IDENTIFICATION OF SUITABLE SITES FOR RAIN WATER HARVESTING IN A HARD ROCK TERRAIN OF EASTERN GHATS, INDIA USING REMOTE SENSING AND GIS

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ABSTRACT

Groundwater development through rain water harvesting in the hard rock terrain of Eastern Ghats, Visakhapatnam district, Andhra Pradesh state, southern India was considered as a sample study to determine the main source of groundwater in the area. Most of the regions of India have become increasingly depend on groundwater for domestic, agriculture and industrial needs that resulted in the drastic depletion of groundwater resources. Though, the development of groundwater in hard rock regions is very limited and is predominantly available in weathered mantle and lineament zones. Rainwater harvesting is one of the important structural component at watershed or local level as it is helpful to recharge the groundwater. Various thematic maps such as geomorphology, geology, lineament density, drainage density, slope, land use and land cover were considered by assigning suitable weights and different ranks to each of them and their sub units based on the expert knowledge through multi criteria decision analysis. These maps were integrated by developing a raster model in a GIS environment to categorize various groundwater prospective zones as poor (87.3 km^2), moderate (202.9 km^2) and good (30.8 km^2). The obtained results were verified with the groundwater level data of the study area. About fifty per cent of total storm rainfall lost as surface runoff which was estimated by using empirical SCS-CN model. To improve groundwater levels in the study area, various rainwater harvesting structures such as check dams, percolation tanks, contour bunds, bench terraces were suggested as per IMSD guidelines in GIS platform. Geospatial methods can assist for generating various models in a logical and scientific way towards groundwater development with the available data.

INTRODUCTION

In India, majority of rural population depends on groundwater water for domestic and other purposes. Excessive use and continuous mismanagement of this valuable natural resource in various purposes like irrigation, industrial and other uses led to ever increasing water demand in the world and India in particular. The recent trend of increasing population and the degradation of physical environment in developing countries like India are diminishing the human access to safe drinking water. The country will contribute more human population in the years to come (UNICEF 2013). The unproductive monsoons, deforestation, and over exploitation of resources resulting in drastic depletion of groundwater levels and the scarcity of water are experiencing now across the country. This unprecedented problem could be managed to certain extent through recharging the potential aquifers by the construction of artificial harvesting structures. The groundwater occurrence particularly in a hard rock terrain is very limited and mainly confined to fractured and weather horizons. The topography, slope, extent of weathering, type of weathered material, geological structure, land use and overall assemblage of different landforms plays an important role in defining the groundwater regime, especially in the hard rocks (Krishnamurthy et al. 1996). Spatial information technologies like remote sensing (RS) and geographical information system (GIS) provide diverse datasets over remotely inaccessible regions that can be efficiently utilized in groundwater management studies. Satellite imageries are increasingly being used in groundwater exploration because of their utility in identifying and outlining various ground features, which may serve as either direct or indirect indicators of the presence of groundwater. Various studies have been conducted across the globe in identification of probable zones for groundwater development and exploration (Murthy and Mamob 2009; Fashae et al. 2014). A few researchers have been used a set of weights and assigned relative rankings for different themes and their individual units based on personal judgments considering their relative importance from the artificial recharge view point. Then the themes were integrated in a GIS environment to delineate different groundwater potential zones and constructing suitable sites for water harvesting structures for developing groundwater levels through artificial recharge using various numerical models (Saraf and Choudhury, 1998; Kumar et al. 2008; Ratnakar et al. 2013). The main aim of the study was carried out to identify suitable rain water harvesting structures to construct in the hard rock terrain of the upper Gosthani river basin by using RS, GIS, Multi-Criteria Decision Analysis (MCDA) and field techniques.

The study area, Thatipudi watershed, lies in between 18^0 08' 30" N to 18^0 20' 54"N latitudes and 82^0 56' 10"E to 83^0 13' 33"E longitudes covering with an area of 321.1 sq km. located northwest of Visakhapatnam city of Andhra Pradesh (AP) state, India (Figure 1). The study area is a part of the Eastern Ghats hard rock terrain and the river Gosthani and its tributaries are draining through the watershed. The average annual rainfall is 1472 mm received mostly from the south-west monsoon and the maximum average annual temperature is 35ºC. Out of 23,379 total population of the watershed nearly 92% belongs to Scheduled Tribes including particularly vulnerable tribal groups namely Bhagata, Gadaba, Poorja, Valmiki, Khond, Kammara, Kotia etc. Thatipudi reservoir project was constructed across the Gosthani River in 1968 with the aim of irrigate 6224 hectares in Vizianagaram district and to provide drinking water (9 mgd) to the needs of Visakhapatnam urban population. The water supply from Greater Visakhapatnam Municipal Corporation (GVMC) inadequate to meet the daily domestic and industrial demands of the growing population hence, there is a need to develop other alternative water sources.

