunda	Antalia	Quartzite, granite, granite-gneiss
Palaeo Proterozoic	Aravalli	Nathdwara	Rama	Dolomitic marble, crystalline limestone, meta-basics, meta-siltstone, marble and meta-conglomerate, quartzite
			Kadmal	
			Haldighati	
		Jharol	Samlaji	Marble, crystalline limestone, meta-conglomerate, mica schist, phyllites, chlorite schist, phyllites with impure marble, quartzite, serpentine-talc
			Goran	
		Bari Lake	Khamnor	Dolomitic marble, crystalline limestone, meta-basics, meta-conglomerate, meta-siltstone, phyllite, chlorite schist, impure marble, quartzite, granite, gneiss, meta-volcanics, massive limestone
			Varla	
			Sajjangarh	
		Udaipur	Nimachmata	Granite, gneiss, marble, crystalline limestone, massive limestone, dolomite, chlorite schist, dolomitic marble, meta-siltstone, meta-conglomerate, meta-basics, phyllite, quartzite
			Balicha	
			Eklinggarh	
			Sabina	
		Debari	Dakankotra	Dolomitic marble, gneiss, granite, marble, crystalline limestone, massive limestone, dolomite, meta-basics, meta-conglomerate, meta-arkose, meta-siltstone, meta-volcanics, migmatite complex, phyllite, quartzite, schist
			Berwas	
			Jaisamand	
			Delwara	
			Gurali	
– ———————— Unconformity ————————				
Archaean	Bhilwara	Mangalwar Complex	Lasaria / Suwana	Dolomitic marble, gneiss, granite, marble, meta-conglomerate, migmatite complex, quartzite, schist

Source Geological Survey of India, 2011

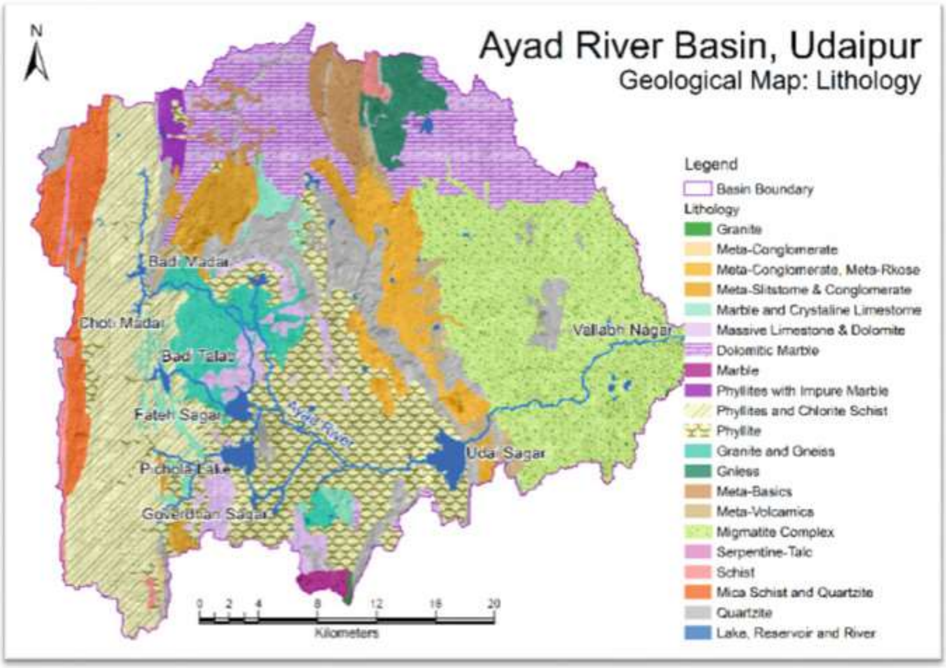


Fig. 9.5 Geological map of Ayad River basin, Udaipur

seasonal streamflow with reference to surface geology, and found extreme hydrological behaviors, with igneous rocks (mainly granite) and metamorphic rocks (mainly quartzite, gneiss, dolomitic, marble, schist, phyllites, serpentine-talc, migmatite) being characterized by a fast-responding hydrological regime due to the presence of low-permeability rocks and the sedimentary rocks (mainly limestone, siltstone, conglomerate) being dominated by highly permeable lithological units resulting in a slower response.

9.5.1.4 Geomorphology

Geomorphology is the scientific study of landforms with reference to processes of genetic and evolution development (Hills 1975; Rosengren 1984; Ahnert 1988; Pareta et al. 2012). Geomorphological map can act as a preliminary tool for land management and geomorphological and geological risk management, as well as providing baseline data for other applied sectors of environmental research (Cooke et al. 1993; Dramis et al. 2011; Paron et al. 2011).

Remote sensing data has played a significant role for the preparation of geomorphological information of any area. A detailed geomorphological map of Ayad River basin, Udaipur by visual image interpretation of Landsat-9 OLI-2 satellite imagery (30 m spatial resolution), SRTM DEM data (30 m spatial resolution), published geological map (GSI) at 1:250,000 scale, Survey of India (SoI) topographical maps

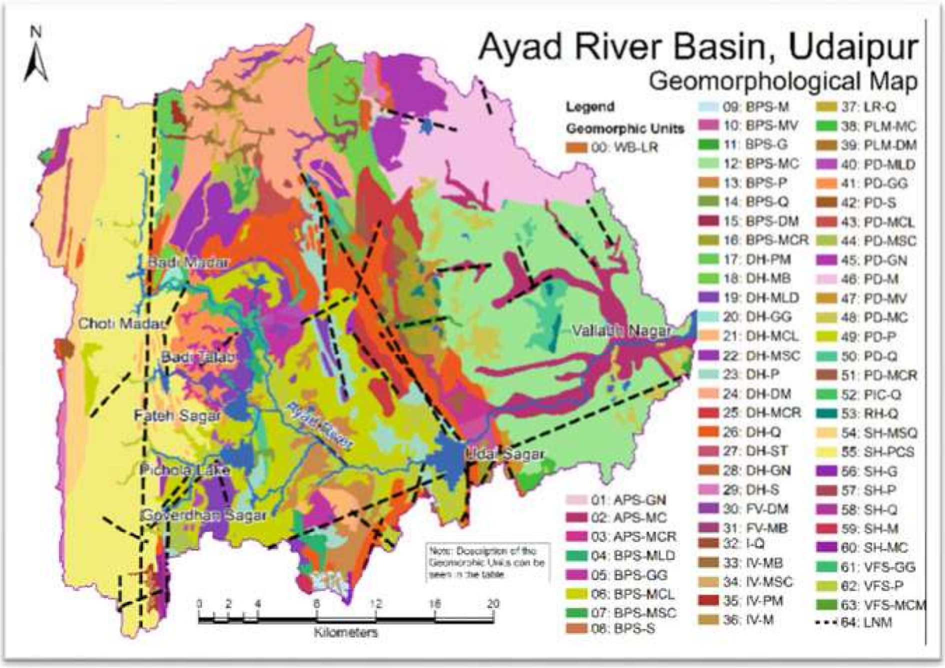


Fig. 9.6 Geomorphological map of Ayad River Basin, Udaipur

at 1:50,000 scale, and limited field observations and shown in Fig. 9.6. The various geomorphic units and their component were identified and mapped. Geomorphologically, the Ayad River basin has been classified into 13 broad geomorphic units, and 63 micro-geomorphic units, which are given in Table 9.4.

