

**ASSESSMENT OF GROUNDWATER RESOURCE SUSTAINABILITY
IN THE KHAPRI WATERSHED OF DANGS DISTRICT, GUJARAT:
A REMOTE SENSING AND GIS APPROACH**

Synopsis of the thesis

to be submitted to

The Maharaja Sayajirao University of Baroda

BY

CHINMAY UDAY DONGARE

(Reg. No. FOS/2186, date of registration 05/05/2020)

GUIDE

PROF. BHUSHAN S. DEOTA

CO-GUIDE

PROF. RAJENDRA D. DESHPANDE

Department of Geology,

Faculty of Science,

The Maharaja Sayajirao University of Baroda,

Vadodara-390002.

SEPTEMBER 2023

1. Origin of the problem

The district Dangs marks the extension of Western Ghats in Gujarat state, western India. It is characterized by uniformly spread less transmissible basaltic rocks, rugged trappean highlands and moderate to very steeply sloping surfaces along with highest average annual rainfall of 2000 mm (Kumar et al. 2017) in the state of Gujarat. These critical terrain conditions give rise to higher runoff than infiltration, leading to water crisis during non-rainy period. During this crisis time, the groundwater is the main source of freshwater for the people and thus holds the utmost importance (Dongare et al. 2022; Dongare and Deota, 2023). The occurrence, distribution, recharge and quality of groundwater is dependent on variations in spatial distribution of vivid geo-environmental parameters such as geology, drainage, geomorphology, slope, lineaments, soil and land-use (Krishnamurthy et al. 1996, Sarkar et al. 2001, Kanagaraj et al. 2019). Therefore, with reference to groundwater quantity and quality, it is an imperative task to study the interdependency among the geo-environmental parameters, their spatial distribution and groundwater occurrences. In case of Dangs district, no previous systematic work, except the regional scale studies of National Remote Sensing Centre (NRSC) on groundwater prospects under Rajiv Gandhi National Drinking Water Mission (RGNDWM-2005) exists. The groundwater structures in the area have failed due to lack of watershed-based assessments of groundwater controlling parameters. Watershed based assessments are opportune for evaluating the hydrological processes as it coincides with the groundwater basin and thereby influence the groundwater potential (Limaye, 2010). Khapri watershed cover the maximum area of district Dangs and experiences acute shortage of groundwater as compared to other parts of the district. *Hence, the present study focuses on assessment of geo-environmental parameters for determining the groundwater potential zones, synthesize the status of groundwater quality for drinking as well as irrigation and understand groundwater recharge pattern in Khapri watershed.*

2. The Khapri watershed

The district Dangs forms the southernmost part of trappean highlands of mainland Gujarat. It is drained by four rivers viz. Ambica, Purna and their major ephemeral tributaries Khapri and Gira respectively. Present study focuses on the river Khapri that originates near village Vanar on the western slope of trappean highlands and drains almost the central portion of the district covering Ahwa and Waghai Talukas. To the south, it is bounded by river Ambica and to the north by river Purna. The longest stretch of river Khapri (50.7 km) lies in NW

direction and continues its journey through villages viz., Anjankund, Galkund, Ahwa, Khapri, Pimpri, and finally meets the river Ambica near village Vati. The prominent high standing trappean flows marks the watershed divides with an elevation varying from 86 m amsl at the confluence of river Ambica and Khapri to 1083 m amsl near Saputara hill station. The Khapri watershed is located between 73° 27' 12.42" E and 73° 50' 13.53" E longitude and 20° 53' 27.52" N and 20° 35' 6.91" N latitude (Figure 1) of Survey of India (SOI) topographic maps no. 46H/5, 46H/9, 46H/10, 46H/13, 46H/14 and covers the aerial extent of 523 km². The Khapri watershed exhibits dendritic to modified-dendritic drainage pattern with local pockets of trellis pattern in south-eastern and north-western extremities. The river Khapri and its tributaries are mainly controlled by NE-SW, NW-SE, NNE-SSW and NNW-SSE lineaments. Presence of dendritic drainage pattern in the watershed is attributed to uniform occurrence of massive basaltic flows disposed horizontally (GSI, 2005). While, the modified dendritic drainage pattern and localized trellis pattern are the manifestation of lineaments dispensed in the watershed.

