Natural Resources, 2020, 11, 127-145
https://www.scirp.org/journal/nr
ISSN Online: 2158-7086
ISSN Print: 2158-706X

Mapping of Potential Groundwater Recharge Zones in the Kolleru Lake Catchment, India, by Using Remote Sensing and GIS Techniques

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How to cite this paper: Kolli, M.K., Opp, C. and Groll, M. (2020) Mapping of Potential Groundwater Recharge Zones in the Kolleru Lake Catchment, India, by Using Remote Sensing and GIS Techniques. *Natural Resources*, **11**, 127-145.
https://doi.org/10.4236/nr.2020.113008

Received: February 19, 2020
Accepted: March 23, 2020
Published: March 26, 2020

Abstract

Water scarcity is the major problem in India where the population has been tremendously increasing, which results in invading natural resources, thus affects on hydrological processes. Because of this, significant surface water bodies have been disappearing continuously. Therefore, more pressure on groundwater resources is a consequence of that. The integration of remote sensing and geographical information system (GIS), which helps in groundwater research for the investigation of potential groundwater availability, is essential to assess, monitor, and conserve groundwater resources. This analysis reports on the mapping of various potential groundwater resources in the Kolleru Lake catchment, India, by using remote sensing and GIS techniques. For this, a survey of India toposheets and IRC-1C satellite imageries was used to prepare thematic layers of geomorphology, drainage density, lineament, slope, land-use, soil, rainfall, and NDVI converted into raster format in ArcGIS. The raster maps of these thematic layers were assigned to a weight-based factor depending on the catchment characteristics and its topographic influence. The results demonstrated that about 7% of the area is under excellent groundwater potential recharge. Good, moderate, and lower potential conditions are 42%, 38%, and 13%, respectively. The results indicated that the management of groundwater potential zones should be targeted on the middle-catchment region. Further, the results were validated with the borehole data obtained from the Government of Andhra Pradesh-Groundwater Department. These results are useful for better both planning and groundwater management sources in the Kolleru Lake catchment.

Keywords

Groundwater Potential Zones, Kolleru Lake Catchment, India, Remote Sensing, GIS, Weighted Overlay Analysis

1. Introduction

Groundwater is a hidden natural resource that serves many purposes for living beings. There is always a second choice of the available groundwater next to the surface water bodies. Rainfall is the primary source of groundwater recharge through infiltration [1]. However, different physiographic, geomorphic, and geologic properties play a significant role in infiltration rates, like elevation and slope extended to climatic conditions that confront the potential groundwater sources [2] [3] [4] [5]. In recent years, rapid industrialization and urban infrastructure exploit groundwater resources, resulting in adverse impacts. During the dry season, the groundwater is reaching its maximum depth, and it is difficult to extract it. In this situation, water scarcity is a common phenomenon in India.

There are numerous methods to explore groundwater resources. However, conventional ground survey methods are the most reliable and standard methods for determining the location of boreholes and aquifer thickness [6]. Such approaches need skilled persons, and they are time-consuming and cost-effective [7] [8]. Many spatial problems give rise to GIS-based multi-criteria decision analysis [9]. With the introduction of remote sensing and Geographical Information System (GIS) techniques, an easy procedure to estimate the spatial distribution of groundwater sources from very high to low levels became possible [10]-[18]. A GIS framework was developed and analyzed by Das *et al.* [19] for the investigation of potential groundwater resources. Many researchers have been used GIS methods to explore potential groundwater zones, further demonstrated that different topographic, physiographic, and geologic terrains cause in different depths of water levels [20]-[25]. Surface phenomena not always control both the occurrence and the movement of groundwater by porosity and permeability [26]. But many sub-surface aquifers are governed by surface features like elevation, slope, drainage density, rainfall, soil textural properties, lineament density, land-use patterns, lithology, water bodies, etc. For example, higher elevation and steeper slopes increase surface runoff and while the presence of depressions strives to increase infiltration rates, thus optimizing the groundwater recharge potential.

Various types of information can be extracted from remote sensing data, *i.e.*, hydrologic, geologic, surface features, etc. extended to the below ground level [27] [28] [29]. However, a lack of precision in *in-situ* analysis requires validation with borehole data [30]. This study was conducted to develop a digital database of groundwater availability in the Kolleru Lake catchment, India, by using geological, hydrological, structural information and remote sensing data as well for the rough estimation of crop patterns. The data was collected from various Indian organizations and prepared in a GIS database for overlay analysis to achieve the objective of this study. To further analyze, the results were validated with the borehole data obtained from the Government of Andhra Pradesh-Ground Water Department.

2. Study Area

The Kolleru Lake has situated between 16˚24'10" and 17˚23'44" North latitude, and 80˚41'5.5" and 81˚39'27.5" East longitude in the south-eastern part of India (Figure 1). It is the largest freshwater lake in India located in the state of Andhra Pradesh and forms the largest shallow freshwater lake in Asia, with a catchment area of 5,052 km^2, a water surface area of 901 km^2 at +10 MSL (mean sea level) [31]. The average temperature of 28˚C, and the annual mean precipitation is 1,094 mm [32]. More than >70% of the annual rainfall occurs between June and September by South-West monsoons, and the North-East monsoons bring one-third of rainfall in October. Sixty-eight minor irrigation channels are flowing into the lake. It has only one outlet river, the Upputeru River, which connects the Kolleru Lake to the Bay of Bengal [33] [34]. The lake has a rich biodiversity, and thereby, the international Ramsar Convention declared it as a wetland of international importance in November 2002 [35].