MATERIALS AND METHODS

The three spectral bands of LISS-IV (IRS-Resourcesat 2) with 5.8 m spatial resolution (2012) and PAN (IRS-P5: Cartosat-1) 2.5 m high spatial resolution (2013) were used. The area falls in path/rows of 104/60 for LISS-IV and 567 & 568/312 for PAN, respectively. ArcGIS and ERDAS Imagine software were used to create geospatial data base and analysis. Geometric rectification of the data was performed by assigning the projection UTM-WGS-84. A standard false colour composite (FCC) was prepared to delineate various topographical features based on image characteristics. Drainage network was delineated from ASTER GDEM data (http://www.gdem.aster.ersdac.or.jp/) and updated with the help of satellite images. The order was given to each stream by following Strahler (1964) stream ordering technique. Slope map was generated from the digital elevation model. Land use and land cover analysis was carried out using unsupervised classification technique. Soil texture map was used in the delineation of hydrologic soil groups (HSG). The daily rainfall data collected from Indian Meteorological Department (IMD) center established at vicinity of the basin were used in the runoff estimation for each storm event during 2014-16. The runoff potential was estimated using various combinations of hydrologic soil group (HSG), land use, and antecedent moisture condition (AMC) by following the procedure of SCS-CN method (SCS 1985). A collective approach involving a systematic visual interpretation of the image besides with the collateral information obtained from different sources, and ample field checks were done in the finalization of various themes viz. geomorphology, geology, land use and land cover, lineament, soil, drainage, slope on the standard scale (Figure 1 and 2).

Groundwater potential zones (GWPZ) were delineated using weighted index overlay (WIO) method. WIO analysis is a simple mathematical model for a combined analysis of multi-parameters. One of the classic problems in decision theory or multi-parameter analysis is the determination of the relative importance (weights) of each parameter with respect to the other. This is a problem that requires human judgment supplemented by scientific tools. As all the thematic variables cannot be weighted equal for suitability assessment, it is essential that a weighted method needs to be employed where the relative importance of the parameters defines the weightage. One of the most accepted methods is weighted index overlay for assigning weights and relative ranks based on the multi-criteria evaluations for decision making. Various themes such as geomorphology, geology, lineament density, drainage density, slope, and land use/land cover generated in the study were assigned a weight depending on its influence on the movement and storage of groundwater. Relative ranking of each variable in a theme were assigned as knowledge based hierarchy that shows the rank 1 is good, rank 2 denotes moderate and rank 3 assigned for poor prospect for the demarcation of groundwater prospective zones (Table 1) (Dinesh Kumar et al. 2007; Narendra et al. 2013). Model used in the study was Weighted Overlay tool in Spatial Analyst of ArcGIS. The resultant output map was classified as poor, moderate and good groundwater prospective zones (Figure 2). Identification of suitable areas for constructing water harvesting structures depends on many variables such as slope, drainage, land use/land cover, soil texture, lineaments and groundwater prospective zones. These thematic maps were associated with knowledge based decision rules including with IMSD technical guidelines were applied in MCDA for constructing artificial recharge structures namely check dam, percolation tank, contour bund, and bench terraces (Table 2). The data sets were integrated in Knowledge Engineer tool in ERDAS Imagine (Figure 2). The suggested structures in the proposed sites for rainwater harvesting were crosschecked by groundwater level data, for which, the availability of water for these artificial recharge structures are confirmed from field investigation. Accuracy assessment was done with the existing structures identified at ground truth survey in the suggested final map.

RESULTS AND DISCUSSION

Geomorphology (Gm)

Landforms play an important role in defining the groundwater regime, especially in the hard rocks. The synoptic view of satellite data facilitates better interpretation of landforms and helps in mapping of different geomorphic units. High spatial resolution of NIR band has used for geomorphic investigations. The underlying lithology, slope and the type of drainage pattern generally influence the genesis and processes of different geomorphic units. Geomorphologically, the area consists of five main units such as structural hills, denudation hills, buried pediment, weathered pediplain and valley fills (Figure 1). Geomorphology was assigned highest weight due to its importance in the movement and storage of groundwater in the study area (Narendra et al. 2013).

Structural hills These are occurred as a group of massive hills with resistant rock bodies consist of khondalite and charnockite group of rocks covering with thick vegetation. This unit is associated with faulting, fracturing and structures. These are marked by sharp and rugged tops with steep slopes and dark red colour exhibiting on the image. Because of steep slopes and high relief, this zone is not suitable for groundwater prospecting.

Denudation hills These are developed as isolated patches found at lower altitudes as compared to the structural hills. Denudation hills are identified on the imagery as dark grey to light red tone due to sparse vegetative cover. These units are fractured and weathered, and show the formation of khondalite suite of rocks. Denudation hills are also considered as poor zones because of limited weathered material, and of high slopes and runoff.