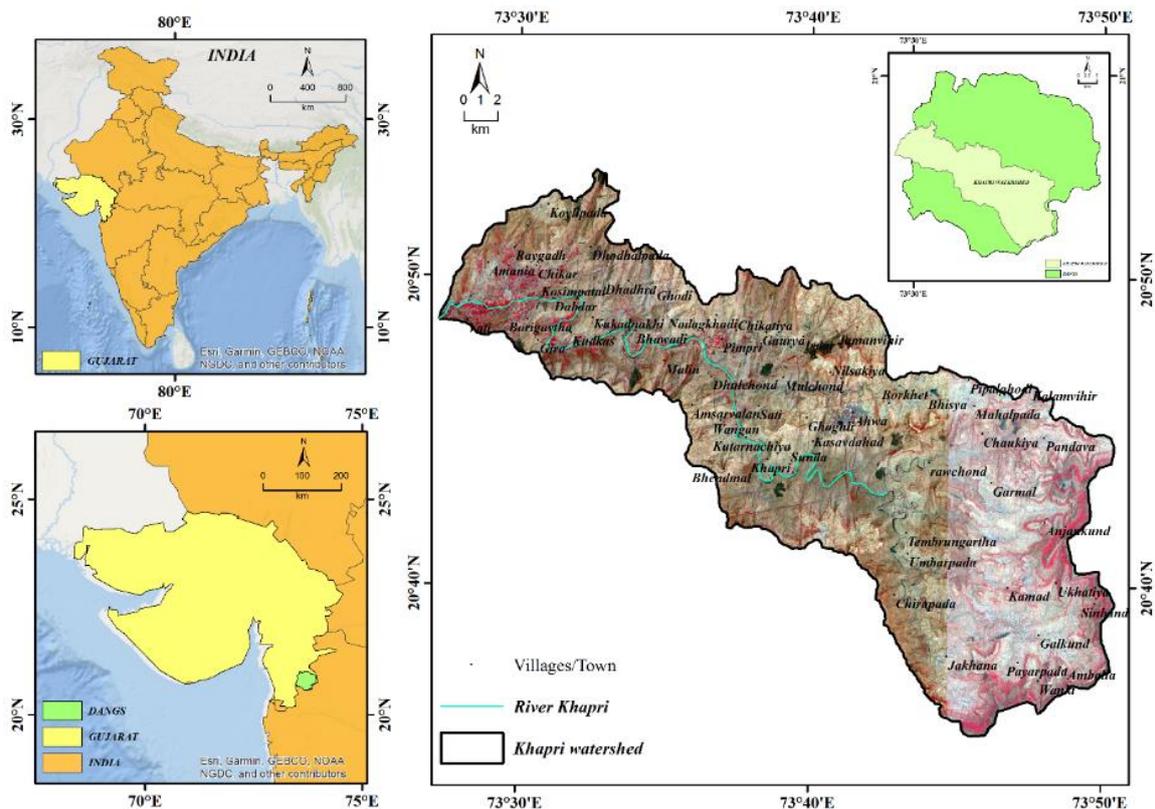


Figure 1 Geographic location of Northwest-Southeast oriented Khapri watershed shown by IRS LISS-III False Colour Composite (FCC) image of Band 432 (After Dongare and Deota, 2023).

In the light of previously mentioned research gaps, the objectives formulated are:

3. Objectives

- 1) Identification and demarcation of the groundwater potential zones in the Khapri watershed.
- 2) Assessment of groundwater quality and its suitability for drinking and irrigation purposes.
- 3) To decipher the groundwater recharge patterns and suggest suitable locations for the groundwater recharge structures.

4. Methodology

The methodology adopted to achieve the objectives is as follows:

- Extensive national and local review of scientific literature pertaining to the study area is carried out for identification of research gaps, to understand the physiographic, geological and climatic setup, natural resources, demographic profile and selection of the most suitable approach to address the research gap.
- Collection and analysis of Survey of India (SOI) topographic maps, remote sensing and ancillary data for generating thematic maps of geo-environmental parameters controlling the groundwater occurrences (Geology, Drainage, Geomorphology, Slope, Lineaments, Land-use and Soil) in Arc GIS 10.4.
- Drainage morphometric analysis with view to understand the hydrological setup of the study area.
- Ground truth verification of thematic maps, collection of samples for groundwater quality and isotope analysis and monitor seasonal groundwater levels.
- Application of multi-criteria decision method – Analytical Hierarchical Process (MCDM-AHP) based Weighted Overlay Analysis (WOA) in Arc GIS 10.4 for identification of the groundwater potential zones and their validation with the field data.
- Hydro-geochemical analysis of groundwater samples following typical India Standards for water quality analysis.
- Mapping spatial distribution of physicochemical parameters of groundwater quality using GIS technique and determine its suitability for drinking and irrigational purposes.
- Isotope Ratio Mass Spectrometry (IRMS) studies at PRL, Ahmedabad for stable isotope systematics of collected water samples and understand groundwater recharge patterns.

- Recommending specific locations for groundwater recharge structures, for the year around sustainability of the groundwater resource following IMSD, NRSC (1995) and isotope data.

5. Results and inferences

Objective I - Identification and demarcation of the groundwater potential zones in the Khapri watershed.

The groundwater potential can be described as the physical ability of a terrain to retain and yield sufficient groundwater quantity for the definite uses (domestic, agriculture or industrial) (Diaz and Martinez, 2019). It is the cumulative result of interaction between the various geo-environmental parameters (GEPs) viz., geology, geomorphology, slope, drainage density, lineament density, land use and soil. Therefore, to map groundwater potential zones, it is essential to study the interdependency among GEPs and their spatial distribution.

To identify groundwater potential zones, the thematic layers of GEPs are evaluated through Multi Criteria Decision Analysis (MCDA) - Analytical Hierarchical Process – (AHP) to derive their weightages. The sub-classes of each GEP are ranked as 1 to 5, where 1 being the least favourable while 5 represent most favourable for groundwater occurrence. Finally, overlay analysis based on AHP derived weightages is carried out to determine the groundwater potential zones in Khapri watershed. For validation, the correlation of groundwater potential zones with seasonal groundwater level fluctuation is performed. A brief account of various GEPs is given in sub-sections to follow.