9.5.2 *Hydrological Characteristics*

9.5.2.1 Climate

Climatologically, the Ayad River basin, Udaipur, can be categorized as semi-arid, meaning that the annual potential evapotranspiration loss is quite higher than the annual rainfall causing soil moisture deficit. The basin area has three distinct seasons in a year, the winter season starting from Nov to Feb with temperature ranging between 3.5° and 18 °C and mostly pleasant. March is a pleasant transition month to summer. The summer season from Apr to Jun with an average temperature of around 37 °C, May–June are the hottest month, when temperature reach to 48 °C. The monsoon season from Jul to mid-Oct has received rainfall by south-west monsoon which contributes almost 90% of the annual rainfall. The average annual rainfall of Ayad River basin is 640 mm (LPA: 1901–2021).

Table 9.4 Important geomorphic units of the Ayad River Basin, Udaipur

S.No	Geomorphic Units	Map Symbol	Lithology	Description of groundwater prospects
1	Alluvial Plain—Shallow	APS-GN	Gneiss	Prospect increases with availability of water in stream
2		APS-MC	Migmatite Complex	
3		APS-MCR	Meta-Conglomerate, Meta-Rkose	
4	Buried Pediplain Shallow	BPS-MLD	Massive Limestone / Dolomite	Horizontal boring in weaker zone may increase yield
5		BPS-GG	Granite and Gneiss	
6		BPS-MCL	Marble and Crystalline Limestone	
7		BPS-MSC	Meta-Siltstone and Meta-Conglomerate	
8		BPS-S	Schist	Horizontal boring in fractures and joint
9		BPS-M	Marble	
10		BPS-MV	Meta-Volcanics	Horizontal boring if weaker zone available
11		BPS-G	Granite	
12		BPS-MC	Migmatite Complex	
13		BPS-P	Phyllite	
14		BPS-Q	Quartzite	
15		BPS-DM	Dolomitic Marble	
16		BPS-MCR	Meta-Conglomerate, Meta-Rkose	Low success rate of wells due to shallow weathered zone
17	Denudational Hills	DH-PM	Phyllites with Impure Marble	Mainly runoff zone. Limited prospects expected along features and valley portions
18		DH-MB	Meta-Basics	
19		DH-MLD	Massive Limestone / Dolomite	Mainly runoff zone
20		DH-GG	Granite and Gneiss	
21		DH-MCL	Marble and Crystalline Limestone	
22		DH-MSC	Meta-siltstone and Meta-Conglomerate	
23		DH-P	Phyllite	
24		DH-DM	Dolomitic Marble	
25		DH-MCR	Meta-Conglomerate, Meta-Rkose	

(continued)

Table 9.4 (continued)

S.No	Geomorphic Units	Map Symbol	Lithology	Description of groundwater prospects
26		DH-Q	Quartzite	Mainly runoff zone. Prospect limited to valley portion only
27		DH-ST	Serpentine-Talc	
28		DH-GN	Gneiss	
29		DH-S	Schist	
30	Fracture Valley	FV-DM	Dolomitic Marble	Fracture zones are more suitable for groundwater development. Good recharge conditions
31		FV-MB	Meta-Basics	
32	Inselberg	I-Q	Quartzite	Mainly runoff zone
33	Intermontane Valley	IV-MB	Meta-Basics	Groundwater prospects are good along fracture zones only. Good recharge conditions
34		IV-MSC	Meta-siltstone and Meta-Conglomerate	
35		IV-PM	Phyllite	
36		IV-M	Marble	
37	Linear Ridge	LR-Q	Quartzite	Mainly runoff zone
38	Moderately Dissected Plateau	PLM-MC	Migmatite Complex	Mainly runoff zone. Prospect limited to fractures and valley portions
39		PLM-DM	Dolomitic Marble	
40	Pediment	PD-MLD	Massive Limestone/ Dolomite	Localized prospect only in fractured zone
41		PD-GG	Granite and Gneiss	
42		PD-S	Schist	
43		PD-MCL	Marble and Crystalline Limestone	
44		PD-MSC	Meta-siltstone and Meta-Conglomerate	
45		PD-GN	Gneiss	
46		PD-M	Marble	
47		PD-MV	Meta-Volcanics	
48		PD-MC	Migmatite Complex	
49		PD-P	Phyllite	
50		PD-Q	Quartzite	
51		PD-MCR	Meta-Conglomerate, Meta-Rkose	
52	Pediment Inselberg Complex	PIC-Q	Quartzite	Inselbergs act as runoff zones. Prospects limited to pediment part only
53	Residual Hills	RH-Q	Quartzite	Mainly runoff zone

(continued)

Table 9.4 (continued)

S.No	Geomorphic Units	Map Symbol	Lithology	Description of groundwater prospects
54	Structural Hills	SH-MSQ	Mica Schist and Quartzite	Mainly runoff zone. Limited prospects expected along features and valley portions
55		SH-PCS	Phyllites and Chlorite Schist	
56		SH-G	Granite	Prospect limited to valley portion only
57		SH-P	Phyllite	
58		SH-Q	Quartzite	
59		SH-M	Marble	
60		SH-MC	Meta-Conglomerate	
61	Valley Fill-Shallow	VFS-GG	Granite and Gneiss	Prospect varies with the availability of water in stream
62		VFS-P	Phyllite	
63		VFS-MCM	Meta-Conglomerate, Meta-Rkose	
64	Lineaments	LNM		

9.5.2.2 Rainfall Analysis

The monthly rainfall data of the Ayad River basin has been downloaded from Water Resource Department, Rajasthan between 1901 and 2021 (121 years in total). The data obtained from the above sources were tabulated and summary statistics, namely, mean, standard deviation (SD), and coefficient of variation (CV) were reported. For detecting the trends, time series graphs were plotted, and Mann–Kendall's test was used for the selected variables. Annual rainfall variability is shown in Fig. 9.7 from which can be concluded that the average annual rainfall of Ayad River basin is 640 mm with CV 32.82%. The 1st highest (1222.8 mm), and 2nd highest (1184 mm) rainfall were realized during the year 1917, and 2019, respectively, while the lowest (127.8 mm) during 1938. The annual rainfall during 1917 was about 91% more than the long period average (LPA-640 mm).

The Mann–Kendall's Trend Test

The significance of the trends was tested by a nonparametric test known as the Mann–Kendall (MK) test. It recognizes trends in the data of time series. The test was presented by Mann (1945) and Kendall (1975) and has been extensively used in environmental time series analysis (Hipel et al. 1994). The Mann-Kendal (MK) test examines a trend in a time series without stipulating whether the trend is linear or nonlinear. The Mann–Kendall test for perceiving monotonic trends in hydrologic time series is designated by Yue et al. (2002). Statistics summary is shown in Table 9.5.

