

Table of Contents

CHAPTER	PAGE
1 - INTRODUCTION	1-14
1.1 General.....	01
1.2 Groundwater in soft and hard rock terrains.....	02
1.3 Groundwater in the Deccan Trap Province (DTP).....	02
1.4 Groundwater in Deccan Trap Province (DTP) of Gujarat.....	03
1.5 Problem statement.....	07
1.6 Objectives.....	08
1.7 Methodology.....	08
1.8 Study area.....	11
1.8.1. Location and extent.....	11
1.8.2. Communication.....	12
1.8.3. Topography.....	12
1.8.4. Climate.....	12
1.8.5. Flora and fauna.....	13
2 - GEOLOGY AND LINEAMENTS OF THE KHAPRI WATERSHED	15-34
2.1 Regional geology.....	15
2.2 Geological setup of the Dangs district.....	19
2.3 Geological setup of the Khapri watershed.....	20
2.4 Lineaments.....	25
2.5 Lineament framework of the Khapri watershed.....	25
2.6 Epilogue.....	33
3 - DRAINAGE CHARACTERISTICS OF THE KHAPRI WATERSHED	35-57
3.1 Introduction.....	35
3.2 Methodology.....	36
3.3 Drainage pattern of the Khapri watershed.....	37
3.4 Morphometric analysis.....	37
3.4.1. Linear morphometric parameters (1-D).....	37
3.4.2. Aerial morphometric parameters (2-D).....	41
3.4.3. Relief morphometric parameters (3-D).....	49
3.5 Hypsometric curve and Hypsometric integral.....	55
3.6 Epilogue.....	56
4 - HYDROGEOMORPHOLOGY OF THE KHAPRI WATERSHED	58-76
4.1 Introduction.....	58
4.2 Datasets and methodology.....	62
4.3 Hydrogeomorphic features of the Khapri watershed.....	63
4.3.1. Landforms.....	63

4.3.1.1 Escarpment.....	65
4.3.1.2 Highly dissected plateau.....	66
4.3.1.3 Moderately dissected plateau.....	67
4.3.1.4 Low dissected plateau.....	68
4.3.1.5 Planation surfaces.....	68
4.3.1.6 Pediments.....	70
4.3.1.7 Pediplains.....	70
4.3.1.8 Alluvial plains.....	72
4.3.1.9 Valley fills.....	72
4.3.2. Slope.....	73
4.4 Epilogue.....	76

5 - SOILS AND LAND USE OF THE KHAPRI WATERSHED 77-92

5.1 Soil.....	77
5.2 Soil characteristics of the Dangs district.....	79
5.3 Soil characteristics of the Khapri watershed.....	79
5.3.1. 140-Ahwa series.....	81
5.3.2. 142-Bedmal series.....	81
5.3.3. 144-Vadhvania series.....	82
5.4 Land-use.....	82
5.5 Datasets and methodology.....	84
5.6 Land-use/Land cover of the Khapri watershed.....	86
5.6.1. Dense and scattered forest.....	87
5.6.2. Agricultural land.....	87
5.6.3. Mixed built-up land.....	89
5.6.4. Built-up land.....	89
5.6.5. Water bodies.....	90
5.6.6 Barren land.....	91
5.7 Epilogue.....	91

6 - GEO-ENVIRONMENTAL PARAMETERS CONTROLLING GROUNDWATER POTENTIAL ZONES 93-123

6.1 Introduction.....	93
6.2 Groundwater Potential Zones.....	94
6.3 Remote sensing and GIS in Groundwater Potential Zone Mapping.....	94
6.4 Methodology.....	97
6.5 Analytical Hierarchical Process (AHP).....	99
6.6 Geo-Environmental Parameters (GEPs) controlling groundwater potential	103
6.6.1. Geology.....	103
6.6.2. Geomorphology.....	104
6.6.3. Drainage density.....	107
6.6.4. Lineament.....	107
6.6.5. Slope.....	109
6.6.6. Land-use and Land cover.....	110

6.6.7. Soil.....	112
6.7 Overlay analysis and Groundwater Potential Zones.....	114
6.8 Accuracy assessment of Groundwater Potential Zones.....	116
6.9 Quantitative validation of AHP through Receiver Operating Characteristic (ROC) curve.....	121
6.10 Epilogue.....	122