Geo-environmental parameters (GEPs)

a) Geology

The geological setup and hydraulic characteristic of rock types strongly govern the occurrence, distribution and movement of groundwater, reflecting its potential. Geologically the Khapri watershed is completely underlined by Deccan basalts (nine flows) of Cretaceous-Eocene age (Figure 2a). These Deccan basalts are overlain by weathered profile, in-situ residual soil (Sharma et al. 2006), thin veneer of recent alluvium and alluvio-colluvial sediments of Quaternary age (GSI, 2005 and CGWB, 2014). The areas with alluvium supports good groundwater accumulation due to presence of primary porosity and permeability. The basalts

on the other hand support moderate to poor groundwater accumulation depending upon the nature of secondary porosity and permeability.

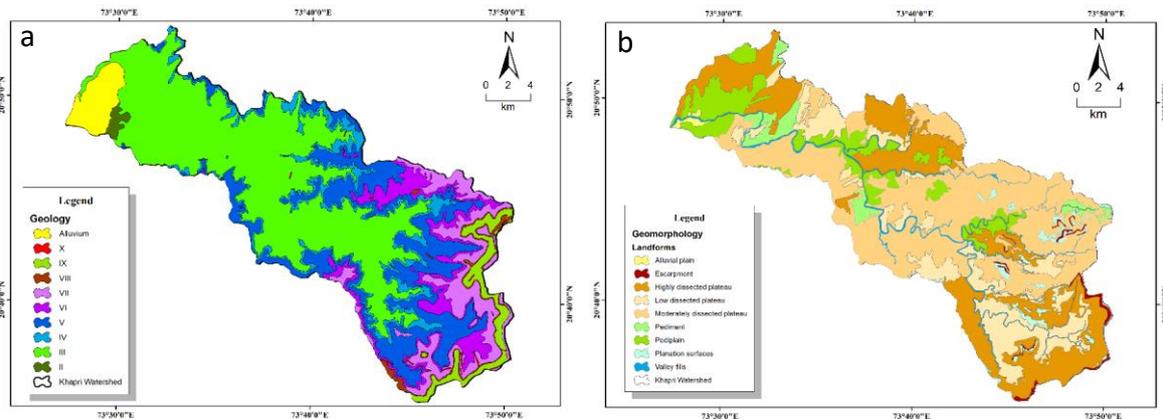


Figure 2: a. Geological map of Khapri watershed (After GSI, 2005); b. Geomorphological map of Khapri watershed (After Dongare and Deota, 2023)

b) Geomorphology

Geomorphology facilitates the characterization and analysis of environmental conditions responsible for water circulation vis-a-vis groundwater occurrence and potential (Verstappen, 1983). The Khapri watershed is characterized by unique assemblages of nine landforms from south-east to north-west directions viz., escarpments, highly dissected plateaus, moderately dissected plateaus, low dissected plateaus, planation surfaces, pediments, pediplains, alluvial plains and valley fill deposits (Figure 2b). Each of this landform has varying capacity of runoff-infiltration and acts as good indicator of groundwater potential (Dongare and Deota 2023).

c) Drainage density

Drainage density (D_d) is directly related to the measure of stream lengths and governs the duration of concentration and magnitude of discharge (Horton 1945, Strahler 1957). The drainage density of Khapri watershed ranges between 0.02 and 6.34 km/km^2 , which is classified into 4 classes viz. very low ($<1 \text{ km}/\text{km}^2$), low ($1-2 \text{ km}/\text{km}^2$), moderate ($2-3 \text{ km}/\text{km}^2$) and high ($>3 \text{ km}/\text{km}^2$) (Figure 3a). Low drainage density in the watershed reflects the permeable nature of underlying rocks that support infiltration and groundwater enrichment (Hajam et al. 2013; Horton, 1945; Selvan et al. 2011). The high drainage density value of Khapri watershed ($3.07 \text{ km}/\text{km}^2$) is attributed to less transmissible nature of underlying rocks, hilly topography and steep slopes, leading to less infiltration and increased runoff. In other

words, the drainage density shows an inverse relation to infiltration in Khapri watershed (Dongare et al. 2022).

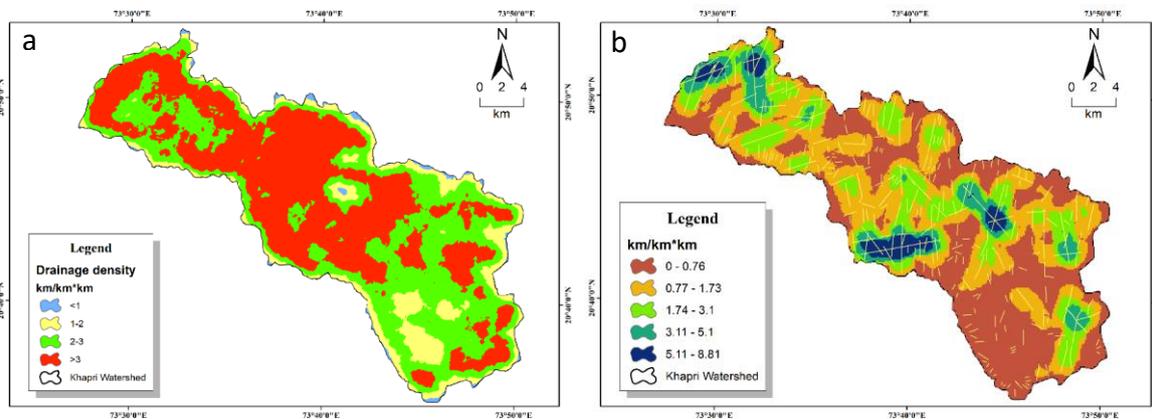


Figure 3: a. Drainage density map of Khapri watershed (Dongare et al. 2022); b. Lineament density map of Khapri watershed