Two perennial rivers, the Krishna and the Godavari, formed its catchment, which gives the lake a unique characteristic and has led to its role as a natural flood-balancing reservoir between these two river basins. The catchment is served with both surface water and groundwater sources. The Government of Andhra Pradesh Ground Water Department [36] reported that the catchment area holds deep water levels of more than 20 m depth to the water table. However, the quality of water is good and suitable for both drinking and irrigation purposes, except for the southern part of the deltaic region. Salinity and waterlogging are the major problems in the deltaic aquifers. The Kolleru Lake catchment is characterized by much abundance in the surface runoff, with many irrigation canals and a high sediment transport capacity. The whole catchment

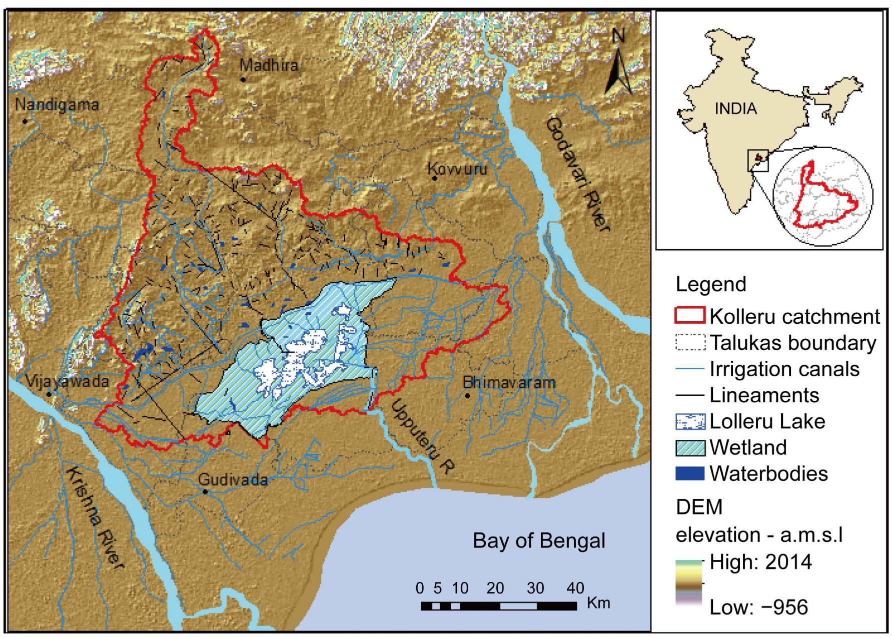

Figure 1. Location of the Kolleru Lake catchment in South India.

water resources are mainly used for agriculture and industrial purposes. Despite the high amount of surface water provided by the Kolleru Lake wetland ecosystem, the surface water levels always fluctuated by seasonal variations, thus massive flooding during the monsoon period, and partial drying out during the dry season.

3. Database and Methods

The data used in this study obtained from various Indian organizations are summarised in Table 1. The base map of the Kolleru Lake was prepared based on the Survey of India topographic maps (65H/2, 5, 6) on a 1:50,000 scale. The drainage network for the study area was extracted from DEM (Digital Elevation Model), depending on flow direction and flow accumulation from Arc Hydro Tools. The slope map was prepared from DEM in the ArcGIS Spatial Analyst tool. The rainfall map was prepared from the data obtained from the Indian Meteorological Department (IMD) gauge stations, by using Kriging interpolation to prepare the spatial distribution of rainfall maps. The drainage density and lineament density maps were prepared by using the line density analysis tool in the ArcGIS.

Satellite images from IRS-1C, LISS-III sensor, on a scale of 1:50,000 were georeferenced into the UTM projected coordinate system, and have been used for delineation of thematic layers of a soil map. Land use, lineament, and geomorphology were converted into a raster format with a 30 m grid resolution. The methodology adopted in this study is shown in Figure 2. According to the catchment area characteristics, the most sensitive parameters to the groundwater potential recharge are derived in equation 1, where the study area is comprised of the wetland ecosystem, and a maximum of cropland in the northern region, and Lacustrine terrain in the deltaic region.

Table 1. Description of available data of the Kolleru Lake catchment.

Data used	Scale	Spatial resolution	Data description	Data source
DEM	1:12,500	30 m × 30 m	Elevation, slope, streams	National Remote Sensing Centre (NRSC), Hyderabad
Landuse	1:50,000	30 m × 30 m	Landuse types	Indian Space Research Organization (ISRO), Bangalore
Soil map	1:500,000	250 m × 250 m	Soil physical & chemical properties	National Bureau of Soil Survey and Landuse Planning (NBSS&LUP), Nagpur
Weather data	Rain gauge	Monthly records	Rainfall data	Indian Meteorological Department (IMD), Hyderabad
Geomorphology	1:50,000	30 m × 30 m	Landform & topography	National Remote Sensing Centre (NRSC), Hyderabad
Lineament map	1:50,000	30 m × 30 m	Faults, joints, fractures	National Remote Sensing Centre (NRSC), Hyderabad