Burried pediment This unit is occurred parallel to the foothills of the hilly terrain as gently undulating plains with moderate slopes. It is made up of loose to semi-consolidated coarse materials including boulders derived from the upper hills and got deposited on the lower slopes. This unit consists of weathered zones (2 to 8 m) mostly confined to base of various hills underlain by gneisses. Infiltration rate in this zone is moderate to high. This unit is considered as moderate zone for groundwater development.

Weathered pediplain It is designated as gently undulating landscape broken by isolated residual uplands and covered by a varying thickness of overburden material with red soil cover. This geomorphic unit consists of semi-stratified deposits of sediments that are regularly carried out from upland areas of the catchments. These deposited sediments are admixed with sandy loam to clay fragments. Compositionally these are made up of alluvio-fluvial materials of different sizes, shapes and composition i.e. gravel, rubble, pebble, red sand etc. Wethered pediplains are considered as good zones for groundwater potential.

Valley fills It consist of both alluvial and colluvial materials, and are mostly identified along the higher order streams and at the level to gentle slopes. Irrigated crops are observed in this zone. This geomorphic unit acts as good prospective zone for groundwater development. The porosity and permeability of the valley fills are very high so they are considered as very good prospective zones for groundwater exploration.

Geology (Ge)

The study area forms a part of the Eastern Ghats comprising predominantly khondalites and charnockites group of rocks of Archaean age and alluvium of Recent age. The rock types include under the khondalite group are garnet-sillimanite gneiss, quartzite bands and migmatite gneiss. Limestone and the bauxitic laterite cappings overlies the khondalites in the study region. Alluvium occupies mainly in the lower elevation area consists of coarse to medium grained sandy soil, silty clay, loam, sandy loam, and sandy clay loam. Alluvium is considered to be water bearing and is an important source of groundwater in the study area. More than 70% of the watershed area is covered by the dissected khondalites and charnockites indicating low potential for groundwater prospecting. The litho-units in the study area were evaluated and assigned suitable weightages as per their hydrogeological properties (Table 1).

Lineament Density (Ld)

Lineaments are favourable for the movement of groundwater since these are surface expressions of joints, fractures and shear zones. Basically the study area is hard rock terrain so that the groundwater confined to secondary porosity. Lineaments play a prominent role in this hard rock terrain. Lineaments had demarcated from satellite imagery and with the help of drainage and topomaps. These are appeared as linear to curvilinear lines on the image. Lineaments are the manifestation of linear features that can play a major role in delineating groundwater prospective zones and identifying suitable sites for groundwater recharge. The purpose of lineament density is to calculate frequency of the lineaments per unit area. Lineament density calculated using Kernel density in ArcGIS and are converted into categories of different lineament densities, viz. low (<0.5 km/sq km), moderate (0.5-0.75 km/sq km) and high (>0.75 km/sq km). Moderate to high lineament density contribute the highest percentage of the area which is highly suitable for groundwater development.

Drainage Density (Dd)

The drainage pattern in the basin area is dendritic, sub-dendritic and parallel type. Thatipudi watershed is the 6^{th} order drainage basin. The drainage network and density maps were generated using ArcGIS. The availability of the total quantity of surface water is proportional to the drainage order and some particular structures are suitable at a particular drainage order only. Higher order streams make a larger catchment area and the water reaches it, the runoff velocity is quite high. So, most of the water flows out and there is a little chance of recharge. Drainage density (D_d) explains the landscape dissection, infiltration capacity of the land, runoff potential and the status of vegetative cover. The drainage density is categorized as low Dd < 2 km/sq km, medium Dd with 2 to 4 km/sq km and high Dd >4 km/sq km (Figure 2). Thus, low Dd was assigned for good ranking which indicates high groundwater prospects whereas high Dd is not considered for groundwater development.

Slope (S)

Slope is an important parameter in the construction of engineering structures, planning, and management of land and water resources projects, and it affects the runoff, recharge, and movement of surface water. 76.3% of the watershed area falls under strong to very steep slope category (Figure 1). Thus, the terrain with high slopes of the study area is producing rapid and excessive runoff, and increased erosion rate with insignificant recharge potential. Nearly level to gentle slopes (0-5%) indicate the presence of high groundwater potential zones, high slope (>10%) shows the presence of poor groundwater potential zones, as water runs rapidly off the surface.

Land Use and Land Cover (LULC)

Land use and land cover is considered to be an important parameter to assess the groundwater prospects and in the selection of suitable sites for artificial recharge of groundwater. Unsupervised classification and expert visual interpretation techniques in ERDAS Imagine used to extract the LULC information. Forty five spectral clusters with 95% convergence value were selected to perform the classification in identifying nine valid classes in the study area. The classes namely built-up (2.3%), crop land (26.1%), fallow (2.7%), plantation (4%), deciduous forest (37%), degraded forest (15.5%), scrub (4.9%), wastelands (3.9%) and water bodies (3.6%) were delineated. Crop lands with vegetation and water bodies are favourable for groundwater recharge and fallow land is poor for it (Narendra et al. 2013). These LULC classes were assigned as poor, moderate and good categories according to their properties related to water prospects.