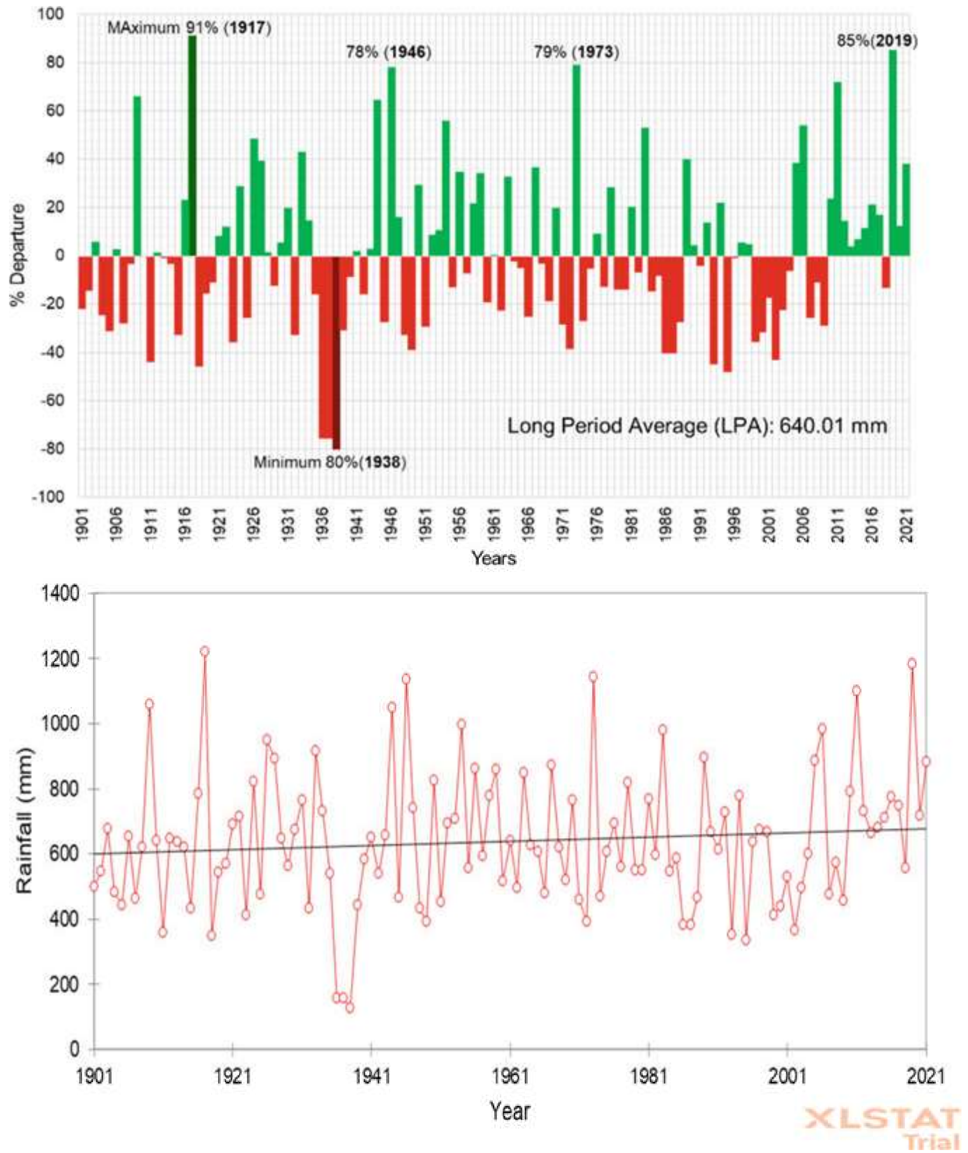


Fig. 9.7 Percentage departure of annual rainfall from LPA: 640 mm and trend analysis of rainfall in Ayad River Basin, Udaipur

9.5.2.3 Residual Mass Curve

For preparation of residual mass curve for Ayad River basin, the annual rainfall for 121 years (1901–2021) has been considered, which has been prepared by taking the cumulative departure from the average annual rainfall against the number of years and it has been divided into different cycle based on the departure from the average annual rainfall (Fig. 9.8). The parts of the curves, which are above the base line,

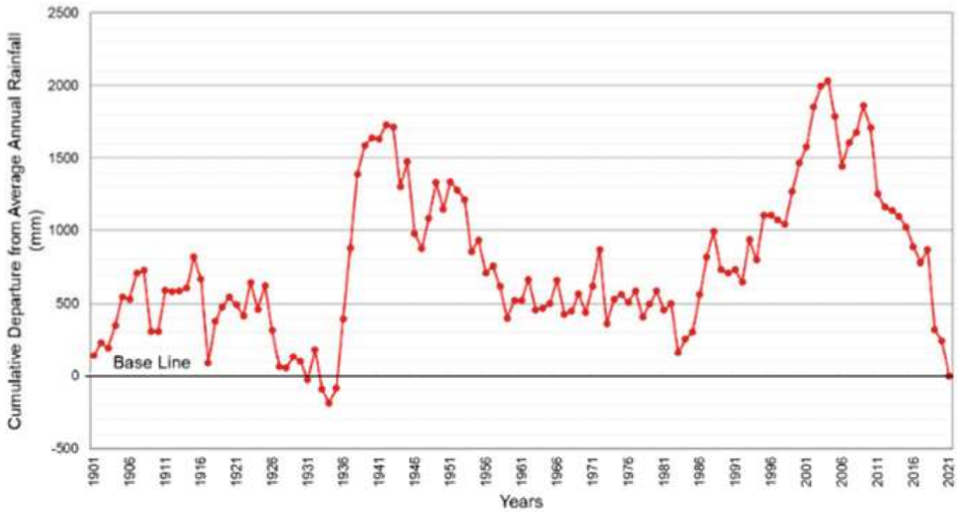


Fig. 9.8 Annual residual mass curve of Ayad River Basin, Udaipur

Table 9.5 Summary Statistics and Mann–Kendall Trend Test

Summary Statistics			Mann–Kendall Trend Test (Rainfall (mm))		
1	Observations data	121	1	Kendall's tau	0.073
2	Minimum	127.8 (1938)	2	S	529.000
3	Maximum	1222.8 (1917)	3	Var(S)	199,245.667
4	Mean	640.0	4	p-value (Two-tailed)	0.237
5	Std. deviation	210.1	5	alpha	0.050

(representing the average annual rainfall for the number of years under consideration) indicate better period of recharge and filtration condition for the groundwater. Briefly of residual mass curve can be divided into three cycles: 1901–1930, 1931–1935, and 1936–2021, out-of-these cycles, 2nd cycle (1931–1935) lie below baseline and indicate negative values of cumulative departure, which indicate the drought condition of Ayad River basin. The other two cycles lie above base line and indicate positive values of cumulative departure, which indicate the better condition for annual groundwater increment during the period of 1901–1930 and 1936–2021.

9.5.2.4 Drainage Pattern

The streams of the study area have been ranked according to Strahler's classification (Strahler 1957). Drainage patterns produced by stream erosion over time reveal the types of rocks and geologic structures in a landscaped area drained by streams. The drainage pattern in Ayad River basin is mostly dendritic and sub-dendritic, but a radial type of drainage can be seen on Amberi Hill near the Mewar Biodiversity Park, Amberi (Udaipur) (Fig. 9.9). The dendritic pattern is most common, and develops in areas where the rock or non-aggregated material beneath the stream has no fabric or structure and can be eroded equally easily in all directions. In the radial drainage system, the streams radiate outwards from a central high point. Volcanoes usually display excellent radial drainage. The radial drainage pattern in Ayad River basin is noticed on calcareous quartzite rock of Aravalli supergroup.

The drainage density is an important index to show fluvial geomorphology (Horton 1945; and Langbein 1947). The study on drainage density is helpful to understand the evolution of the whole hydrological and geomorphic process (Montgomery, 1989). Drainage density of Ayad River basin has been generated by using drainage network, which has been extracted from SRTM DEM data. The drainage density of the basin is ranging between 0.46 and 3.45 (Km/Km^2) (Fig. 9.9). The spatial characteristics of drainage density are analysed, and the relationship between drainage density and its influencing factors, e.g., the topography, lithology, precipitation, and vegetation coverage, is explored. Our results show that terrains with a plan curvature ≥ 3 can represent the channels in the study area. drainage density decreases with increasing average slope and average local relief.