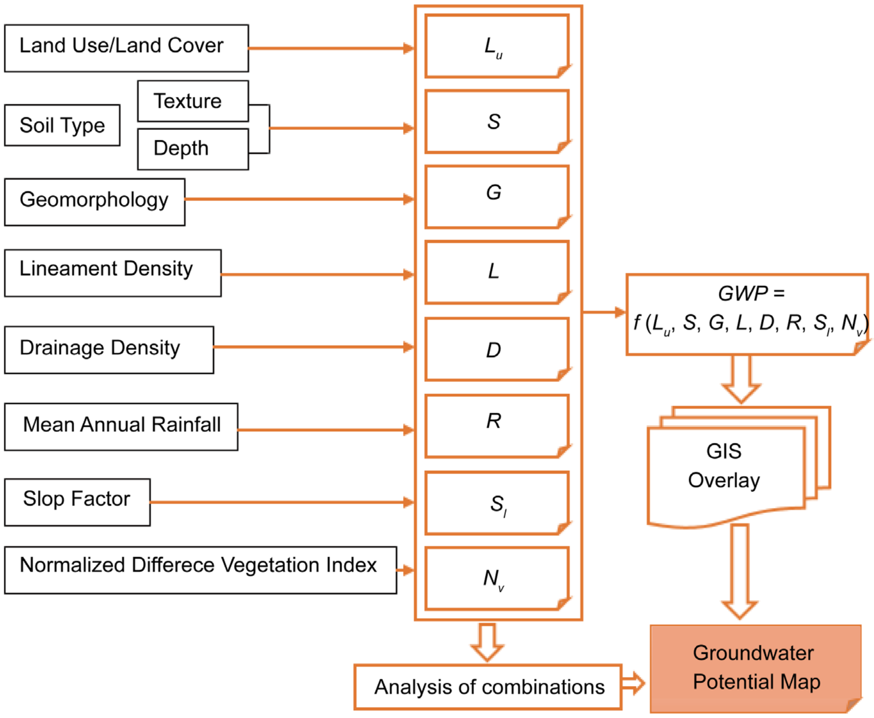

Figure 2. Methodology flowchart used for deriving potential groundwater zones.

$$GWP = f\left(L_u, S, G, L, D, R, S_l, N_v\right) \tag{1}$$

where GWP refers to the groundwater potential, L_u is the land-use classification, S is the soil type, G is the geomorphology, L is the lineament density, D is the drainage density, R is the mean annual rainfall, S_l is the slope classification and N_v is the normalized difference vegetation index (NDVI).

During the delineation of potential groundwater zones, each factor has its own characteristic influence on groundwater recharge, and every factor was independent [37]. The catchment characteristics were analyzed and based on the previous literature sources, and the thematic weight was assigned to evaluate potential groundwater zones are outlined in Table 2.

4. Results and Discussions

The fluctuations of groundwater in the Kolleru Lake catchment are governed by several parameters such as land-use, soil type, lineament density, geomorphology, drainage density, slope, and rainfall, which are discussed below.

4.1. Landuse Map

Landuse plays a significant role in surface runoff and available moisture conditions. Urban areas contribute more surface runoff, whereas agricultural areas contribute to less runoff as compared to the urban area, but not more than forest areas. Where the surface runoff is higher, it implies less influence on the infiltration rate. Landuse map for this study area delineated from IRS LISS-III satellite data based on NRSC (National Remote Sensing Centre)-LULC classification is

Table 2. Classification of weighted thematic factors influencing potential groundwater zones.

Factor	Domain of effect	Assigned weight	Thematic assigned
Landuse	Built-up land	1	
	Wasteland	2	
	Mangrove forest/dense forest	3	4
	Shrubland	4	
	Cropland	5	
	Wetland/lake	6	
Soil type	Very fine, moderately well-drained, clayey soils	1	
	Imperfectly drained clayey soils	2	
	Excessively drained, sandy soils	3	
	Moderately drained, clays soils	4	5
	Deep, well-drained, clayey soils	5	
	Very deep and moderately well-drained, fine loamy soils	6	
	Fine loamy soils	7	
	Well-drained gravelly loam soils	8	
Geomorphology	Denudation origin-pediment, Pedi plain complex	1	
	Dissected Hills & Valleys	2	
	Lower Plateau	3	
	Lacustrine Terrain	4	2
	Deltaic Plain	5	
	Older Coastal Plain	6	
	Fluvial origin active flood plain	7	
Lineament density	Very low	1	
	Low	2	
	Medium	3	3
	High	4	
	Very high	5	
Drainage density	Very low	1	
	Low	2	
	Medium	3	1
	High	4	
	Very high	5	
Mean rainfall	921.5 - 961.2	1	
	961.2 - 986.4	2	
	986.4 - 1,010.3	3	7
	1,010.3 - 1,036.1	4	
	1,036.1 - 1,082.3	5	
Slope	18.4 - 51.4	1	
	9.89 - 18.3	2	
	5.86 - 9.88	3	6
	2.83 - 5.85	4	
	0 - 2.82	5	

depicted in Figure 3(a). Land-use data were mainly classified into agricultural land (for paddy cultivation), fishponds, urban, barren land (unused or uncultivated land), and forest areas. Present up-slope in the headwaters are covered by shrub vegetation and forest areas. The runoff from the upper catchment passes the agricultural fields of the middle part before entering into the lake. Agricultural land is the dominant land use cover (68%) of the catchment, followed by fishponds (16%), mangrove forests on gently sloped areas (10%), and the urban area does not exceed 3% of the total area. The high weight assigned for the forest, agricultural land, and waterbody, whereas the low weight assigned for built-up land, shrubland for groundwater delineation.

4.2. Soil Map

The soil map was obtained from the ICAR – National Bureau of Soil Survey & Land Use Planning, Nagpur, India (ICAR-NBSS&LUP). It was georeferenced to the UTM projected coordinate system in ArcGIS. Further, the map was precisely geo-coded to each soil profile at different categoric levels in classifying soils. The catchment area is composed of 38 different soil types, dominantly with clayey texture is depicted in Figure 3(b). The insight of data provides soil depth, drainage, texture, erosion, and soil taxonomy is summarised in Table 3 [38] [39]. According to this data, 46.7% of the catchment is largely extended to the well-drained condition, 19% is a moderately well-drained, while 27.8% is composed of imperfectly drained, and 2.4% is excessively drained. The field capacity of the soil for this catchment is mainly depended upon the soil depth and drainage condition. Very deep soils (55%) are predominantly identified within the