7 – HYDROCHEMISTRY OF GROUNDWATER 124-151

7.1 Introduction.....	124
7.2 Sampling procedures for groundwater quality analysis.....	125
7.3 Analytical procedures for physicochemical parameters.....	127
7.3.1. Total Alkalinity (TA).....	127
7.3.2. Total Hardness (TH), Calcium and Magnesium concentration....	127
7.3.3. Sodium and Potassium concentration.....	128
7.3.4. Chloride concentration.....	129
7.3.5. Nitrate and Sulphate concentration.....	129
7.4 Significance and spatial variations in physicochemical parameters.....	130
7.4.1. Power of Hydrogen (pH).....	131
7.4.2. Electrical Conductivity (EC).....	132
7.4.3. Total Dissolved Solids (TDS) and Total Hardness (TH).....	133
7.4.4. Calcium.....	133
7.4.5. Magnesium.....	135
7.4.6. Sodium.....	136
7.4.7. Potassium.....	137
7.4.8. Bicarbonate alkalinity.....	138
7.4.9. Chloride.....	139
7.4.10. Sulphate.....	140
7.4.11. Nitrate.....	141
7.5 Gibbs diagram.....	143
7.6 Hydro-chemical facies and characterisation of groundwater.....	144
7.7 Suitability of groundwater for drinking purpose.....	147
7.8 Suitability of groundwater for irrigation purpose.....	148
7.9 Epilogue.....	150

8 - APPLICATION OF STABLE ISOTOPE FOR DECIPHERING GROUNDWATER RECHARGE PATTERNS IN THE KHAPRI WATERSHED 152-163

8.1 Introduction.....	152
8.2 Water sampling for stable isotope analysis.....	153
8.3 Stable isotope analysis.....	154
8.4 Stable isotope composition of rainwater and the meteoric water line for the Khapri watershed.....	155
8.5 Stable isotope composition of groundwater and river water samples.....	158
8.6 Salient features of stable isotope analysis.....	161

9 - GROUNDWATER RECHARGE STRUCTURES FOR SUSTAINABLE DEVELOPMENT OF THE KHAPRI WATERSHED	164-172
9.1 Introduction.....	164
9.2 Site selection of groundwater recharge structures.....	164
9.3 Proposed structures and sites for augmenting groundwater recharge.....	165
9.3.1. <i>Percolation tank</i>	166
9.3.2. <i>Check dams and Nala bunds</i>	167
9.3.3. <i>Gabions and Gully plugs</i>	169
9.3.4. <i>Necklace trenches and Recharging ponds</i>	170
10 - SUMMARY AND CONCLUSIONS	173-179
10.1 Summary.....	173
10.2 Conclusions.....	178
ANNEXURE – I	180
ANNEXURE – II	182
REFERENCES	183-205
LIST OF PUBLICATIONS	206-208

LIST OF TABLES

Table	Description	Page no.
2.1	<i>Generalized stratigraphy of Gujarat (After Merh, 1995 and GSI, 2012).</i>	17
2.2	<i>Lithostratigraphy of the Dangs district (After GSI, 2005).</i>	20
2.3	<i>Geological succession of the Khapri watershed (After GSI, 2005).</i>	22
3.1	<i>Datasets used for morphometric analysis.</i>	37
3.2	<i>Empirical formulae to compute linear morphometric parameters.</i>	38
3.3	<i>Results of linear morphometric parameters of the Khapri watershed.</i>	42
3.4	<i>Results of linear morphometric parameters of the Khapri watershed at sub-watershed level.</i>	45
3.5	<i>Empirical formulae to compute aerial morphometric parameters.</i>	46
3.6	<i>Results of aerial morphometric parameters of the Khapri watershed.</i>	46
3.7	<i>Results of aerial morphometric parameters of the Khapri watershed at sub-watershed level.</i>	49
3.8	<i>Empirical formulae to compute relief morphometric parameters.</i>	50
3.9	<i>Results of relief morphometric parameters of the Khapri watershed.</i>	50
3.10	<i>Results of relief morphometric parameters of the Khapri watershed at sub-watershed level.</i>	53
4.1	<i>Datasets used for mapping hydrogeomorphic indicators.</i>	63
6.1	<i>Saaty's fundamental scale (After Saaty, 1980).</i>	99
6.2	<i>Pair wise comparison matrix of geo-environmental parameters.</i>	102
6.3	<i>Normalized pair wise comparison matrix of geo-environmental parameters.</i>	102
6.4	<i>Saaty's random inconsistency indices for n = 10 parameters.</i>	103
6.5	<i>Assigned ranks to lithology/flows of the Khapri watershed.</i>	104
6.6	<i>Ranks assigned to geomorphic features of the Khapri watershed.</i>	106
6.7	<i>Ranks assigned to drainage density of the Khapri watershed.</i>	107
6.8	<i>Ranks assigned to lineament density of the Khapri watershed.</i>	108
6.9	<i>Ranks assigned to slope categories of the Khapri watershed.</i>	110
6.10	<i>Ranks assigned to Land-use/Land cover categories of the Khapri watershed.</i>	111
6.11	<i>Ranks assigned to soil textural classes of the Khapri watershed.</i>	113
6.12	<i>Aerial coverage of Groundwater Potential Zones in the Khapri</i>	116