d) Lineament density

Lineament is defined as any linear or curvilinear mappable feature of the earth’s surface with distinct patterns (O’Leary et al. 1976, Ahmadi and Pekkan 2021). In the present study, the lineaments are classified as (i) Positive lineaments and (ii) Negative lineaments. The ridges, plateaus and dykes on the satellite data are categorized as positive lineaments (Abdullah et al. 2010). While, offsets, regional and decipherable local joints, straight stream segments are categorized as negative lineaments (Lattman 1958, Abdullah et al. 2010). The primary reason of categorization is to assign appropriate importance based on their water infiltration potential capacity. In general, the positive lineaments due to their exposed bare rock surface and steeply sloping surfaces will not allow water to infiltrate as effectively (Javed and Wani 2009) as the negative lineaments. Moreover, along the negative lineaments there will be presence of prominent zones of localized weathering that give rise to secondary porosity and permeability and thus forming a good groundwater repository (Deota et al. 2005). To assess the groundwater potential for Khapri watershed, the negative lineament density is considered. The negative lineament density varies from 0.1 to 8.8 km/km² and is directly related to infiltration. It is classified into 5 categories viz., Very low (0.1 – 0.76 km/km²), Low (0.77 – 1.73 km/km²), Moderate (1.74 – 3.1 km/km²), High (3.11 – 5.1 km/km²) and Very high (5.11 – 8.81 km/km²) (Figure 3b).

e) Slope

Slope is one of the significant geomorphic indicators that remarkably governs runoff and infiltration capacity of the watershed (Nassif and Wilson, 1975, Deota and Desai, 1995). The gentle slopes allow water to remain in contact with the surface for longer durations and increases the probability of infiltration as compared to the moderate and steep slopes (Sarkar et al. 2001). However, the effect of slope may enhance or diminish with respect to other GEPs. The slope of Khapri watershed varies from 0° to 67° and classified into seven classes (Dongare et al. 2022 and Dongare and Deota, 2023) viz. flat to very gently sloping ($0^\circ - 3^\circ$), very gently sloping ($3^\circ - 6^\circ$), gently sloping ($6^\circ - 10^\circ$), moderately sloping ($10^\circ - 18^\circ$), moderately steep sloping ($18^\circ - 35^\circ$), steeply sloping ($35^\circ - 45^\circ$) and very steeply sloping ($>45^\circ$) (Figure 4a). The slope is inversely related to the infiltration of water hence, the areas with flat to gently sloping categories generally possess good to excellent ability of water infiltration and thereby groundwater potential. While, the areas with moderate to steep slopes reduces the infiltration and thereby leading to poor groundwater potential.

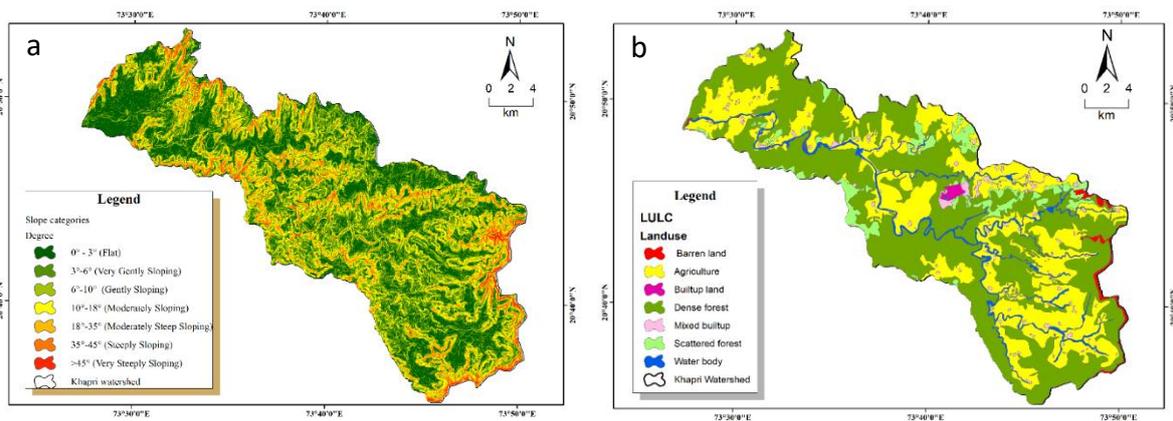


Figure 4: a. Slope map of Khapri watershed (After Dongare and Deota, 2023); b. Land use map of Khapri watershed

f) Land use

The term land use indicate the utilization of land parcel for different human activities, while the land cover specifies the entities that shelters the land parcel. Definite land uses such as natural vegetation, forest, barren lands etc. are characterized by varied infiltration capacity and eventually influence the groundwater potential (Valdiya, 2013). For example, the infiltration of precipitation on land with dense forest will be 60 to 100%, agricultural land 45-50%, mixed built-up land 50 to 60 % and urban land exhibits hardly 10%. Thus, it is important to link the land-use and groundwater potential. The land use and land cover of Khapri

watershed has been classified into seven classes viz. dense forest, scattered forest, agriculture, mixed built-up, built-up land and barren land (Figure 4b). The aerial coverage of the different land uses are, dense forest 51.08%, agriculture 36.11%, scattered forest 5.12%, water bodies 4.76%, mixed built-up 1.67%, barren lands 0.88% and built-up land 0.38%.