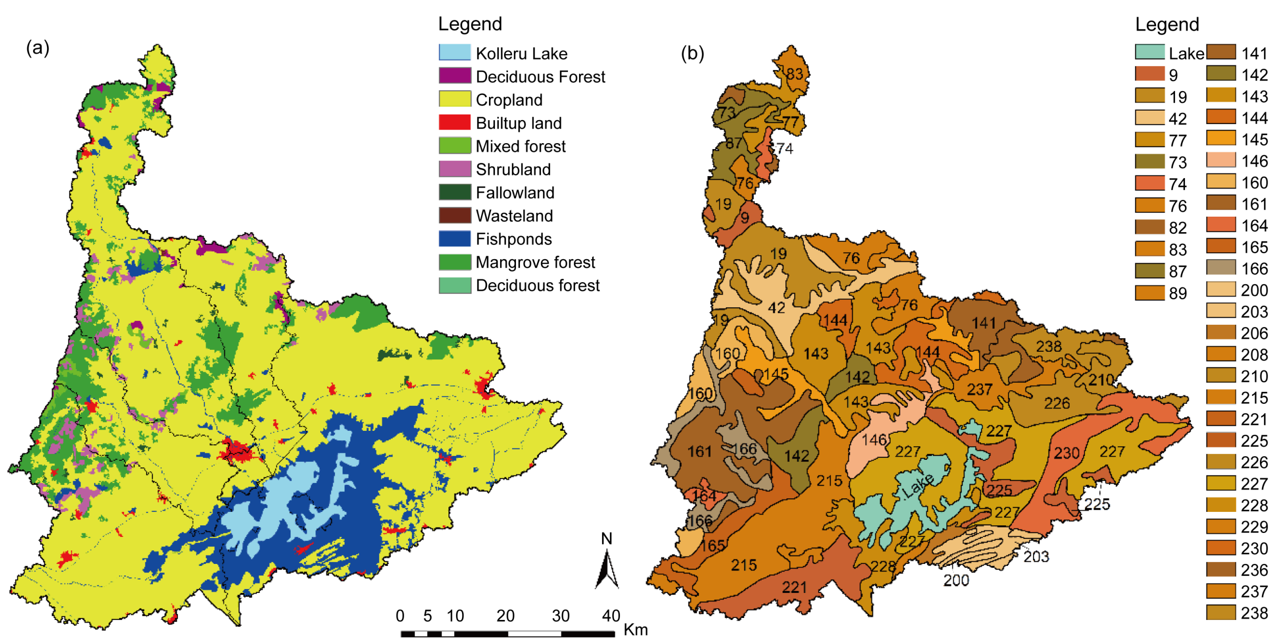

Figure 3. (a) Land use and land cover map; (b) soil classification map of the Kolleru Lake catchment. (*i.e.*, the reference code of the soil data is presented based on their original data source) [Note: the physical properties of the soil for the whole catchment area is outlined in Table 3].

Table 3. Soil type and its characteristics of the Kolleru Lake catchment.

Soil Code	Soil Depth	Drainage	Texture	Erosion	Soil Taxonomy	Area (%)
9	Moderately deep	Well-drained	Gravelly clay soils	Moderately eroded	Clayey – Skeletal, Typic Rhodustalfs	37.34 (0.73)
19	Moderately deep	Well-drained	Clayey soils	Moderately eroded	Fine, mixed, Typic Haplustalfs	269.36 (5.33)
42	Very deep	Moderately well-drained	Cracking-clay	–	Fine, montmorillonite, Vertic Ustropepts	208.51 (4.12)
73	Deep	Well-drained	Loamy soils	Moderately eroded	Fine loamy, mixed, Typic Paleustalfs	42.64 (0.84)
74	Very deep	Well-drained	Loamy soils	Moderately eroded	Fine loamy, mixed, Typic Paleustalfs	19.5 (0.38)
76	Very deep	Well-drained	Clayey soils	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	171.62 (3.39)
77	Very deep	Well-drained	Clayey soils	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	72.2 (1.42)
82	Shallow	Excessively drained	Gravelly loam soils	Severely eroded	Loamy-skeletal, Lithic Ustorthents	16.77 (0.33)
83	Very shallow	Excessively drained	Loamy soils	Very severely eroded	Loamy, mixed, Lithic Ustorthents	31.8 (0.62)
87	Very deep	Moderately well-drained	Cracking-clay	Slightly eroded	Fine, montmorillonitic, Vertic, Ustropepts	72.45 (1.43)
89	Very shallow	Excessively drained	Gravelly loam soils	Severely eroded	Loamy-skeletal, Lithic Ustorthents	14.84 (0.29)
141	Very deep	Well-drained	Clayey soils	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	91.27 (1.81)
142	Deep	Well-drained	Clayey soils	Moderately eroded	Fine, mixed, Ultic, Paleustalfs	127.31 (2.51)
143	Very deep	Well-drained	Clayey soils	Slightly eroded	Fine, mixed, Typic Ustropepts	291.13 (5.76)
144	Very deep	Well-drained	Clayey soils	Severely eroded	Fine, mixed, Typic Ustropepts	189.12 (3.74)
145	Very deep	Well-drained	Clayey soils	Slightly eroded	Fine, mixed, Typic Ustropepts	132.51 (2.62)
146	Very deep	Moderately well-drained	Cracking clay soils	Moderately eroded	Fine, montmorillonitic, Typic Haplusterts	112.62 (2.22)
160	Deep	Well-drained	Clayey soils	Moderately eroded	Fine, mixed, Typic Paleustalfs	125.56 (2.48)
161	Very deep	Well-drained	Clayey soils	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	316.03 (6.25)
164	Shallow	Excessively drained	Gravelly loam soils	Severely eroded	Loamy-skeletal, Lithic Ustorthents	21.18 (0.42)
165	Very shallow	Well-drained	Gravelly loam	Severely eroded	Loamy-skeletal, Lithic Ustorthents	129.23 (2.55)
166	Deep	Moderately well-drained	Loamy soils	Slightly eroded	Fine loamy, mixed, Typic Ustorpepts	146.69 (2.90)
200	Very deep	Excessively drained	Sandy soils	Slightly eroded	Mixed, Typic Ustipsamments	40.04 (0.79)