9.5.2.5 River and Lake Link

The inner plain of the basin is surrounded by the western and central Aravalli hills, and its water drains into the Ayad River. Eight man-made lakes are connected in a chain in the saucer-shaped valley of Udaipur, which is the first historic river-linking project in Udaipur and helped the city to sustain its water requirements (Rathore 2010). These river and lake links are Govardhan Sagar to Lake Pichola; Lake Pichola is linked to Doodh Talai, Amarkund, and Kumharia Talab with channels; Kumharia Talab is linked to Rang Sagar; Rang Sagar links to Swaroop Sagar and Amarkund; Swaroop Sagar overflows into Fateh Sagar which comprises of the eighth link channel. River and lake link map of Ayad River basin is shown in Fig. 9.10.

9.5.3 Hydro-Geological Characteristics

9.5.3.1 Groundwater Level

The Ayad River basin has a well-distributed network of groundwater monitoring stations (45 in total, within the basin) owned by Central Ground Water Board (CGWB). The available data of groundwater monitoring stations have total depth of well, pre-post depth-to-water-level from 2011 to 2020, and lithology / formation as shown in Fig. 9.11. Out-of-45 groundwater monitoring stations, eleven locations

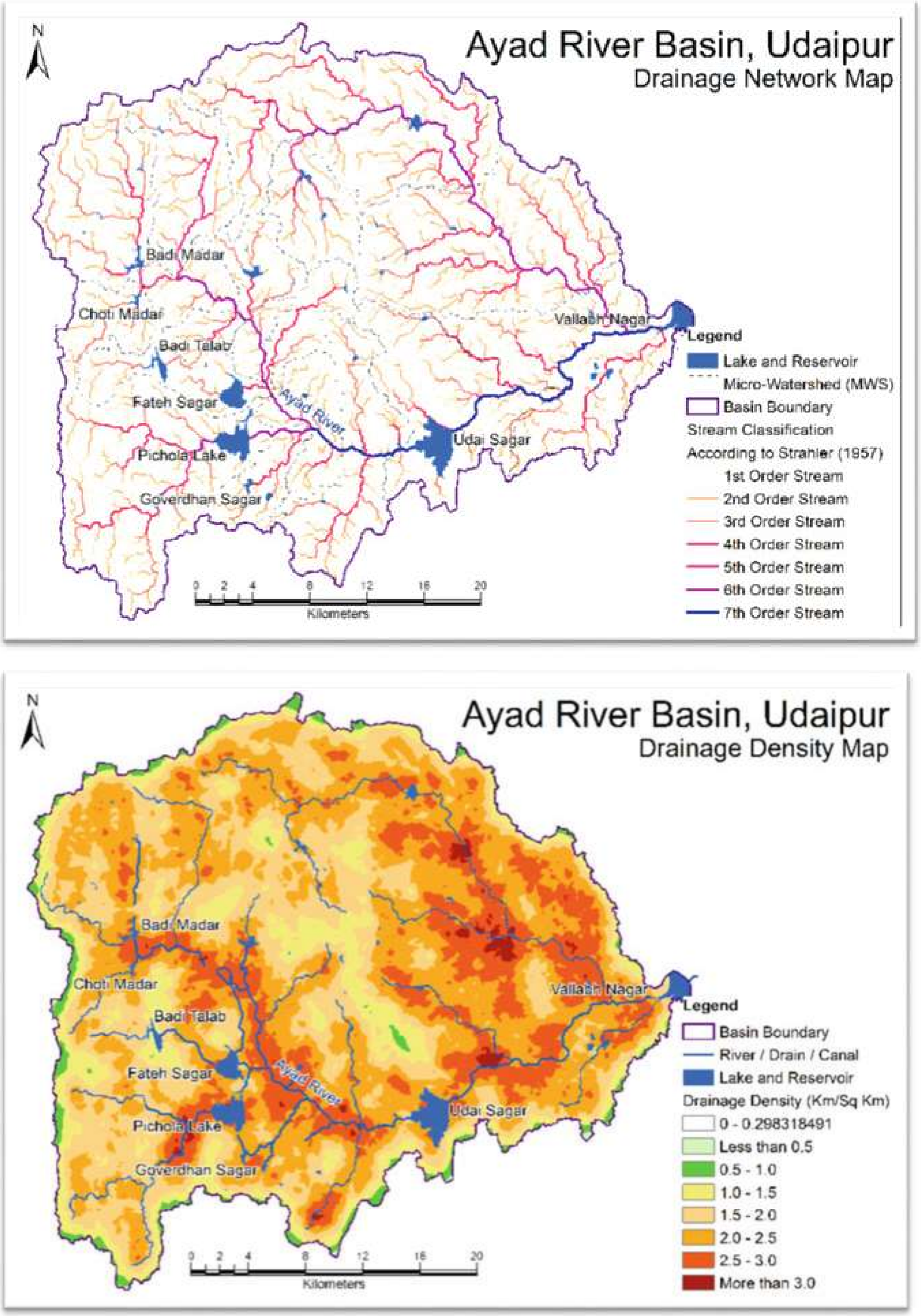


Fig. 9.9 Drainage network and drainage density map of Ayad River Basin, Udaipur

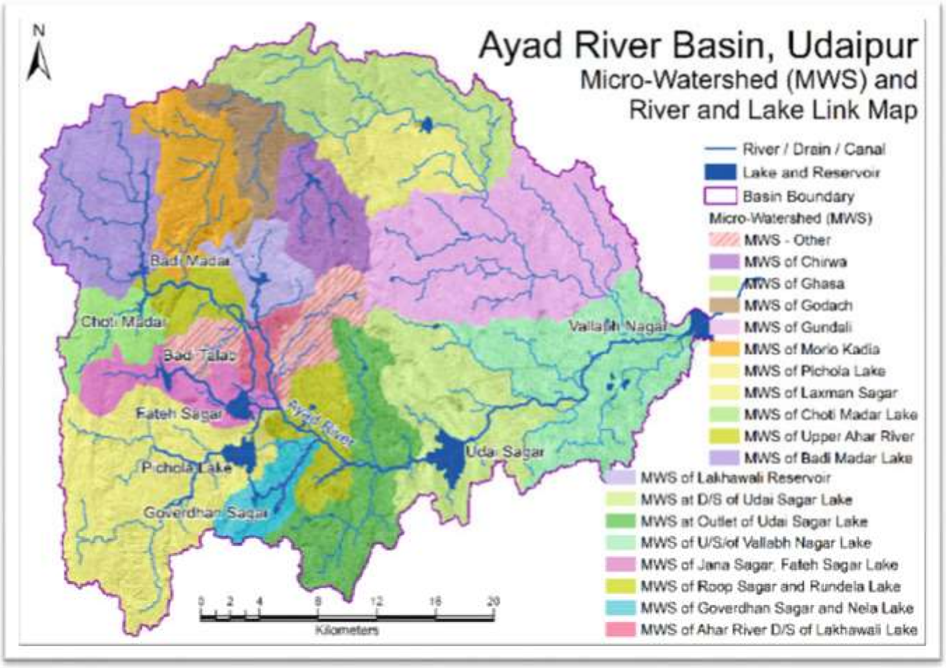


Fig. 9.10 Micro-watershed and river–lake link map of Ayad River Basin, Udaipur

are situated in Gneiss, five locations are situated in limestone, twenty-one locations are situated in phyllite, four locations are situated in Phyllite/Schist, and only four locations are situated in dolomitic marble formation. Ten years average water levels (m, bgl) of pre- and post-monsoon in gneiss, limestone, phyllite, phyllite/schist, and dolomitic-marble formation are 12.30 m–5.62 m, 16.35 m–9.48 m, 10.06 m– 3.97 m, 15.13 m– 6.29 m, and 13.64 m– 8.38 m, respectively. Depth-to-water-level (DTWL) represents the position of water table with reference to ground surface, which is useful to delineate the areas of recharge, discharge, and water logging conditions.