g) Soil

The porosity and permeability of the soil, which affects its ability to infiltrate and recharge water to underlying aquifers is dependent on soil texture. Clayey soils, characterized by smaller particles and pore spaces, typically have a low infiltration rate compared to sandy soils, which have larger particles and pore spaces (Brady 2008 pp.152-156). This suggest that the water can easily infiltrate in sandy soils, giving rise to faster groundwater recharge if suitable conditions prevail. The Khapri watershed is characterized by three soil series viz. 140-Ahwa series, 142-Bedmal series and 144-Vadhvania series (NBSS&LUP) (Figure 5a). The soil of Ahwa series is very shallow and hardly reaches the depth of 0-90 cm (Sharma et al. 2006). The soil is excessively drained and is not able to hold the moisture leading to moderate groundwater accumulation. Mostly this soil is found on gently to moderately sloping surfaces and shows severe erosion characteristics. In comparison to Ahwa series, the Bedmal series is very shallow and reach only up to the depth of 0-50 cm (Sharma et al. 2006). The soil is excessively drained and possess loamy skeletal texture and is not favorable for groundwater accumulation. The soil of Vadhvania series supports poor groundwater accumulation.

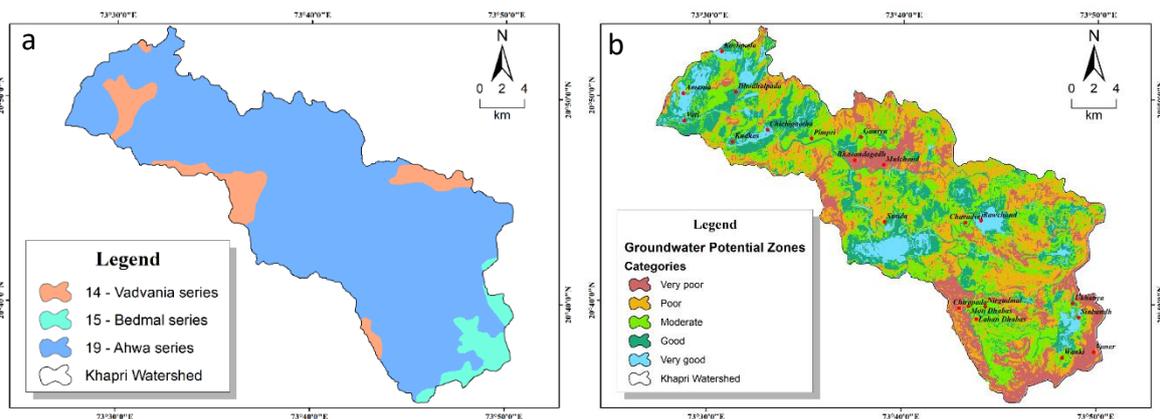


Figure 5: a. Soil map of Khapri watershed (After, NBSS&LUP); b. Groundwater potential zone map of Khapri watershed

Groundwater Potential Zones

The final groundwater potential zone map resulted from the overlay analysis of seven GEPs and is classified into five categories viz. Very good, Good, Moderate Poor and Very poor (Figure 5b).

The groundwater potential zone map shows distribution of very good groundwater potential in upper reaches (near villages Sinband, Ukhatiya, Chavadvel and Rawchond), middle reaches (to the south of village Sunda) and lower reaches (villages Chichigaontha, Dhodhalpada, Koylipada and Amania). The very good groundwater potential zone is the comprehensive result of parameters like alluvial plain, valley fills, low dissected plateau, high to very high lineament density, gentle slope and land uses such as dense forest or agriculture. The existence of good to moderate groundwater potential zones throughout the watershed reflect the interplay of geomorphic features like pediments and pediplains, moderate lineament density, gentle to moderate slope and agriculture land-use. Escarpments, highly dissected plateaus, very low lineament density and very steep slopes ($> 45^\circ$), which are unfavourable for the occurrence of groundwater, characterize the poor and very poor categories of groundwater potential zones. The poor category of groundwater potential zones show ubiquitous distribution, while the very poor category is restricted to the south western and central part of the watershed near villages Vanar, Wanki, Chirapada, Gaurya, Bhavandagadh and Mulchond. The critical analysis of the groundwater potential zones of Khapri watershed suggests dominant control of geomorphology, lineament density and slope characteristics over the other GEPs.

The data of seasonal groundwater level fluctuation from 64 dug wells is used to check the accuracy of the groundwater potential zone map. The low groundwater fluctuation is indicative of good to very good groundwater potential, whereas high groundwater fluctuation suggests moderate to poor groundwater potential, which is also reported from other regions (Varni et al. 2013, Kumar and Pandey 2016 and Kumar et al. 2020). The accuracy assessment indicate that 48 dug wells are in agreement with seasonal groundwater fluctuation data, resulting into 75% accuracy of the groundwater potential zone map of Khapri watershed.