Continued

203	Deep	Moderately well-drained	Clayey soils	Slightly eroded	Fine, mixed, Typic Ustropepts	70.46 (1.39)
206	Deep	Imperfectly drained	Cracking clay	Slightly flooded	Very fine, Typic Haplusterts	25.02 (0.49)
208	Deep	Well-drained	Loamy soils	Moderately eroded	Fine loamy, mixed, Typic Haplustalfs	19.38 (0.38)
210	Deep	Well-drained	Clayey soils	Slightly eroded	Fine, mixed, Typic Ustropepts	66.97 (1.32)
215	Moderately deep	Moderately well-drained	Cracking clay	Slightly eroded	Fine, montmorillonitic, Vertic Ustropepts	399.18 (7.90)
221	Very deep	Imperfectly drained	Cracking clay	–	Fine, montmorillonitic, Typic Haplusterts	184.11 (3.64)
225	Very deep	Imperfectly drained	Clayey soils	Slightly flooded	Fine, montmorillonitic, Aquic Ustropepts	119.9 (2.37)
226	Very deep	Imperfectly drained	Cracking clay soils	Slightly flooded	Fine, montmorillonitic, Typic Haplusterts	123.38 (2.44)
227	Very deep	Imperfectly drained	Cracking clay soils	Slightly flooded	Very fine, montmorillonitic, Typic Haplusterts	597.14 (11.8)
228	Deep	Imperfectly drained	Cracking clay	Slightly flooded	Very fine, Typic Haplusterts	124.14 (2.45)
229	Very deep	Imperfectly drained	Cracking clay soils	Slightly flooded	Very fine, Entic Haplusterts	14.02 (0.27)
230	Deep	Imperfectly drained	Cracking clay soils	Slightly flooded	Very fine, Chromic Haplusterts	220.92 (4.37)
236	Very deep	Well-drained	Clayey soils	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	57.76 (1.14)
237	Deep	Well-drained	Clayey soils	Moderately eroded	Fine, mixed, Rhodic Paleustalfs	109.64 (2.16)
238	Deep	Well-drained	Gravelly clay soils	Moderately eroded	Clayey-skeletal, Typic Rhodustalfs	100.24 (1.98)

catchment area, with clay dominance in texture and pore in coarse and medium pores. The soil type is an essential factor for the amount of water that can infiltrate into the subsurface and influence on groundwater recharge [40] [41]. Therefore, the high weight assigned for the excessively drained soil and the low weight assigned for the imperfectly drained.

4.3. Geomorphology

Geomorphologically the catchment can be divided into five most distinct units; Pediplain complex, Lacustrine Terrain, Active Flood Plain, Coastal Plain, and Deltaic Plain. The major part of the catchment in the northern region underlain by the Pediplain complex consists of hills and ridges, which is overlain by valley-fill sediments. In contrast, the southern part of the area represented by the alluvial plains forming the Krishna and Godavari deltas. The Krishna and Godavari rivers and its tributaries have contributed to the formation of the alluvial plain. The deltaic part is a relatively flat surface. The major course of rivers forms the flood plain deposits. The relief, slope, type of wethering material, thickness of alluvium, nature of the deposited material, and the overall formation of deposits play a vital role in defining the groundwater regime [42]. The most important of the catchment overlain by the Lacustrine Terrain is the Kolleru Lake wetland ecosystem. The study area consists of a different composition of landforms such as wetlands, floodplain deposits, alluvial plains, and natural terrains, which together form a unique relief characteristic of the catchment (Figure 4(a)).

4.4. Lineament

Lineaments are natural faults, joints, and fractures, which can easily be distinguished from satellite images by their relatively linear alignments. Lineaments represent the zones of faulting and fracturing, resulting in increased secondary porosity and permeability (Yeh *et al*., 2016). Lineaments are the one form of the natural permeable layer directly represent groundwater moment. If there is a presence of lineament, it reveals that there is good groundwater potential. The lineament map of the study was obtained from the National Remote Sensing Centre (NRSC), thereby the lineament density map was prepared in ArcGIS by using the line density tool is depicted in Figure 4(b). The lineament of the study is highly concentrated in northern and western areas of the catchment, because of the southern part its presence of a wetland, since it is already a permeable layer.

4.5. Rainfall

Rainfall is the major factor of the hydrological cycle that significantly influences