Groundwater Potential Zones (GWPZ)

Groundwater potential zones map was generated on the basis of weights and ranks assigned to different features of the thematic layers in GIS model and is further classified into different groundwater potential zones based on the decision as poor, moderate and good (Figure 2). The map reveals that waterbodies, valley fills, and associated with high frequency of lineaments are identified in relatively good prospective zones, while the steep sloping hills underlain by compact lithology and high drainage density are exhibited as poor prospective zones. The weathered pediplain, buried pediments with moderate slope and underlain by hard rock but traversed by lineament areas are inventoried as under moderate prospects. The good category of groundwater potential area covers 38.8 sq km of total geographical area. In these areas, the presence of valley fill and high lineament density, found to have excellent yield. The remaining area of about 202.9 sq km has moderate potential and about 87.3 sq km of the area is nil to poor condition of the groundwater prospects. It was observed that about 90% of the watershed has moderate to poor potential for groundwater prospecting.

Estimation of Runoff Potential

SCS-CN Model

Mathematically SCS-CN equation can be expressed as,

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)}$$

$$S = 25.4\left(\frac{1000}{CN} - 10\right)$$

Where Q is the direct runoff (mm), P is the total precipitation (mm), S is the potential maximum retention or infiltration (mm). CN *is* a dimensionless number varies from 0 to 100. CN is determined from the standard SCS-CN table, based on land use, HSG, and antecedent moisture condition (AMC)-II. The CN_n is then adjusted for the existing moisture condition. HSG-A, -B, -C, and -D were derived from soil texture classes based on the soil infiltration rate. AMC-I, -II and -III were calculated according to rainfall limits for dormant and growing seasons. These are determined by total rainfall in the 5-day spell preceding a storm. As the soil moisture increases due to rainfall in early spell, runoff during storm event increases. The weighted curve number of the watershed was calculated using the following equation.

$$CN_w = \sum_{i=1}^{n} \frac{CN_i \times A_i}{A_i}$$

where CNw is the weighted curve number, CN_i is the curve number for each land use-hydrologic soil group, A_i is the area for each land use-hydrologic soil group, n is the class number of land use-hydrologic soil group.

The curve number estimation depend on HSG and different LULC categories. Soil is one of the important parameter for the percolation of surface runoff. The infiltration rate of the soil determines the type of structure to be located and the surface runoff potential also depends on the soil texture of the area. The main soil textural classes found in the study area are sandy loam/loamy sand, silty loam, sandy clay loam, sandy clay and clay loam covered with thick vegetation. These classes were further grouped into various hydrologic soil groups HSG-A,B,C and D. HSG-A consists of sandy loam and loamy sand soils covering 17.3% of the total area, group B (silty loam) occupies 3.2%, C (sandy clay loam) covers with the central portion of the watershed stretches along the river course and HSG-D (sandy clay and clay loam) soils distributes 73.8% of the watershed which is very low infiltration and high runoff potential (Table 3). Curve numbers were assigned for each LULC classes such as built-up, crop land, fallow, plantation, deciduous forest, degraded forest, scrub, wastelands, and HSG (A,B,C,D) combinations to determine weighted CN value. The resultant weighted CN for the watershed for CN-II is 81 for AMC-II, where as 64 (CN-I) and 91 (CN-III) for corresponding AMC-I, and AMC-III, respectively. In the present study, the rainfall in a storm event of below 50 mm was not considered as it is supposed to be any significant runoff. The storm events majorly are occurred in the months of September and October and most of the rainfall during cyclonic storms flows as runoff which results peak flows in the streams. Such cyclonic storms are very common during late August, September, October and November months. During monsoon period, most of the rainwater goes as surface runoff where as in the non-monsoon period is found to be almost rainless that leads to dry situation. The average annual runoff is 489.6 mm (51.2%) of average annual rainfall of the study area (Table 4).

Suitable Sites for Rainwater Harvesting

Due to water shortages during the summer period, rain water harvesting is considered to be a suitable method to overcome the problem in the study area. Rainwater harvesting is the technique of collection and storage of rainwater at surface or in the sub-surface aquifer, before it is lost as surface runoff. Though the watershed area receives good amount of rainfall but most of it drains out as runoff. One of the reasons is that unscientific agricultural practices practiced by the farmers in this region causes to water scarcity particularly in non-monsoon seasons. Most of the inhabitants in the area depends on groundwater for domestic needs.