Objective-II Assessment of groundwater quality and its suitability for domestic and irrigation purposes.

In the present study, an attempt has been made to determine the suitability of groundwater for drinking and agriculture purposes as well as to understand the dominant mechanism controlling the water chemistry.

To collect representative water of the aquifers, the electric pumps wherever available are used and are allowed to drain water for 10 minutes, to remove the stagnant water in the pipes. For sampling locations where pumps are not available, the sampler has been lowered to the central bottom most part of the well. All the samples are collected in the pre-rinsed high-density polyethylene bottles (HDPE) of 1000 ml. capacity. The pre-rinsed bottles are again rinsed two to three times with the same groundwater sample, which is to be collected. Simultaneously, the GPS is used to record the geographical position and elevation of the sampling location. The in-situ recording of physicochemical parameters such as pH, EC, TDS and temperature is carried out using Hanna Portable Pen type pH and TDS-EC-TEMP meters. Later in lab, the parameters such as total hardness (TH), total alkalinity (TA), cations (Calcium (Ca^{+2}), Magnesium (Mg^{+2}), Sodium (Na^{+}) and Potassium (K^{+})), anions (Nitrate (NO_3^{-}), Sulphate (SO_4^{2-}), Chloride (Cl^{-}) and Bicarbonate (HCO_3^{-})) are analysed for pre-monsoon groundwater samples collected in May-2023. The trace elements such as Fe, Mn, Zn, Cu and Ni are also analysed through ICP-MS. The range of concentration of physicochemical parameters and trace elements along with acceptable limit for drinking water as per BIS are given in table 1. The suitability of groundwater for irrigation purpose is determined based on indices such as Sodium Absorption Ratio (SAR), Residual Sodium Carbonate (RSC) and Kelly's ratio. To understand the dominant mechanism that govern the groundwater chemistry, Gibbs, 1970 diagram is used.

The analytical results of pH indicate neutral to weakly alkaline, E_c indicate low conductive and TDS indicate fresh nature of groundwater in Khapri watershed. The chemical analysis of groundwater suggests, the calcium and magnesium are the dominant cations followed by sodium and potassium. Among anions, the bicarbonate is dominant followed by chloride > sulphate > nitrate. The higher values of bicarbonate may attribute to silicate weathering of the basalt (Dethier, 1986 and Nikumbh 1997). The Piper trilinear diagram indicates the Ca-HCO_3^{-} type chemical character of groundwater (Piper, 1944). The Gibbs diagram reflects rock weathering is the dominant mechanism governing the groundwater

chemistry. The comparison of the cations and anions in the groundwater with BIS standards (Table 1) indicates that the water is suitable for drinking.

The SAR is the measure of sodium hazard of irrigation water to form exchangeable sodium in the soil (Richard 1954 and Shankar et al. 2011). The SAR value of groundwater samples ranges between 0.02-0.4 in Khapri watershed, indicating excellent groundwater quality for irrigation and negligible sodium hazard. The RSC of groundwater sample indicates the alkalinity hazard for the soil. The RSC of groundwater samples ranges from -1.21 to 2.12. The values suggest the good suitability of groundwater for irrigation. Kelly's ratio evaluates the water quality for irrigation based on the Na concentration measured against Ca and Mg (Kelly, 1940). The Kelley's ratio of groundwater samples ranges from 0.11 to 0.194. The Kelly's ratio less than 1 indicates water is suitable for irrigation purposes. The analysis of all these indices suggests that the groundwater is suitable for irrigation purposes.

Table 1 Groundwater suitability for drinking and irrigation

May 2023	Groundwater		BIS reference values for drinking water (2012)	Remark
Physicochemical parameter	Minimum	Maximum		
pH	6.9	8.5	6.5-8.5	Acceptable
Electrical conductivity ($\mu\text{S}/\text{cm}$)	208	571	≤ 750	Acceptable
Total Dissolved Salts	104	285	≤ 500	Acceptable
Calcium (mg/L)	19.5	56	≤ 75	Acceptable
Magnesium (mg/L)	1.18	40.05	≤ 30	Acceptable
Sodium (mg/L)	1.05	13.98	≤ 200	Acceptable
Potassium (mg/L)	0.04	3.26	≤ 12 (WHO)	Acceptable
Bicarbonate (mg/L)	112	285	≤ 400	Acceptable
Chloride (mg/L)	9.075	59.98	≤ 250	Acceptable
Nitrate (mg/L)	0	6.55	≤ 50	Acceptable
Sulphate (mg/L)	0.7	30.95	≤ 200	Acceptable
Total alkalinity (mg/L)	112	285	≤ 200	Acceptable

Fe (mg/L)	0.005049	0.26	≤ 0.3 (WHO)	Acceptable
Mn (mg/L)	0.000275	0.0566	≤ 0.1	Acceptable
Zn (mg/L)	0.000452	0.8	≤ 5	Acceptable
Cu (mg/L)	0.000329	0.0965	≤ 3	Acceptable
Ni (mg/L)	0.000108	0.0964	≤ 0.1	Acceptable
Groundwater suitability for irrigation				
<i>Indices</i>	<i>Minimum</i>	<i>Maximum</i>	<i>Suitability for irrigation</i>	
SAR	0.02	0.40	Excellent	
RSC	-1.21	2.12	Good	
Kelly ratio	0.011	0.194	Suitable	