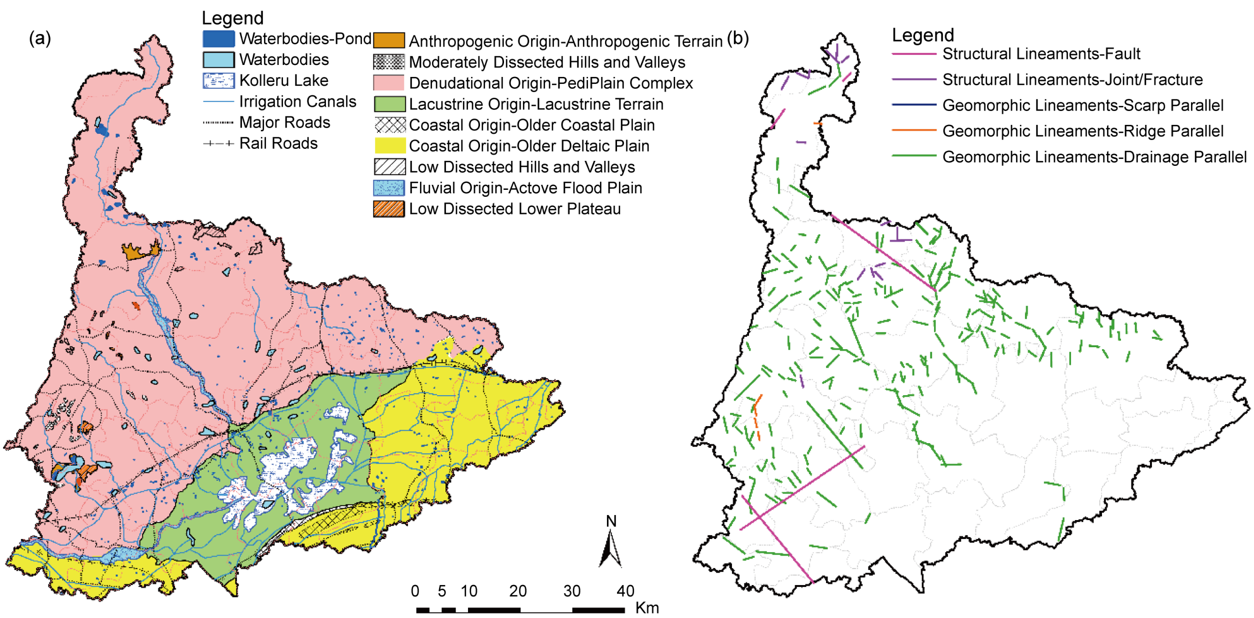

Figure 4. (a) Geomorphology and (b) Lineament of the Kolleru Lake catchment.

surface runoff and infiltration. The high infiltration rate contributes to groundwater recharge, which depends on the very high intensity and the duration of the rainfall. The annual average rainfall of the catchment is 1,094 mm. More than 70% of the annual rainfall occurs between June and September by South-West monsoons, and the North-East monsoons (25%) bring one-third of rain from October to March. For this study, rainfall data of 2018 was used. Further, the Kriging interpolation method applied to generate a spatial distribution of rainfall map is depicted in **Figure 5(a)**. The annual average rainfall range from 921.5 mm to 1,082 mm. For the groundwater potential, high weights are assigned to the high rainfall data.

4.6. Slope

The slope is an essential factor for the delineation of potential groundwater zones. A higher degree slope indicates a rapid runoff, which might accelerate the erosion rate with feeble recharge potential [43] [44]. The slope map of the study area prepared from the DEM using the ArcHydro Tool in ArcGIS. The sloping grid is identified as "the maximum rate of change in value from each cell to its neighbors" [45]. A maximum of 45% of the catchment falls under the 0 - 2.82˚ slope classification, which means that the study area has excellent potential for a high infiltration rate. Similarly, 28% of the areas having a slope of 2.83˚ - 5.85˚ causing significant runoff and considered as a good infiltration rate, and the areas having a slope of 5.86˚ - 9.88˚ cause relatively high runoff as categorized as a moderate infiltration rate. Whereas the areas having a slope of 9.89˚ - 18.3˚ and 18.4˚ - 51.4˚ are considered as a very poor infiltration rate, and the runoff is extremely high, as well as the infiltration rate is very low. **Figure 5(b)** illustrates the slope map of the study area.

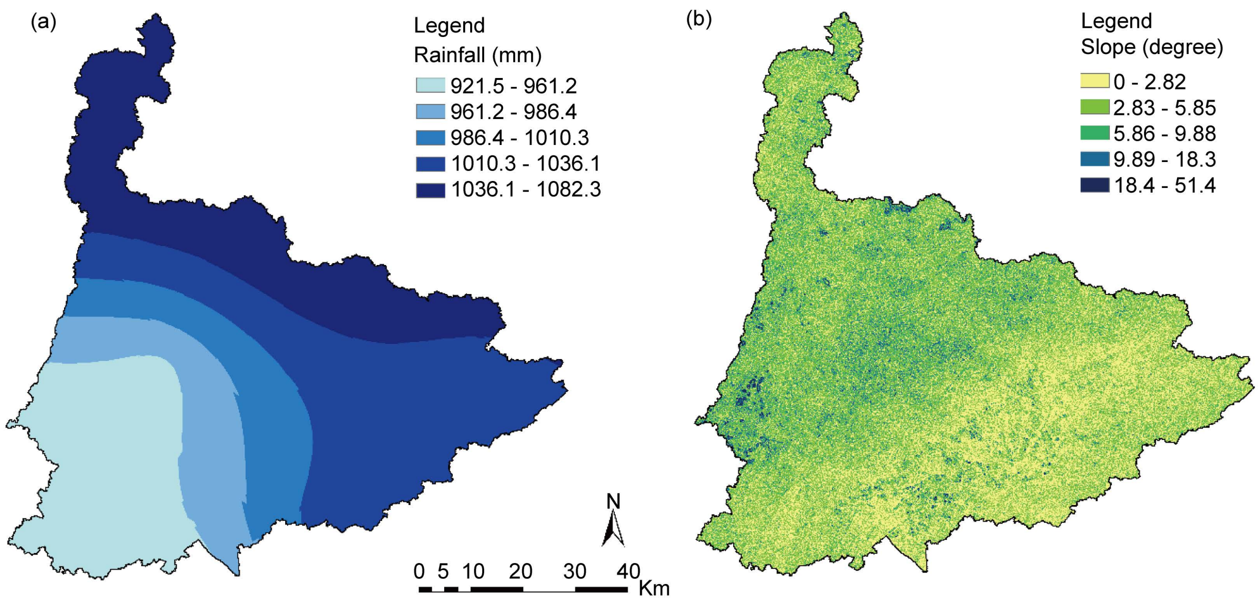

Figure 5. (a) Rainfall distribution map; (b) Slope map of the Kolleru Lake catchment.