Decision rules in selecting suitable sites Data integration in GIS is prerequisite for the purpose of multi-criteria decision making in site suitability analysis selecting water harvesting structures. Identifying suitable sites for water harvesting structures is a multi-objective and multi-criterion problem. Here objectives are finding suitable sites for check dams (CD), percolation tanks (PT), bench terrace (BT), and contour bund (CB). Criteria are suitable slopes (S), drainage (D), land use and land cover (LULC), soil texture (ST), lineaments (L), groundwater prospective zones (GWPZ) and its variables. These thematic maps associated with knowledge based decision rules (Table 2) are integrated using Knowledge Engineer tool in ERDAS Imagine. This provides the interface for an expert with firsthand knowledge of the data and the application to identify the variables, rules and output classes of interest that creates in the form of hierarchical decision tree. A decision tree is a hierarchical data structure consisting of nodes, which stores information or knowledge and branches, which connect the nodes and also consists of hypothesis, rules and variables (factors). A rule is a conditional statement or list of conditional statements, about the variable's data values and/or attributes that determine an informational component or hypothesis. Multiple rules and hypothesis can be linked together into a hierarchy that ultimately provides desired output classes CD, PT, BT, CB.

Steep slopes are not suitable for constructing water harvesting structures. The very gentle to moderate slope categories (1 to 10%) of the terrain have been considered for constructing check dams and bench terracing. Percolation tanks are to be selected for considering the category of slopes nearly level to gentle where as gentle to moderate slopes are for contour bunds. Second or third order drainage were considered for suggesting check dams and percolation tanks and also the catchment area must be between 40 and 100 ha. Stream order 2 to 5 was taken into consideration for bench terracing. Various land cover classes were used as input variables such as agricultural, forest and wastelands for the identification of suitable areas for check dams and bench terracing, whereas agricultural and forest lands were considered for percolation tank and contour bunds. Highly permeable soils were selected in constructing suitable structures whereas any soil type for bench terracing and contour bund. Presence of lineaments was selected for sites water harvesting structures. Construction of check dams and percolation tanks are suitable on highly fractured and weathered rock for speedy recharge of the surface runoff. To identify suitable locations for various water harvesting structures, moderate to good groundwater prospective zones were considered. By integrating various input thematic maps and applying the decision rules, the selected validation points for suitable sites were verified with ground truth observations and they are confirmed. After detailed analysis and assessment, 13 suitable sites for constructing check dams, 5 locations for the excavation of percolation tanks, 7 sites each for bench terrace and contour bunds were identified (Figure 2).

Validation and Accuracy Assessment

Groundwater levels were measured from 23 dug wells during pre-monsoon (PMS) and post-monsoon seasons (POMS) in the Month of April and December, respectively, during 2013-14 covering with different water prospective zones. Well depth range between 4 and 9.2 m below ground level (mbgl) and radius vary from 2.5 to 10 m. Depth to water level (DWL) varied from 2.1 to 8 m and 1.7 to 5.9 m bgl for PMS and POMS in 2013, while in 2014, it ranged between 2.2 to 8.2 m and 1.8 to 6.2 m, respectively (Table 5). It was also observed that the dug wells sustain continuous pumping for 3-4 hours with a 5 HP pump yielding 55 to 120 m^3/day. The observed water levels from open wells in the watershed area indicating the draft exceeds the recharge.

CONCLUSIONS

Watershed management practices are necessary in the development of groundwater particularly in hard rock hilly regions. Thatipudi watershed located in Eastern Ghats hard rock terrain of Andhra Pradesh State, India, has been suffering from water scarcity for the past few years. In the present study, remote sensing, GIS, MCDM and field techniques have been successfully used for identification suitable sites for artificial recharge. A four-step methodology consisting preparation of various themes, assignments of weights and ranks, overlay analysis to find groundwater potential zones, SCS-CN model for deriving runoff potential and IMSD technical guidelines with expert knowledge to find sites for harvesting structures. Satellite data along with conventional information were used in the preparation of thematic maps. Groundwater potential zones were delineated as poor, moderate and good categories based on MCDA techniques. It was found that moderate to good category occupies 83.53 % of the total area. The generated map was verified with the water levels data and found good agreement. The area covering with thick vegetation, high relief, greater slopes leads to excess runoff and reduced recharge of groundwater resulting water scarcity. The depletion of water levels was observed in the summer season. Erratic rainfall with long intervals of dry spells in non-monsoon months and intense rainfall in monsoon months are caused to high runoff. In order to improve groundwater levels, a total of 32 water harvesting structures were suggested for constructing check dams, percolation tanks, bench terrace and contour bunds. Integration of remote sensing and GIS has demonstrated the capabilities for demarcation of different artificial recharge zones of groundwater. The methodology adopted in this study can be used for any region with similar conditions along with appropriate modifications. It is also recommended that the suggested rainwater harvesting structures and other measures may be implemented in the moderate to good potential zones to overcome the water scarcity problem in the study area.