	<i>watershed.</i>	
6.13	<i>Seasonal groundwater fluctuation in 64 dug wells.</i>	<i>117</i>
6.14	<i>Groundwater Potential Zones and corresponding groundwater fluctuation.</i>	<i>120</i>
6.15	<i>AUC classification (Sammut and Webb, 2011).</i>	<i>122</i>
7.1	<i>Range of physicochemical parameters of pre-monsoon groundwater samples and their comparison with BIS (2012) standards for drinking water.</i>	<i>148</i>
7.2	<i>Range of indices used for assessing groundwater suitability for irrigation.</i>	<i>150</i>
8.1	<i>Results of $\delta^{18}\text{O}$, $\delta^2\text{H}$ and d-excess of different water samples.</i>	<i>156</i>
9.1	<i>Sub-watershed wise proposed recharge structures in the Khapri watershed.</i>	<i>171</i>

LIST OF FIGURES

Figure	Description	Page no.
1.1	<i>Spatial distribution of Deccan Trap Province in west-central India (Modified, after Deshmukh 1988).</i>	3
1.2	<i>Basaltic aquifer system of Gujarat (after CGWB, 2020).</i>	4
1.3	<i>Hardworking homemakers bringing water from a well located around 2 km away from their residence, village Chankhal and Temburgartha, Dangs.</i>	7
1.4	<i>Work flow of the present study.</i>	9
1.5	<i>Generalized methodology.</i>	10
1.6	<i>Location map of the Khapri watershed.</i>	11
1.7	<i>Digital Elevation Model of the Khapri watershed.</i>	13
2.1	<i>Geological map of Gujarat (After Merh, 1995).</i>	16
2.2	<i>Geological map representing nine flows (II to X) in the Khapri watershed (After GSI, 2005).</i>	21
2.3	<i>Various types of basalts observed during ground truth verification a) Porphyritic basalt (flow-II), b) Massive fine grained basalt (flow-III), c) Glomeroporphyritic basalt (flow-IV), d) Honey yellow colored basalt and fine grained basalt with spotted appearance (flow-V), e) Mega phenocrysts basalt (flow-VI), f) Fine grained basalt with ribs and furrows structure and vesicles (flow-VII).</i>	23
2.4	<i>a) Vesicular basalt (flow-VII), b) Amygdaloidal basalt (flow-IX), c) Intrusive, d) Agglutinated surface of lava channel, e) Warping in basaltic flow, f) Spheroidal weathering in basalt.</i>	24
2.5	<i>Ground truth verification and measuement lineament trend.</i>	26
2.6	<i>Extraction of geological lineaments from IRS LISS-III FCC satellite data. Inset rosette diagram represents the prominent trend of lineaments.</i>	27
2.7	<i>Extraction of lineaments from shaded relief map having (a) 45° azimuth angle (b) 90° azimuth angle. Inset rosette diagram represents the trend of lineaments.</i>	28
2.8	<i>Extraction of lineaments from shaded relief map having (c)</i>	29