9.5.3.2 Groundwater Fluctuation

Water level fluctuation of Ayad River basin is shown in Fig. 9.12, where fluctuations are ranging between 0 m and 21.2 m over the period (2011–2020). The low water level fluctuation (from pre-monsoon to post-monsoon) indicates overexploitation, which is represented by red colour in Fig. 9.12. The areas represented by green colour have the highest deviation with dense drainage, higher hydraulic conductivity, and fertile soils. There are several factors involved in difference of water level fluctuation in distinct part of Ayad River basin that may be naturally over time due to difference in seasonal variation, precipitation patterns, streamflow, and change in geological formation. Artificial factors may also be affecting the water level fluctuation, these

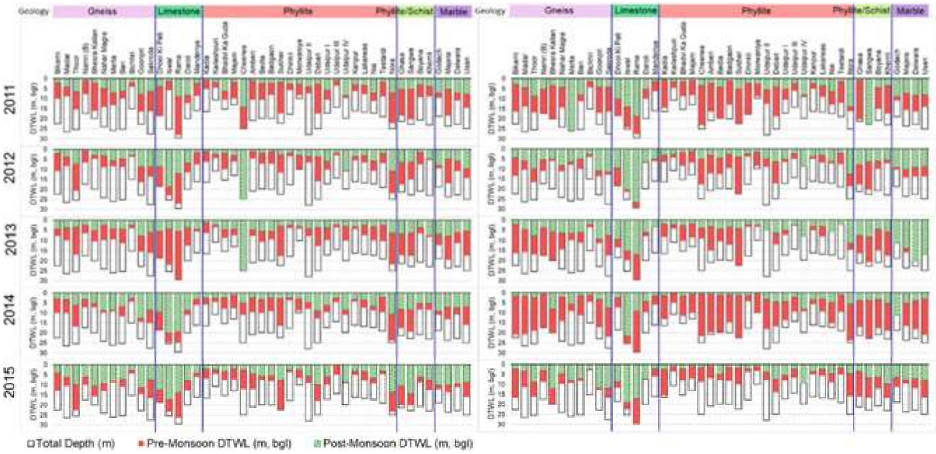


Fig. 9.11 Pre-and-post-monsoon depth-to-water-level data from 2011 to 2020 in Ayad River Basin, Udaipur

are mining activities, excess pumping out for different purposes, deforestation, and impervious surfaces on the landscape.

9.5.3.3 Groundwater Flow Direction

Groundwater flow in the subsurface is driven by differences in energy-water flows from high energy areas to low energy. Groundwater therefore flows from regions of high hydraulic head to areas of low hydraulic head. The creation of potentiometric maps of unconfined and confined aquifers, as well as representations of numerous aquifers in complex groundwater systems, is an important component in analysing groundwater flow conditions. In order to define groundwater flow directions through aquifers, individual measurements (ten years average from 2011 to 2020) of hydraulic head are combined to generate contour maps of water level for pre- and post-monsoon (Fig. 9.13). These maps define the potentiometric surface, which is much like a topographic contour map but defines the distribution of potential energy in the groundwater system. Each contour / equipotential represents a line of equal hydraulic head. The potential for exchange across aquifers and the horizontal and vertical directions of groundwater flow are both interpreted using head measurements from field investigations.

The location of recharge and discharge zones may be determined by interpreting the mapping gradients and the behaviour of groundwater flow. The area around Rama, Iswal groundwater stations which is situated at north, north-east in the Ayad River basin is the best recharge zone, because groundwater is moving here from the surrounding areas in both periods. While the area around Amberi, Bedla, Badgaon, Sukher, Dhinkli, Udaipur groundwater stations which is situated at central in the basin is the discharge zone, here groundwater is moving towards outside in pre- and

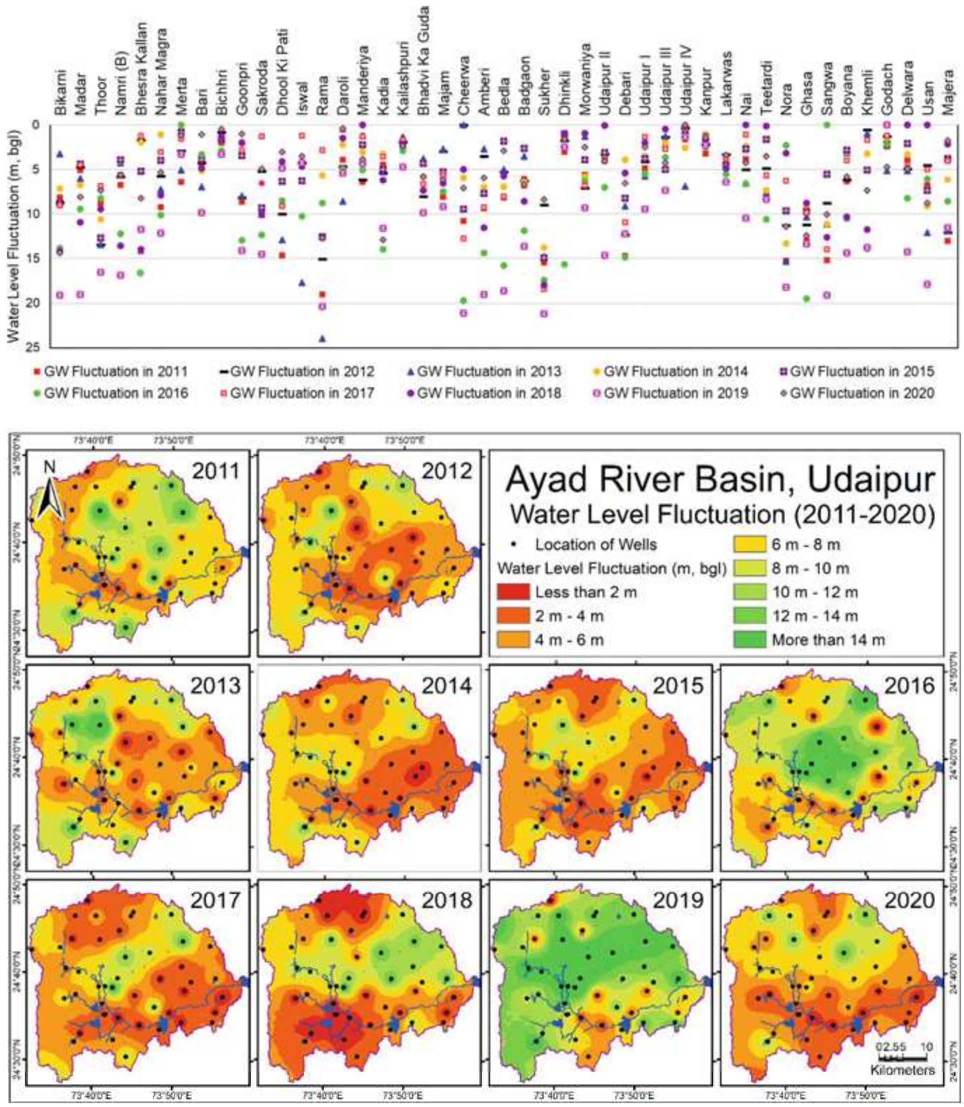
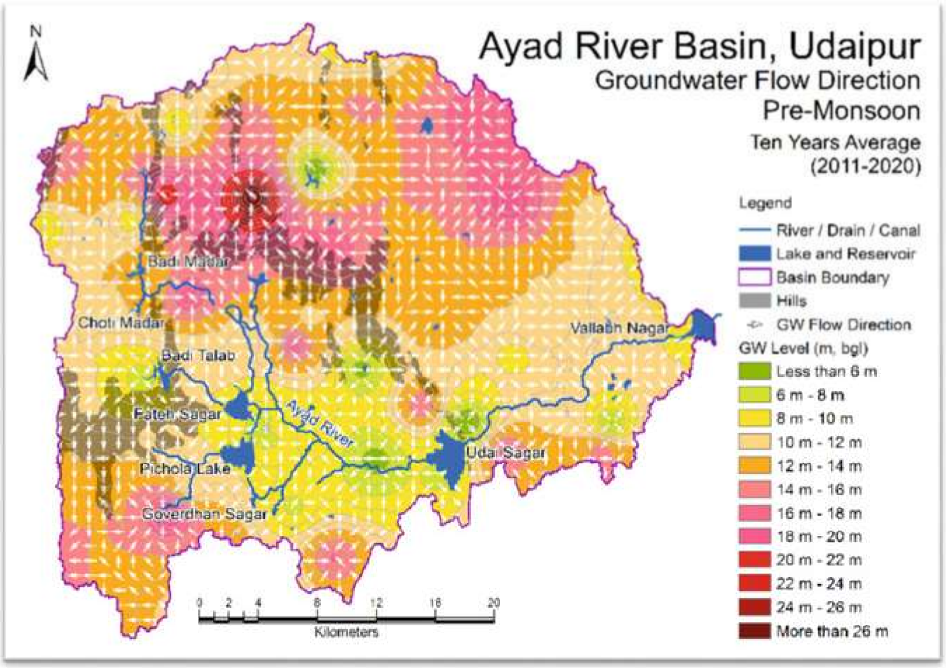