Objective-III To decipher the groundwater recharge patterns and suggest suitable locations for the groundwater recharge structures

To decipher the groundwater recharge patterns stable isotope and hydrodynamic methods are generally used (Adyalkar and Rao, 1979 and Hameed et al. 2015), however at present the emphasis is given to stable isotope studies of groundwater, river water and rainwater. For stable isotope analysis, the groundwater samples are collected during May-2022 and January-2023 from the wells, which are in daily use. In addition to groundwater samples, the rainwater samples (August 2022), river water samples (September-2022 and January-2023) and spring water sample are collected and analysed for stable isotopes. The samples are stored in the HDPE bottles of 100 ml capacity. The HDPE bottles are filled up to the top with no space inside and are closed tightly to avoid isotope exchange with the air moisture.

Inferences from $\delta^{18}\text{O}$ data of pre-monsoon groundwater samples of Khapri watershed

The overall isotopic depletion (-2.5‰ to -0.5 ‰) observed in groundwater of Khapri watershed may be on account of:

1. direct recharge of rainwater from lineaments or,
2. the presence of dense canopy in many parts of the watershed, which diminish the effects of evaporation and retards isotopic enrichment or,
3. the recharge that is taking place from the irrigation return flow of deeper groundwater which is being utilized for the irrigation during non-rainy seasons and similar is also observed in adjacent areas by Pandey et al. 2023.

Once the stable isotope data of rainwater, post-monsoon groundwater samples and river water samples is obtained, it will be interpreted and incorporated accordingly.

6. References

- Abdullah, A., Akhir, J. M., & Abdullah, I. (2010). Automatic mapping of lineaments using shaded relief images derived from digital elevation model (DEMs) in the Maran-Sungi Lembing area, Malaysia. *Electronic Journal of Geotechnical Engineering*, 15(6), 949-958.
- Adyalkar, P. G., & Rao, S. S. (1979). Hydrodynamic Method of Assessing Groundwater Recharge by Precipitation in Deccan Trap Terrain-A Case Study. *Geological Society of India*, 20(3), 134-137.
- Ahmadi, H., & Pekkan, E. (2021). Fault-based geological lineaments extraction using remote sensing and GIS—a review. *Geosciences*, 11(5), 183.
- Ajay Kumar, V., Mondal, N. C., & Ahmed, S. (2020). Identification of groundwater potential zones using RS, GIS and AHP techniques: a case study in a part of Deccan volcanic province (DVP), Maharashtra, India. *Journal of the Indian Society of Remote Sensing*, 48, 497-511.
- B. Ranganath, R.S. Rana, P.Gandhi, and S.N.Bhagat, (2005), Specialised Thematic Mapping To Establish The Lava Stratigraphy Of Various Flows Of Deccan Traps In Dang District, Gujarat. Gsi Field Report.
- Brady, N. C., Weil, R. R., & Weil, R. R. (2008). *The nature and properties of soils* (Vol. 13, pp. 662-710). Upper Saddle River, NJ: Prentice Hall. Pp 152-156.
- Central Ground Water Board, (2014). Technical report series groundwater brochure the Dang district Gujarat, Govt. of India, Ministry of Water Resources, Dept. of Water Res (2014), pp. 1-24
- Deota, Bhushan, Limaye, M., Mehta, Mandar, (2005). Probable Groundwater Potential Zones of Sasutan Watershed. Gujarat - GIS Approach. 1.95103. https://www.researchgate.net/publication/359580014_Probable_Groundwater_Potential_Zones_of_Sasutan_Watershed_Gujarat_-_GIS_Approach.
- Deota, Bhushan, Nikhil, Desai, (1995). Slope Controlled Land Use Pattern: A Case Study of SouthGujarat.https://www.researchgate.net/publication/359579670_Slope_controlled_land_use_pattern_A_case_study_of_south_Gujarat.
- Dethier, D. P., & Colman, S. M. (1986). Weathering rates and the chemical flux from catchments in the Pacific Northwest, USA. *Rates of Chemical Weathering of Rocks and Minerals*, 503-530.
- Díaz-Alcaide, S., & Martínez-Santos, P. (2019). Advances in groundwater potential mapping. *Hydrogeology Journal*, 27(7), 2307-2324.
- Dongare, C. U., & Deota, B. S. (2023). Significance of geomorphic indicators for identification of groundwater recharge potential in the Khapri watershed of Deccan Volcanic