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Table 1. Rank and weightages are assigned for different features of various themes

Thematic layer	Feature/category	Rank	Weightage	Thematic layer	Feature/category	Rank	Weightage
Geomorphology	Ridges	3	20	Slope	0-1%	1	20
	Escarpments	3			1-3%	1	
	Structural hill	3			3-5%	1	
	Denudational hill	2			5-10%	2	
	Residual hill	3			10-15%	2	
	Pediment	2			15-35%	3	
	Weathered pediplain	1			>35%	3	
	Ravines	3		Lineament density	<0.5	2	15
	Bajada	1			0.5-0.75	2	
	Intermontane valley	1			>0.75	1	
	Valley fill	1		Drainage density	<2	1	15
	River	1			2-4	2	
	Islands	1			>4	3	
	Waterbody	1		Land use/land cover	Builtup	3	15
Geology	Khondalites	3	15		Crop land	1	
	Charnockites	3			Fallow	3	
	Laterite cappings	3			Plantations	2	
	Limestone	3			Forest land	2	
	Alluvium	1			Wastelands	3	
					Water bodies	1	

Table 2. Decision rules adopted for the selection of suitable areas for water harvesting structures

Structure	S	D	LULC	S.Tex.	L	GWPZ
Check dam	1-10	2-3	Agricultural, forest and wastelands	Sandy loam/loamy sand, and silty loam	Present	Moderate to good
Percolation tank	0-5	2-3	Agricultural and forest lands	Sandy loam/loamy sand, and silty loam	Present	Moderate to good
Bench terrace	1-10	2-4	Agricultural, forest and wastelands	Sandy loam/loamy sand, silty and clay loam, sandy clay loam	Present	Moderate to good
Contour bund	3-10	-	Agricultural and forest lands	Sandy loam/loamy sand, silty and clay loam, sandy clay loam	Present	Moderate to good

S:slope percentage; D:stream order; LULC:landuse/landcover; S.Tex.:soil texture; L:Lineament; GWPZ:groundwater prospective zones

Table 3. Distribution of HSG and their textural classes

HSG	Description	Soil texture	Distribution	
			sq km	%
A	Deep, well drained, sand and gravelly soils, moderate stony mixed, flat to gentle, characterized by low runoff and high rate of water transmission	Sandy loam and loamy sand	55.6	17.3
B	Moderately deep to deep, moderate to well drained, very gentle to moderate slopes, and moderate rate of water transmission and runoff	Silty loam	10.3	3.2
C	Shallow, high clayey content soils on gentle sloping valleys along the river, moderate to severe erosion, low rate of water transmission and moderate runoff	Sandy clay loam	18.3	5.7
D	Very shallow, soils contain clay layer covered with thick vegetative forest, gentle to steep terraced slopes, moderate to severe erosion, somewhat excessively drained, high runoff potential and very low rate of water transmission.	Clay loam, sandy clay/clay loam (gravelly and cover with forest)	236.9	73.8

Table 4. Runoff observed for different storm events during 2014-2016

Year	Storm event	Storm rainfall (P) mm	5 day Antecedent rainfall mm	AMC class	Runoff (mm) Q	Total P	Total Q mm	Total Q %
2014	Jul 9-12	78	42.2	II	34.8	787.4	447.5	56.8
	Aug 26-31	148.2	22.4	I	54.5			
	Sep 19-24	78.8	0	I	13.1			
	Oct 12-13	482.4	0	I	345.2			
2015	Apr 24-25	52.2	0	I	3.4	744	318.2	42.8
	Jun 2-3	64.4	4.2	I	7.2			
	Jun 17-23	180	7.2	I	77.9			
	Jul 23-24	57	3.4	I	4.7			
	Aug 9-13	107	0	I	27.8			
	Sep 12-17	216.6	75.4	III	189.1			
	Oct 15-16	66.8	0	I	8.1			
2016	May 19-21	140.4	0	I	49.1	1301	703.3	54.1
	Jun 25-Jul 5	113.2	19.2	II	63.8			
	Jul 20-26	112.6	11.2	I	31.1			
	Jul 29-Aug 7	72	73.8	III	48.7			
	Aug 25-29	204.6	0	I	97.2			
	Sep 11-27	425.8	7	I	292.1			
	Oct 1-3	124.2	0	I	38.3			
	Oct 5-8	108.2	158.2	III	83.0			
				Average rainfall-runoff		944.2	489.7	51.2