4.7. Drainage Density

Drainage density defines the spatial closeness of the stream network [46]. It is a value of the total length of streams and rivers in a catchment divided by the total area of the catchment. The inverse proportion exists between drainage density and permeability; therefore, it is one of the main factors in the delineation of the groundwater potential zone. High drainage density causes less permeability of the soil; hence, it doesn't have much concentration of the groundwater availability [47] [48]. Similarly, a low drainage density means that the high ability of the infiltration rate increases the groundwater potential. The drainage density of the catchment was calculated based on the stream network, which depicted in **Figure 6(a)**. It was reclassified into five categories, and these classes were assigned into "Very poor" (0 - 0.215 km/km^2), "Poor" (0.215 - 0.376 km/km^2), "Moderate" (0.376 - 0.538 km/km^2), "Good" (0.538 - 0.735 km/km^2), and "Very good" (0.735 - 1.143 km/km^2). For the estimation of potential groundwater zone, the high weight assigned for the low density and low weight for the high density because of its relation with surface runoff and permeability.

4.8. NDVI

Normalized Difference Vegetation Index (NDVI) was extracted from the Landsat-8 satellite image for the rough estimation of crop patterns in the catchment. Crop estimation indicates that available moisture condition in the soil, further reveals the permeability condition. **Figure 6(b)** illustrates the NDVI classification of the Kolleru Lake catchment. NDVI values range from −0.13 to 0.2, while vegetation represents positive values, and for water bodies, NDVI indicates negative values.

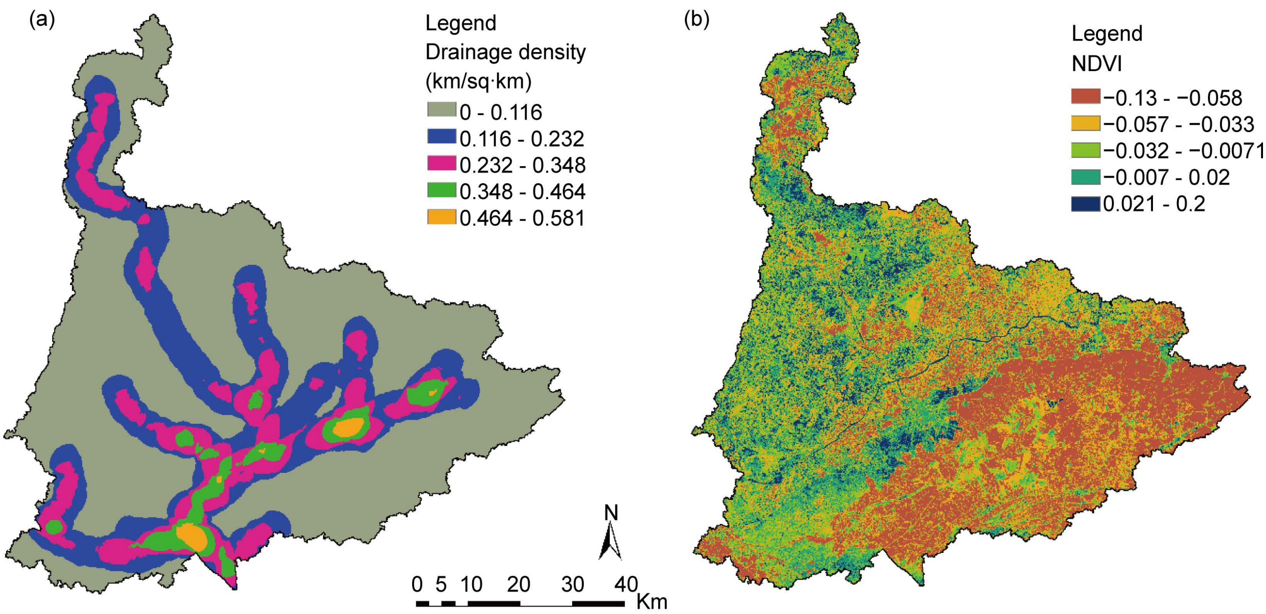

Figure 6. (a) Drainage density; (b) NDVI of the Kolleru Lake catchment.

4.9. Delineating of Groundwater Potential Zone

The potential groundwater zones for the catchment area were delineated by using weighted overlay analysis of various thematic maps, *i.e.*, drainage density, slope, rainfall, soil data, lineament density, land-use, geomorphology, and NDVI using remote sensing and GIS methods. The method of using user-defined ranks based on theoretical concepts of infiltration, runoff, permeability, and available moisture conditions. According to the overlay analysis, potential groundwater zones of this catchment area were classified into five zones, namely very poor, poor, moderate, good, and very good (**Figure 7**). The areas with low potential sources are mainly concentrated in the middle and north-western of the catchment. Due to their higher elevation slopes, these areas don't have water-holding capacities. However, the moderate zones are mainly concentrated in the upstream areas and partly focused on the western part of the catchment due to the agricultural land with high infiltration ability, indicates that soil textural properties and slope are important factors for the groundwater augmentation. Furthermore, excellent potential groundwater sources are located in the downstream area of the catchment, because of the Kolleru wetland ecosystem, the average water depth of 1 m and a maximum water depth of 3 m can be monitored during the southwest monsoon period [49]. Moreover, drainage density and lineament density help the permeability of the accumulated water to the ground. About 13% of the area falls under the poor condition, 38% of the area falls under the moderate condition, 42% of the area under good condition, and about 7% of the area is under excellent condition. The multiple influenced factors of groundwater in weighted overlay analysis based on the GIS model revealed the potential groundwater zones of the Kolleru Lake catchment.

Further, the results were validated with the borehole data obtained from the Government of Andhra Pradesh-Groundwater Department. **Figure 8(a)** illustrates

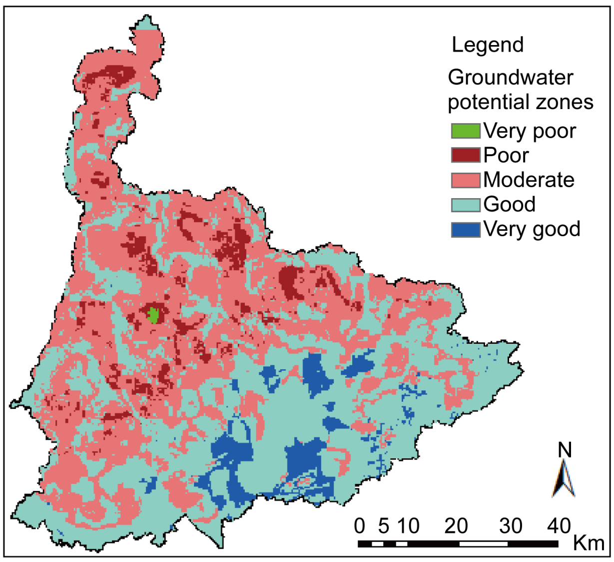

Figure 7. Groundwater potential zones of the study area.