- Province (DVP), district Dangs, western India. *Groundwater for Sustainable Development*, 22, 100956.
- Dongare, C. U., Deota, B. S., & Deshpande, R. D. (2022). High resolution morphometric studies with special reference to hydrological setup of Khapri watershed, Dangs district, Gujarat, Western India. *Geocarto International*, 37(13), 3697-3720.
- Gibbs, R. J. (1970). Mechanisms controlling world water chemistry. *Science*, 170(3962), 1088-1090.
- Hajam RA, Hamid A, Bhat S. (2013). Application of morphometric analysis for geo-hydrological studies using geo-spatial technology—a case study of Vishav Drainage Basin. *Hydrol Curr Res*. 4(3):1–12.
- Hameed, A. S., Resmi, T. R., Suraj, S., Warriar, C. U., Sudheesh, M., & Deshpande, R. D. (2015). Isotopic characterization and mass balance reveals groundwater recharge pattern in Chaliyar river basin, Kerala, India. *Journal of Hydrology: Regional Studies*, 4, 48-58.
- Horton RE. (1945). Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. *Geol Soc Am Bull*. 56(3):275–370.2.0.CO;2]
- J.P.Sharma, J.D. Giri, R.L.Shyampura and K.S. Gajbhiye (2006) “Soil Series of Gujarat” NBSS&LUP publ no. 120, NBSS&LUP, Nagpur-440010, pp. 309-329
- Javed, A., & Wani, M. H. (2009). Delineation of groundwater potential zones in Kakund watershed, Eastern Rajasthan, using remote sensing and GIS techniques. *Journal of the Geological Society of India*, 73, 229-236.
- Kanagaraj, G., Suganthi, S., Elango, L., & Magesh, N. S. (2019). Assessment of groundwater potential zones in Vellore district, Tamil Nadu, India using geospatial techniques. *Earth Science Informatics*, 12, 211-223.
- Kelley, W. P. (1940). Permissible composition and concentration of irrigation water. In *Proceedings of the American society of civil engineers* (Vol. 66, pp. 607-613).
- Krishnamurthy, J., Venkatesa Kumar, N., Jayaraman, V., & Manivel, M. (1996). An approach to demarcate ground water potential zones through remote sensing and a geographical information system. *International journal of Remote sensing*, 17(10), 1867-1884.
- Kumar, A., & Pandey, A. C. (2016). Geoinformatics based groundwater potential assessment in hard rock terrain of Ranchi urban environment, Jharkhand state (India) using MCDM–AHP techniques. *Groundwater for Sustainable Development*, 2, 27-41.
- Kumar, N., Panchal, C. C., Chandrawanshi, S. K., & Thanki, J. D. (2017). Analysis of rainfall by using Mann-Kendall trend, Sen’s slope and variability at five districts of south Gujarat, India. *Mausam*, 68(2), 205-222.
- Lattman, L. H. (1958). Technique of mapping geologic fracture traces and lineaments on aerial photographs. *Photogrammetric Engineering*, 24(4), 568-576.
- Nassif, S.H., Wilson, E.M., (1975). The Influence of Slope and Rain Intensity on Runoff and Infiltration/L’influence de l’inclinaison de terrain et de l’intensité de pluie sur

l'écoulement et l'infiltration. *Hydrol. Sci. Bull.* 20 (4), 539–553. <https://doi.org/10.1080/02626667509491586>.

- Nikumbh, Jaydeep D (1997) Geochemistry of groundwaters from Behedi Basin District Nasik Maharashtra, PhD Thesis, Savitribai Phule Pune University, <http://hdl.handle.net/10603/170648>
- O'leary, D. W., Friedman, J. D., & Pohn, H. A. (1976). Lineament, linear, lineation: some proposed new standards for old terms. *Geological Society of America Bulletin*, 87(10), 1463-1469.
- Pandey, A., Padhya, V., Ganguly, A., Chakra, S., & Deshpande, R. D. (2023). Surface water groundwater interaction in water-stressed semi-arid western India: Insights from environmental isotopes. *Journal of Arid Environments*, 208, 104879.
- Piper, A. M. (1944). A graphic procedure in the geochemical interpretation of water-analyses. *Eos, Transactions American Geophysical Union*, 25(6), 914-928.
- Rajiv Gandhi National Drinking water mission (2005). *Ministry of Rural Development, New Delhi, India*.
- Richards LA (ed) (1954) Diagnosis and improvement of saline and alkali soils, USDA Handbook no. 60, Washington, 160 pp.
- Sarkar, B. C., Deota, B. S., Raju, P. L. N., & Jugran, D. K. (2001). A geographic information system approach to evaluation of groundwater potentiality of Shamri micro-watershed in the Shimla Taluk, Himachal Pradesh. *Journal of the Indian Society of Remote sensing*, 29, 151-164.
- Selvan MT, Ahmad SARFA. R. A. Z, Rashid SM. (2011). Analysis of the geomorphometric parameters in high altitude glacierised terrain using SRTM DEM data in Central Himalaya, India. *ARNP J Sci Technol.* 1(1):22–27.
- Shankar, K., Aravindan, S., & Rajendran, S. (2011). Hydrochemical profile for assessing the groundwater quality of Paravanar river sub-basin, Cuddalore district, Tamil Nadu, India. *Current World Environment*, 6(1), 45.
- Strahler AN. (1957). Quantitative analysis of watershed geomorphology. *Eos Trans AGU.* 38(6):913–920.
- Valdiya, K. S. (2013). *Environmental Geology: Ecology, Resource and Hazard Management*. McGraw-Hill Education. (chapter 5)
- Varni, M., Comas, R., Weinzettel, P., & Dietrich, S. (2013). Application of the water table fluctuation method to characterize groundwater recharge in the Pampa plain, Argentina. *Hydrological Sciences Journal*, 58(7), 1445-1455.
- Verstappen, H. T. (1983). *Applied geomorphology: geomorphological surveys for environmental development*.
- Water-Specification, I. S. D. (2012). Bureau of Indian Standards. New Delhi, India, 1-12.

=====