Table 5. Groundwater levels observed from open wells during 2013-14

Well location	Lat. dd	Long. dd	Well depth m	Depth to water level (mbgl) 2013 April	2013 Dec.	2014 April	2014 Dec.	Water level fluctuation (m) 2013	2014
Chilakalagedda	18.18	83.13	9.1	5.2	3.9	4.8	3.2	1.3	1.6
Venkayyapalem	18.20	83.13	6.4	2.1	1.7	2.2	1.8	0.4	0.4
Pedapadu	18.21	83.16	6.4	4.2	2.6	4.3	1.8	1.6	2.5
Tummanuvalasa	18.21	83.10	4.1	3.2	2.6	3.4	2.8	0.6	0.6
Kasipatnam	18.22	83.12	7.8	4.9	3.2	5.2	3.8	1.7	1.4
Damsarai	18.22	83.09	8.5	6.0	4.8	6.2	4.1	1.2	2.1
Sitampeta	18.24	83.11	9.2	5.1	4.8	5.3	4.8	0.3	0.5
Bhimpolu	18.27	83.11	7.1	4.7	3.2	4.8	3.6	1.5	1.2
Sarupalli	18.28	83.10	5.2	3.9	2.8	3.8	3.0	1.1	0.8
Sivalingapuram	18.21	83.07	4.8	3.9	3.2	4.0	3.4	0.7	0.6
Damuku	18.22	83.04	8.8	5.3	4.2	5.6	4.0	1.1	1.6
Borra	18.28	83.04	9.0	8.0	5.6	8.2	6.2	2.4	2.0
Bheesupuram	18.27	83.00	8.9	6.1	4.2	5.9	4.4	1.9	1.5
Kuruseela	18.32	83.05	7.1	5.2	4.0	5.0	3.9	1.2	1.1
Lotheru	18.34	83.05	8.9	7.2	5.9	7.4	5.8	1.3	1.6
Gannela	18.33	82.99	7.8	6.9	4.1	6.5	4.0	2.8	2.5
Karakavalasa	18.29	82.99	6.2	4.8	3.6	5.1	3.8	1.2	1.3
Limbuguda	18.32	82.95	8.1	6.8	4.4	6.7	4.0	2.4	2.7