Fig. 9.12 Water level fluctuation from 2011 to 2020 in Ayad River Basin, Udaipur

post-monsoon. It is also observed that the groundwater flow is not controlled by the topographic height.



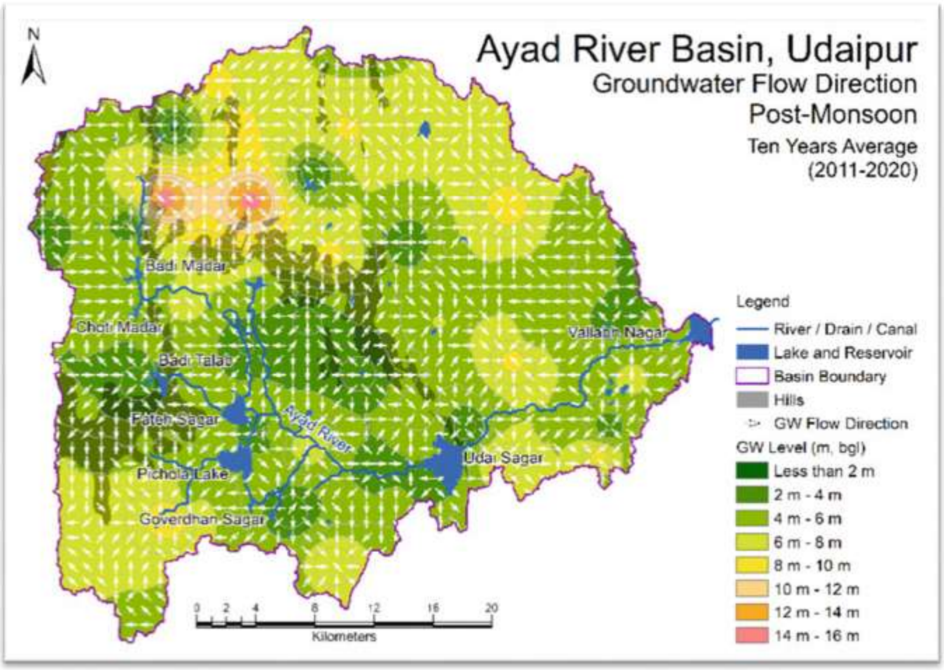


Fig. 9.13 Groundwater flow direction in pre-and-post-monsoon in Ayad River Basin, Udaipur

9.5.4 *Groundwater Resource Evaluation*

9.5.4.1 Groundwater Resource Estimation

Quantification of the groundwater recharge is a basic pre-requisite for efficient groundwater resource development, and this is particularly vital for Rajasthan with widely prevalent semi-arid and arid climate. For rapidly expanding urban, industrial and agricultural water requirement of the study area, groundwater utilization is of fundamental importance. Quantification of groundwater resources is often critical, and no single comprehensive technique is yet identified which can estimate accurate groundwater assessment. The methodologies adopted for computing groundwater resources have undergone a continuous change. The computation methods, like the groundwater resources itself, have been dynamic in nature and gradual refinement has taken place with the generation of more and more data input and with better understanding of science of groundwater.

Govt. of India has established the Groundwater Estimation Committee (GEC) in 1982, and they have recommended two approaches for groundwater resource assessment, namely (i) groundwater level fluctuation and specific yield method and (ii) rainfall infiltration factor method. The committee was again reconstituted in the year 1995 to review the methodology recommended earlier. This reconstituted committee released its report in the year 1997 and suggested several modifications in the methodology based upon groundwater level fluctuation method. The methodology recommended by GEC-1997 was being used for groundwater assessment in the country for the last two-and-half decades.

Under the groundwater level fluctuation and specific yield ($GW_{LF}S_Y$) method the change in storage (ΔS) can be computed by multiplying water level fluctuation between pre- and post-monsoon seasons (h) with the area of assessment (A), and specific yield (Sy), and formula is $\Delta S = h * Sy * A$. Specific yield values of the geological formations for different aquifers have been taken from the published norms/reports (ARDS 1979; NABARD 1984; CGWB 2009), and summarized in column (1) of Table 9.6.

To estimate the groundwater resource, the groundwater level fluctuation method has been adopted by taking the observation well data into consideration. Future, it has been noted that the annual groundwater increment is not only due to rainfall but also the application of surface water for irrigation. To use this method, the area between two contours at 1 m interval of groundwater level fluctuation has been computed using observation well data and inverse distance weighting (IDW) interpolation method in spatial analyst tool of ArcGIS software. Subsequently, the specific yield map of Ayad River basin has been multiplied by the groundwater fluctuation map for each year (from 2011 to 2020) through raster calculator of map algebra script of spatial analyst tool of ArcGIS software for estimation of groundwater resource from 2011 to 2020. This analysis provides the volume of saturated aquifer material that occurred between contours. The saturated volume of aquifer material between successive contours has been summed up for all aquifer to get the total saturated volume of

Table 9.6 Calculation of annual groundwater resource for the year 2011 through groundwater level fluctuation method

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	Groundwater Fluctuation (m) h	0–2	2–4	4–6	6–8	8–10	10–12	12–14	14–18	
Sy (%)	Ave. Fluctuation (m)	1.0	3.0	5.0	7.0	9.0	11.0	13.0	16.0	
	Area of Fluctuation (Km^2) in different Lithology and Formation (A)									Total
6.0	Clayey Alluvium, Alluvial Plain	0.0	1.7	23.9	39.2	6.4	3.2	1.2	0.1	75.6
2.0	Granite, Schist, Gneiss, Limestone	0.0	1.0	12.4	63.9	38.3	2.7	1.0	0.3	119.6
1.5	Marble, Phyllite, Quartzite	0.5	17.0	163.4	118.4	125.9	45.6	13.1	5.6	489.5
0.3	Migmatite Complex, and Meta-Basics	0.0	11.4	55.5	179.1	122.4	61.4	25.9	7.4	463.0
10	Valley Fill	0.3	6.8	24.6	14.3	5.9	2.8	2.8	1.5	59.0
	Total	0.8	37.9	279.8	414.8	298.9	115.6	44.0	15.0	**1206.8**
	Volume of Rock Material in which Fluctuation take place (Cubic Km) in **2011**									
6.0	Clayey Alluvium, Alluvial Plain	0.000	0.005	0.119	0.275	0.058	0.035	0.016	0.001	0.508
2.0	Granite, Schist, Gneiss, Limestone	0.000	0.003	0.062	0.447	0.345	0.030	0.013	0.006	0.905
1.5	Marble, Phyllite, Quartzite	0.000	0.051	0.817	0.828	1.133	0.502	0.171	0.090	3.593
0.3	Migmatite Complex, and Meta-Basics	0.000	0.034	0.277	1.254	1.101	0.675	0.337	0.119	3.797
10	Valley Fill	0.000	0.020	0.123	0.100	0.053	0.030	0.036	0.024	0.388
	Total	0.001	0.114	1.399	2.904	2.690	1.272	0.572	0.240	**9.190**