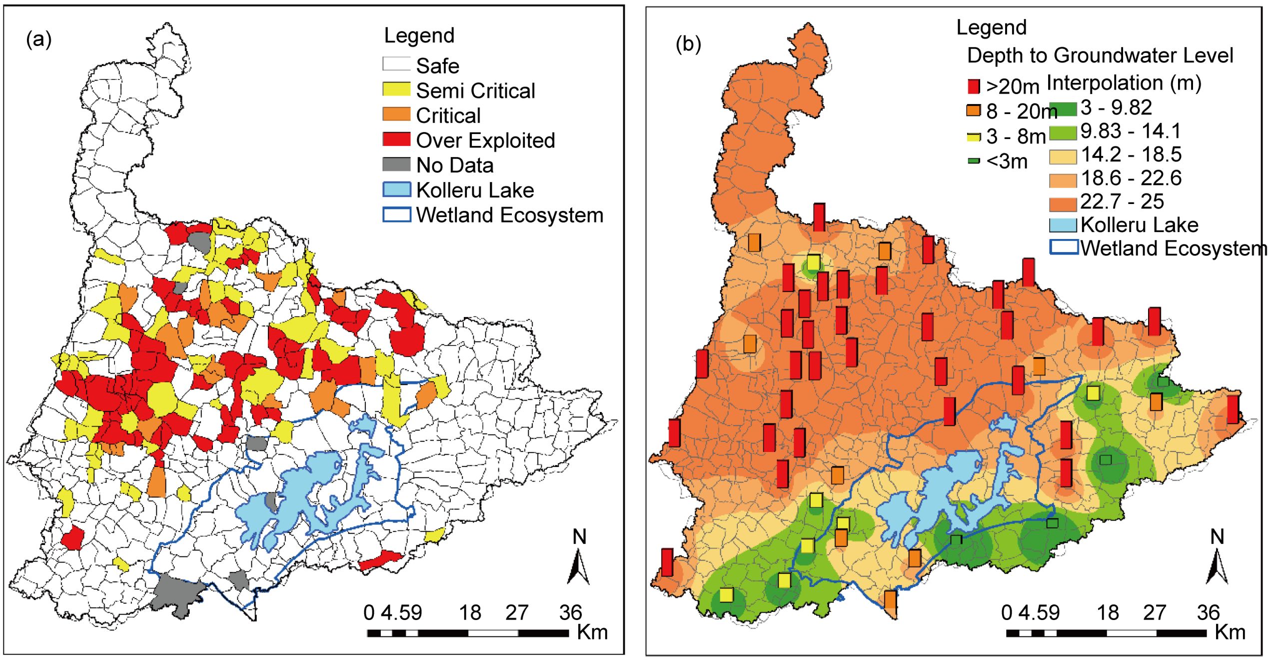

Figure 8. (a) Spatial distribution of village groundwater assessment; (b) depth to groundwater level.

the spatial distribution of village-level groundwater assessment, which was classified into four categories; safe, semi-critical, critical, and overexploited regions. 17.5% of the communities are under the overexploited category and mainly concentrated in the middle-catchment region, because of the high population density as well as the agricultural dominated area there. 9.8% of the communities are under the critical zones, while 15.4% of the regions belonging to the semi-critical zones. The last is concentrated in the middle part of the catchment. However, irrigation canals don't run through these village communities. They are highly dependent on rainfall and groundwater availability. According to Figure 8(b), more communities are falling into the depth of 20 m below the groundwater level. However, the groundwater management level should focus on the middle part of the catchment. These results attributed to the assessment, visualization, and understanding of the existing groundwater levels in the Kolleru Lake catchment.

5. Conclusions

This study successfully delineated the potential groundwater resources in the Kolleru Lake catchment by using remote sensing, GIS, and weighted overlay techniques to enable quick decision-making for sustainable groundwater management. For this, satellite images, topographic maps, and conventional data sets were used to prepare thematic layers of land-use, soil map, drainage density, slope, rainfall, lineament density, geomorphology, and NDVI. The various thematic layers were assigned a proportional weight through weighted overlay analyses that were integrated into the GIS environment to delineate the potential groundwater map of this study area. According to the results, the potential zone map of Kolleru Lake catchment can be divided into five categories, namely, "very poor", "poor", "moderate", "good", and "very good" zones. These results attributed to the future groundwater management projects and artificial recharge plans of the Kolleru Lake catchment to maintain sufficient groundwater levels.

The results were validated with the borehole data of Kolleru Lake catchment which showed that most of the areas located in the middle part of the catchment, are under overexploited zones, need immediate integral water management plans. This study established the interrelationship between geology, lithology, and remote sensing data to explore the potential groundwater levels in the Kolleru Lake catchment. The maps obtained by this can be useful for the water policymakers, as a general understanding of the groundwater deficient areas.

Funding

The partial financial support of the Marburg International Doctorate (MID) award by the third-party financing of DAAD, at the Philipps Universität Marburg, Germany.

Acknowledgements

The authors would like to thank the anonymous reviewers for their review and constructive comments related to this manuscript. We are indebted to the Government of India for providing us with necessary datasets and information to accomplish this work.

Conflicts of Interest

The authors reported no potential conflict of interest.

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