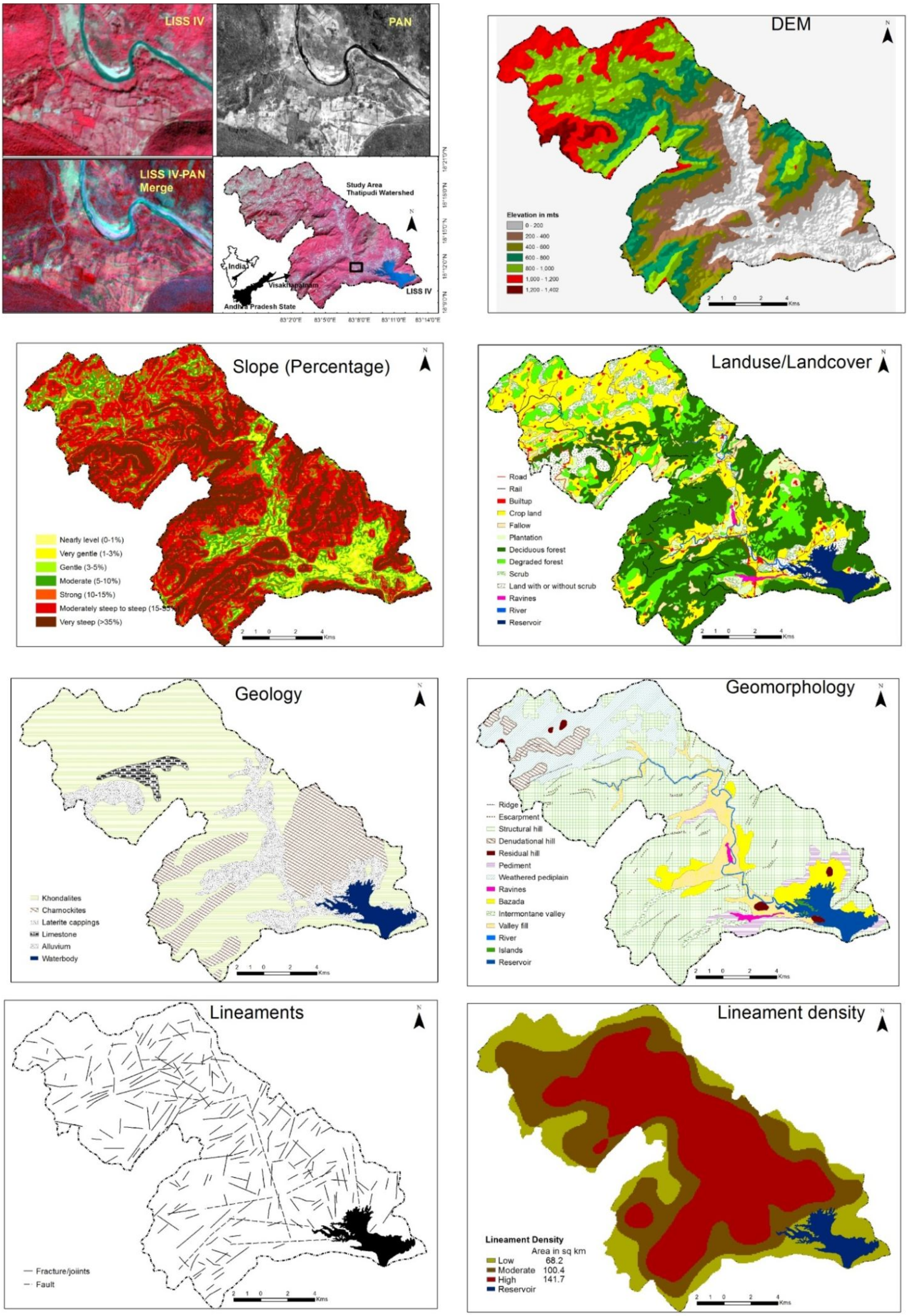
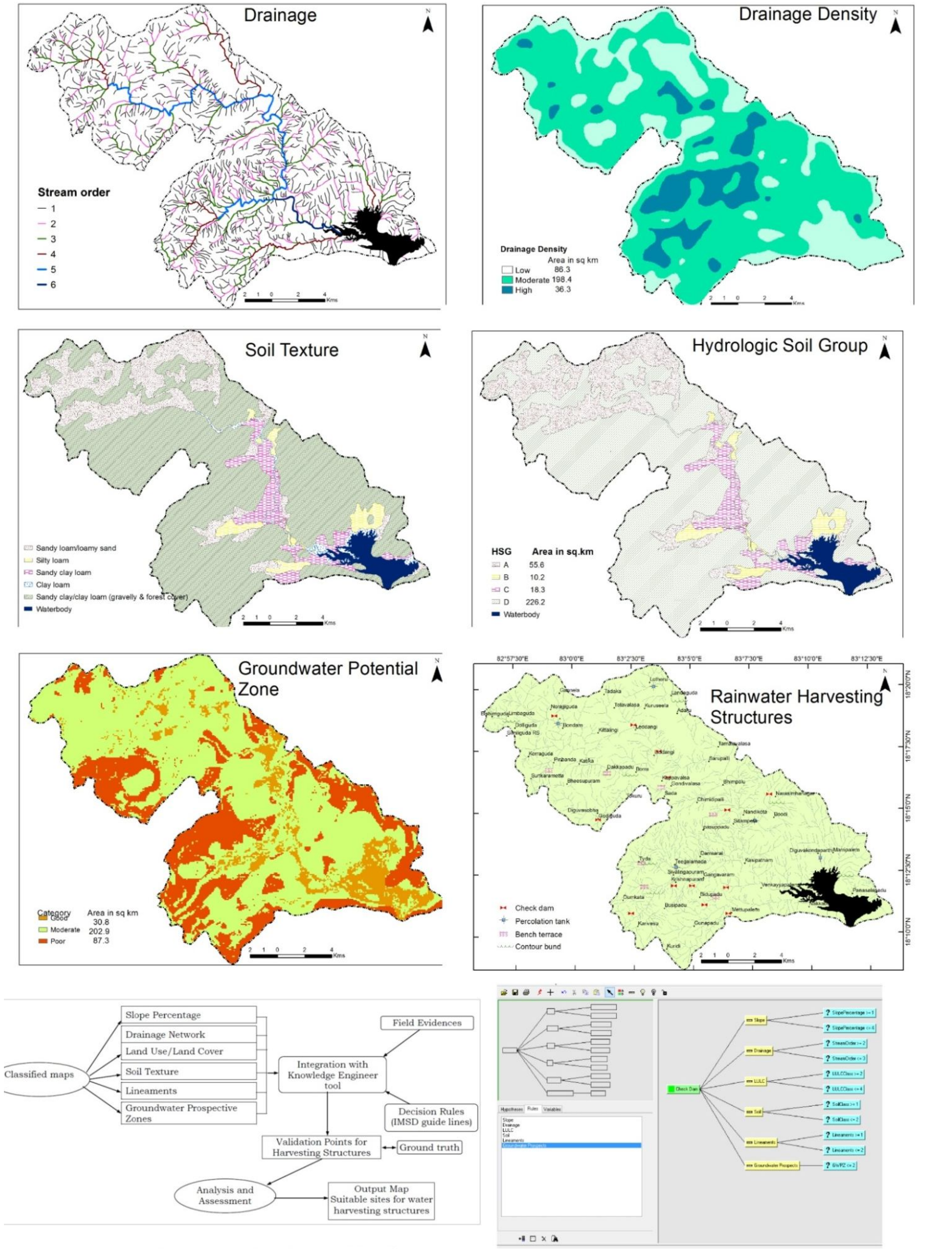


Figure 1. Satellite data and various thematic maps of the study area.



Flow chart shows the process involved in identifying suitable sites for artificial recharge

Software process for identifying suitable sites (eg.check dam)

Figure 2. Various maps and process of the study