	<i>135° azimuth angle (d) 180° azimuth angle. Inset rosette diagram represents the trend of lineaments.</i>	
2.9	<i>Extraction of lineaments from shaded relief map having (e) 225° azimuth angle (f) 270° azimuth angle. Inset rosette diagram represents the trend of lineaments.</i>	30
2.10	<i>Extraction of lineaments from shaded relief map having (g) 315° azimuth angle (h) 360° azimuth angle. Inset rosette diagram represents the trend of lineaments.</i>	31
2.11	<i>Comprehensive lineament map of the Khapri watershed, prepared by combining all the lineaments mapped on IRS LISS-III FCC satellite data and eight shaded-relief maps. Inset rosette diagram represents the prominent trend of lineaments.</i>	32
2.12	<i>(a) Positive and (b) Negative lineaments of the Khapri watershed. Inset rosette diagram represents the prominent trend of lineaments.</i>	33
2.13	<i>Negative lineament density map of the Khapri watershed.</i>	34
3.1	<i>Drainage map showing stream network and stream orders for eleven sub-watersheds of the river Khapri.</i>	38
3.2	<i>Plot of logarithm of stream numbers versus stream order.</i>	40
3.3	<i>Isopleth map of Drainage density. Inset pie diagram represents the aerial coverage of different drainage density classes.</i>	44
3.4	<i>Isopleth map of Stream frequency. Inset pie diagram represents the aerial coverage of different stream frequency classes.</i>	46
3.5	<i>Isopleth map of Drainage texture. Inset pie diagram represents the aerial coverage of different drainage texture classes.</i>	47
3.6	<i>SRTM - Digital Elevation Model (30 m) representing highest elevation of 1083 m asl in southeastern to 86 m asl in northwestern direction of Khapri watershed.</i>	51
3.7	<i>Isopleth map of Relative relief. Inset pie diagram represents the aerial coverage of different relative relief classes.</i>	52
3.8	<i>Isopleth map of Dissection index. Inset pie diagram represents the aerial coverage of different dissection index classes.</i>	54
3.9	<i>Isopleth map of Ruggedness number. Inset pie diagram represents the aerial coverage of different ruggedness number</i>	54

	<i>classes.</i>	
3.10	<i>Hypsometric curve indicating the mature stage of geomorphic evolution of Khapri watershed.</i>	55
4.1	<i>IRS LISS-III (May-2019) FCC image of Band-432 representing the extent of the Khapri watershed.</i>	64
4.2	<i>Geomorphological map representing the vivid landforms of the Khapri watershed.</i>	64
4.3	<i>Pie-diagram representing the aerial coverage (km²) of the landforms.</i>	65
4.4	<i>Escarpment near village Ukhatiya.</i>	66
4.5	<i>Highly dissected plateau near village Isdar.</i>	67
4.6	<i>Moderately dissected plateau as seen from Waghai-Ahwa state highway.</i>	69
4.7	<i>Low dissected plateau near village Jakhana.</i>	69
4.8	<i>Planation surfaces with sparse vegetation near Morzira.</i>	70
4.9	<i>Pediment near village Kudkas.</i>	71
4.10	<i>Pediplain near village Borkhel.</i>	72
4.11	<i>Alluvial plains near village Vati.</i>	73
4.12	<i>Valley fill deposits near village Vati.</i>	73
4.13	<i>Pie diagram representing the percent aerial coverage of different slope classes in Khapri watershed.</i>	74
4.14	<i>Map exhibiting seven categories of slope increasing from west to east as well as from north to south in the Khapri watershed. (After Dongare et al. 2023).</i>	75
4.15	<i>Ground truth verification of slope near Jakhana.</i>	75
5.1	<i>Soil map of the Khapri watershed representing 140-Ahwa, 142-Bedmal and 144-Vadhvania soil series.</i>	80
5.2	<i>Pie diagram representing the percent aerial coverage of 140-Ahwa, 142-Bedmal and 144-Vadhvania soil series.</i>	80
5.3	<i>The amounts of runoff and infiltration depend, among other factors, on the land uses and the texture of soils and the nature and extent of vegetal cover on the soils. (c=coefficient of runoff). (From W. M. Marsh and J. Dozier, 1981, Landscape, Addison-Wesley, Reading, 637 p., Figs. 11.4 and 13.20.;</i>	83

	<i>Validya 2013).</i>	
5.4	<i>Map representing seven categories of land use in the Khapri watershed.</i>	86
5.5	<i>Pie chart representing aerial coverage (km²) of seven land use categories in the Khapri watershed.</i>	86
5.6	<i>Dense forest in the Khapri watershed.</i>	88
5.7	<i>Scattered forest in the Khapri watershed.</i>	88
5.8	<i>Agricultural land in the Khapri watershed.</i>	89
5.9	<i>Mixed built-up land use in the Khapri watershed.</i>	90
5.10	<i>Waterbodies a) tributary of the Khapri watershed and b) check dam in the Khapri watershed.</i>	90
5.11	<i>Barren land in the Khapri watershed.</i>	91
6.1	<i>Schematic diagram of the methodology for identification of Groundwater Potential Zones.</i>	98
6.2	<i>Reclassified geological map of the Khapri watershed based on suitability ranks.</i>	105
6.3	<i>Reclassified geomorphology map of the Khapri watershed based on suitability ranks.</i>	105
6.4	<i>Reclassified drainage density map of the Khapri watershed based on suitability ranks.</i>	108
6.5	<i>Reclassified negative lineament density map of the Khapri watershed based on suitability ranks.</i>	109
6.6	<i>Reclassified slope map of the Khapri watershed based on suitability ranks.</i>	111
6.7	<i>Reclassified land use map of the Khapri watershed based on suitability ranks.</i>	112
6.8	<i>Reclassified soil map of the Khapri watershed based on suitability ranks.</i>	113
6.9	<i>Groundwater Potential Zone map of the Khapri watershed. Inset pie diagram shows percent aerial coverage of Groundwater Potential Zones.</i>	115
6.10	<i>Receiver Operating Characteristic (ROC) curve.</i>	122
7.1	<i>Groundwater sampling locations for water quality analysis.</i>	126
7.2	<i>Collection of groundwater samples a) after draining the</i>	126