(continued)

Table 9.6 (continued)

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
	Annual Groundwater Resource (Cubic Km) (ΔS)									
6.0	Clayey Alluvium, Alluvial Plain	0.000	0.000	0.007	0.016	0.003	0.002	0.001	0.000	0.030
2.0	Granite, Schist, Gneiss, Limestone	0.000	0.000	0.001	0.009	0.007	0.001	0.000	0.000	0.018
1.5	Marble, Phyllite, Quartzite	0.000	0.001	0.012	0.012	0.017	0.008	0.003	0.001	0.054
0.3	Migmatite Complex, and Meta-Basics	0.000	0.000	0.001	0.004	0.003	0.002	0.001	0.000	0.011
10	Valley Fill	0.000	0.002	0.012	0.010	0.005	0.003	0.004	0.002	0.039
	Total	0.000	0.003	0.034	0.052	0.036	0.015	0.008	0.004	**0.15263**
		Average Annual Groundwater Resource (Million Cubic Meters) MCM								**152.63**

the aquifer materials, then this volume has been multiplied by the specific yield to calculate the annual groundwater resources. detailed logical calculation for the year 2011 of groundwater resource by using groundwater fluctuation method is given in Table 9.6, and same calculation has been done from 2012 to 2020. The estimated annual groundwater resource from 2011 to 2020 is given in column (11) of Table 9.6. The average annual groundwater resource in Ayad River basin is 127.81 million cubic meters (MCM).

Groundwater recharge may be estimated using rainfall infiltration factor method. In that method, the rechargeable area under different hydrogeological units (A_{HR}) is multiplied with relevant rainfall infiltration factors (R_{IF}), and normal rainfall (R_N), and formula is Groundwater recharge (R_{GW}) = (A_{HR}) * (R_{IF}) * (R_N). GEC-15 has recommended the rainfall infiltration factors for different hydrogeological units, which has been given in column (4) of Table 9.7. For the estimation of groundwater recharge from 2011 to 2020 through rainfall infiltration method, all analysis has been done by using ArcGIS software, and results are given in column (10) of Table 9.7.

After the groundwater resource was estimated through groundwater level fluctuation and specific yield ($GW_{LF}S_Y$) method, results have been compared with the rainfall infiltration factor method (R_{IF}) and calculated the percentage deviation (PD) by using standard formula: PD = ($GW_{LF}S_Y$ - R_{IF}) / R_{IF} * 100, and results have been given in column (12) of Table 9.7. As per the guideline suggested by GEC-97, if PD is greater than / less than / equal to ± 20%, RIF should be considered. Author has adopted these suggestions and considers the data of groundwater resource obtained through groundwater level fluctuation method.

9.5.4.2 Annual Groundwater Draft

Central Ground Water Board (CGWB) had estimated groundwater resources in 2019 as per the norms recommended by GEC-97. Annual replenishable groundwater resources of the blocks under Ayad River basin have been estimated to be 139.24 MCM. Net annual groundwater availability is estimated as 129.02 MCM, which is matched with annual groundwater resource (127.81 MCM) estimated through groundwater level fluctuation method by author. Annual groundwater withdrawal for all uses is 131.45 MCM. Summarized block wise estimate of dynamic groundwater resources is given in Table 9.8. Overall stage of groundwater development is 101.88%, which is more than the Udaipur district average (101.35%) (CGWB 2019).

The dynamic groundwater resource estimation indicates 101.88% percentage of groundwater development in Ayad River basin is under over-exploited category. However, there are enough static reserves to sustain consumptive groundwater use during drought periods. The author has compared the previous groundwater resource estimation by various experts and authority to the current study, and the detail of these studies are summarized here. (1) CGWB (2009) estimated groundwater resources (GWR) of blocks of Udaipur in Ayad basin by GEC-97 methods, and they estimated the GWR as 139.24 MCM; (2) Pareta and Pareta (2015) also estimated groundwater

Table 9.7 Calculation of annual groundwater recharge through rainfall infiltration factor method

(1)	(2)			(3)	(4)	(5)
S.No	Hydrogeological Units			(A_{HR}) Km^2	(R_{IF}) %	$(A_{HR})*(R_{IF})$ Km^2
1	Clayey Alluvium, Alluvial Plain			75.77	24	18.18
2	Granite, Schist, Gneiss, Limestone			120.30	12	14.44
3	Marble, Phyllite, Quartzite			489.33	10	48.93
4	Migmatite Complex, and Meta-Basics			462.28	9	41.61
5	Valley Fill			59.06	25	14.77
	Total			1,206.75		137.93
(6)	(7)	(8)	(9)	(10)	(11)	(12)
Year	Normal Rainfall (R_N) mm	Normal Rainfall (R_N) m	$(A_{HR})*(R_{IF})*(R_N)$ m^3	Groundwater Recharge (R_{GW}) (MCM) by RIF Method	Annual GW Resource (ΔS) (MCM) by $(GW_{LF}S_Y)$ Method	PD = $(GW_{LF}S_Y-R_{IF})$ / R_{IF} * 100 (%)
2011	1,100.40	1.100	151,772,866.29	151.77	152.63	0.56
2012	730.70	0.731	100,781,927.84	100.78	117.88	16.97
2013	663.50	0.664	91,513,355.86	91.51	117.54	28.44
2014	682.30	0.682	94,106,349.21	94.11	124.40	32.19
2015	711.50	0.712	98,133,764.42	98.13	106.98	9.01
2016	774.70	0.775	106,850,635.69	106.85	141.16	32.11
2017	747.40	0.747	103,085,278.32	103.09	104.83	1.69
2018	556.00	0.556	76,686,399.18	76.69	101.92	32.90
2019	1,184.00	1.184	163,303,411.20	163.30	206.01	26.15
2020	717.91	0.718	99,017,864.81	99.02	104.72	5.76
	Average			108.53	127.81	17.77

resources of Berach basin by GEC-97 methods, and they have estimated an annual groundwater potential of 786 MCM, and GWR as 1165 MCM; (3) Shyam et al., (2020) estimated groundwater resources (GWR) of Udaipur district through mathematical modelling, and they found the groundwater resources as 637 MCM; (4) In the current study Pareta (2023) estimated an annual groundwater potential of 127 MCM in the Ayad river basin using the groundwater fluctuation method and 129 MCM using the rainfall infiltration method. I have compared all above stated studies and calculated the GWR (MCM/Sq Km) and found that CGWB (2009) estimated the GWR 0.105 MCM/Sq Km, Pareta and Pareta (2015) estimated the GWR 0.097 MCM/Sq Km, Shyam et al., (2020) estimated the GWR 0.054 MCM/Sq Km, and current study Pareta (2023) estimated the GWR 0.105 MCM/Sq Km using groundwater fluctuation method, and 0.107 MCM/Sq Km using rainfall infiltration method. After the comparison of GWR with other studies, I have found that the result of this