	<i>stagnant water in pipes, b,c) by lowering the sampler to the central and bottom most part of well in case of absence of electric pumps, d) in high density polyethylene bottles (HDPE) and systematic labelling.</i>	
7.3	<i>Spatial variation in pH of pre-monsoon groundwater samples.</i>	131
7.4	<i>Spatial variation in Electrical Conductivity (EC) of pre-monsoon groundwater samples</i>	132
7.5	<i>Spatial variation in Total Dissolved Solids (TDS) of pre-monsoon groundwater samples.</i>	134
7.6	<i>Spatial variation in Total Hardness (TH) of pre-monsoon groundwater samples.</i>	134
7.7	<i>Spatial variation in Ca⁺² of pre-monsoon groundwater samples.</i>	135
7.8	<i>Spatial variation in Mg⁺² of pre-monsoon groundwater samples.</i>	136
7.9	<i>Spatial variation in Na⁺ of pre-monsoon groundwater samples.</i>	137
7.10	<i>Spatial variation in K⁺ of pre-monsoon groundwater samples.</i>	138
7.11	<i>Spatial variation in Total Alkalinity (TA)/HCO₃⁻ of pre-monsoon groundwater samples.</i>	140
7.12	<i>Spatial variation in Cl⁻ of pre-monsoon groundwater samples.</i>	141
7.13	<i>Spatial variation in SO₄²⁻ of pre-monsoon groundwater samples.</i>	142
7.14	<i>Spatial variation in NO₃⁻ of pre-monsoon groundwater samples.</i>	143
7.15	<i>Gibbs diagram for a) cations b) anions of pre-monsoon groundwater samples.</i>	144
7.16	<i>Hydrochemical facies through graphical distribution a) cations and b) anions of pre-monsoon groundwater samples.</i>	144-145
7.17	<i>Piper tri-linear plot of pre-monsoon groundwater samples of the Khapri watershed.</i>	146
7.18	<i>USSL plot of pre-monsoon groundwater samples of the Khapri watershed.</i>	150
8.1	<i>Water sampling locations for stable isotope analysis</i>	153
8.2	<i>Isotope Ratio Mass Spectrometer (IRMS) at Physical Research Laboratory (PRL), Ahmedabad.</i>	155

8.3	<i>LMWL of the Khapri watershed.</i>	158
8.4	<i>Scatter plot of δ^2H versus $\delta^{18}O$ ‰ for pre-monsoon groundwater samples of the Khapri watershed and LMWL indicates the local meteoric water line.</i>	159
8.5	<i>Scatter plot of d-excess versus $\delta^{18}O$ ‰ for different water samples of the Khapri watershed</i>	160
8.6	<i>Graph of δ^2H versus $\delta^{18}O$ ‰ for post-monsoon groundwater samples of the Khapri watershed and LMWL indicates the local meteoric water line.</i>	160
8.7	<i>Scatter plot of δ^2H versus $\delta^{18}O$ for river water samples of the Khapri watershed and LMWL indicates the local meteoric water line.</i>	161
8.8	<i>Frequency distribution of $\delta^{18}O$‰ in pre-monsoon groundwater samples.</i>	161
8.9	<i>Frequency distribution of $\delta^{18}O$‰ in post-monsoon groundwater samples.</i>	162
9.1	<i>Heavily silted check dams near Garvi and Bhavandagadh.</i>	166
9.2	<i>Percolation tank near Galkund.</i>	167
9.3	<i>Check dam near village Khapri.</i>	168
9.4	<i>Nala bund structure.</i>	169
9.5	<i>(a) Gabion and (b) Gully plugs (After Naseri et al. 2021).</i>	170
9.6	<i>Necklace trench and Recharging ponds.</i>	170
9.7	<i>Location of proposed recharging structures at sub-watersheds level overlaid on Groundwater Potential Zones and Drainage map of the Khapri watershed.</i>	171