Table 9.8 Annual groundwater resource and groundwater draft by CGWB

Block (district)	Annually replenishable GW resource (MCM)	Net annual GW availability (MCM)	Gross GW draft for irrigation (MCM)	Gross GW draft for domestic and industrial users (MCM)	Gross GW draft for all users (MCM)	Stage of GW development (%)	Category
Badgaon (Udaipur)	9.46	8.99	7.68	1.48	9.16	101.98	OE*
Girwa (Udaipur)	37.26	34.00	27.94	6.72	34.66	101.95	OE*
Mavli (Udaipur)	23.13	22.18	19.44	3.26	22.70	102.37	OE*
Gogunda (Udaipur)	23.94	22.02	21.18	1.08	22.26	101.10	OE*
Bhinder (Udaipur)	27.42	25.15	23.01	2.59	25.61	101.83	OE*
Khamnor (Rajsamand)	18.03	16.70	14.70	2.36	17.06	102.17	OE*
Total	139.24	129.02	113.96	17.49	131.45	101.88	OE*

*Over-Exploited. *Source* Central Ground Water Board (CGWB), 2019

study is very compensative and satisfactory, and these will basis for future numerical studies of the Ayad river basin.

9.5.4.3 Status of Groundwater Development

Rainfall in the Ayad River basin is the main source of groundwater recharge. Due to less rainfall and increased groundwater withdrawals, groundwater levels are declining in some parts of the basin, particularly in the northern and central parts. Increasing urbanization and change in lifestyle have led to increased demand of water. Increasing urbanization also leads to reduced recharge. Further groundwater is also an important source for irrigation in the basin. The stage of groundwater development for the Ayad River basin has reached around 102% and it is over-exploited. There is practically no scope left for further groundwater development in the Ayad River basin.

Table 9.9 Deficit/surplus reserves and projected groundwater reserves at different rainfall events

Projected rainfall (mm/annum)	Dynamic reserves (MCM/annum) based on rainfall (mm)	GW draft (MCM/annum)	Deficit/surplus reserves and projected GW reserves (MCM/annum)
100	20.16	131.45	−111.29
200	40.32	131.45	−91.14
300	60.48	131.45	−70.98
400	80.64	131.45	−50.82
500	100.80	131.45	−30.66
600	120.96	131.45	−10.50
640.01	**129.02**	**131.45**	**−2.43**
700	141.12	131.45	9.66
800	161.28	131.45	29.82
900	181.44	131.45	49.98
1000	201.60	131.45	70.14
1100	221.76	131.45	90.30
1200	241.92	131.45	110.46
1300	262.07	131.45	130.62
1400	282.23	131.45	150.78
1500	302.39	131.45	170.94

9.5.5 *Projection of Groundwater Reserves*

ASCE (1987), Shah et al. (2001), Narasimha (2003), Zhang et al. (2009), Ibrahim et al. (2020), Kwon et al. (2020), and Hamdan et al. (2021) have used the random number theory and correlation regression analysis and established a mathematical relationship to estimate the total groundwater reserves in any area for a minimum to maximum rainfall. Based on above said relationship, and linear equation model, author has established a relationship between rainfall (average rainfall 640.01 mm) and deficit/surplus reserves (total deficit reserves is 2.43 MCM), which has been used to project the availability of groundwater. Projected groundwater reserves at different rainfall events are given in Table 9.9.

9.5.6 *Sustainability Management of Groundwater Reserves*

Based on average rainfall (640 mm), the total deficiency reserves are 2.43 MCM/annum. In such a scenario, groundwater recharge measures equal to deficit reserves from large rainwater-harvesting structures, water conservation, reuse-recycle measures, and management of current groundwater draw are essential for sustainable groundwater development (Chatterjee et al. 2009; Wali et al. 2020;

Boryczko and Rak 2020). Future scenarios may see an increase in the draught because of population growth, new industrial development or extension of current industries, mining development or expansion, and the agriculture and mining sectors. Consequently, the net groundwater draught will be greater than what is currently required (Chatterjee et al. 2009; Shin et al. 2018). The deficit reserves are taken from static reserves, and the total amount of dynamic reserves available is 129.02 MCM annually. As a result, it's critical to regulate groundwater abstraction and optimize groundwater usage by updating the current irrigation techniques with a sprinkler-drip irrigation system, achieving more crop per drop. The most urgent requirement right now is for municipalities and panchayats to recycle and reuse water using STP. Additionally, creating maximum groundwater recharge structures and redirecting floodwater to other locations where groundwater is not available might be helpful strategies to support long-term usage (Shekhar 2006; Shekhar et al. 2009).

9.6 Conclusions

The main purpose of this study is to investigate the biophysical-geomorphic, hydrological, and hydro-geological characteristics of Ayad River basin, and to estimate and project the groundwater resource by using the innovative and extensive secondary source data collected from different agencies. LULC maps indicate the decreasing trends in forest area and agricultural area and increasing trends in urban and rural area during the last decade. Soil texture map and geological map have been updated using satellite image, toposheet and DEM data. Majority of soils found in that area are black clayey, brown loamy, brown gravelly loam soils which cover 35%, 33%, and 21% of area, respectively. The red gravelly loam hilly soil covered only 10% of area. Apart from them approx. 47% of area is covered by deep to moderately deep soil (>50 cm). Geology and lithology found in the area are ranging in age from Archaean to Upper Proterozoic; and belong to three geological cycles—Bhilwara, Aravalli, and Delhi supergroups. A very detailed geomorphological map has been developed by visual image interpretation of satellite imagery, DEM data, toposheets, geological map (lithology and structural) with limited field check. The map has been classified into thirteen broad geomorphic units, and 63 micro-geomorphic units. Based on 121 years (1901–2021) rainfall data analysis, the average annual rainfall of the area is 640 mm, and residual mass curve is also indicating the better condition for annual groundwater increment. The drainage pattern in that basin is mostly dendritic and sub-dendritic and drainage density is ranging between 0.46 and 3.45 (Km/Km2). Eight artificial lakes are linked together in a chain in the saucer-shaped valley of Udaipur, which is the first historic river-linking project in Udaipur and it helped the city to meet its water needs.

The area has a good aquifer inside the hard rock materials such as phyllite, schist, gneiss, and quartzite, which is predominantly formed in weathered, fractured, and jointed rock formations. The average water level (bgl) in gneiss, limestone, phyllite, phyllite/schist, and dolomitic-marble formation are 12.30 m–5.62 m, 16.35 m–9.48 m, 10.06 m–3.97 m, 15.13 m–6.29 m, and 13.64 m–8.38 m, respectively. Water level fluctuation of the area is ranging between 0 m and 21.2 m over the period (2011–2020), while low water level fluctuation is indicating the overexploitation of the area. Based on behaviour of groundwater flow recharge and discharge zones has been identified—north and north-east area of the basin (area around Rama, Iswal) is the best recharge zone. While the area around Amberi, Bedla, Badgaon, Sukher, Dhinkli, and Udaipur which is situated at central in the basin is the discharge zone. Based on GEC-1997 method, the average annual groundwater resource (2011–2020) of the area is 127.81 MCM. CGWB 2019 has measured the annual groundwater withdrawal for all uses, which was 131.45 MCM. Overall stage of groundwater development is 101.88%, and it has over-exploited. Based on mini-max rainfall data and deficit / surplus reserves, a mathematical relationship has been established, and the same has been used to project the availability of groundwater. Large rainwater-harvesting structures, water conservation, reuse-recycle measures, and current groundwater management have also been recommended for sustainable management of groundwater reserves.

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