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Identification of potential water harvesting zones in Sumbuk watershed of Sikkim using remote sensing and GIS

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ABSTRACT

Spatial and temporal variation of rainfall, with remarkable decline in the winter rain has increased the demands for water resources in the state of Sikkim. The main aim of the study is to identify potential zones for construction of water harvesting structures in Sumbuk watershed of South Sikkim using Remote Sensing and Geographic Information System (GIS). Different thematic maps such as the slope map, land use/ land cover and soil map were integrated for mapping water harvesting potential zones. Suitable zones were classified using suitability criteria and Analytic Hierarchy Process (AHP) as a decision-making tool. The delineated zone for water harvesting structures was divided into three zones i.e., suitable, moderately suitable and least suitable zone. For check dams, an area under suitable water harvesting potential zone covered about 85.49 ha (2.3 %), moderately suitable and least suitable covered 92.13 ha (2.48 %) and 3529.46 ha (95.2 %), respectively. For contour trenches, the area under suitable water harvesting potential zone covered about 794.23 ha (21.42 %), moderately suitable and least suitable covered 1228.13 ha (33.12 %) and 1684.72 ha (45.44 %), respectively. Upon overlaying the suitability map with the stream order and contour lines; a total of 73 sites suitable for check dam and contour trenches water harvesting structures were identified.

1. Introduction

With the increasing pressure on water resources due to population and climate change, the limited availability of water in India is noticeable. Local community perception in the Himalaya indicate the perceived impact of climate change with less snow in the mountains, intense but short episodes of rainfall, increasing runoff and insufficient groundwater recharge resulting in the drying up of water sources (Chaudhary *et al.*, 2011). This brings into concerns the need for implementing suitable water harvesting structures so that the rain falling over a region is conserved at the maximum. This will help in recharging the natural springs or effectively be utilized for irrigation, domestics or aquaculture purposes.

Inflated with the high cost for construction, the site selection of water-harvesting structures needs to be precise (Rajani *et al.*, 2017). The remote sensing and GIS technology are powerful and cost effective tools that have proved its reliability in identifying the impervious surfaces and water harvesting structures (Gaikwad, 2015). The accuracy of remote sensing and GIS tools in identifying these suitable sites significantly depends on the quality (spatial, spectral and temporal resolution) and availability of the data. The Geo-informatics can be used effectively in the identification of water harvesting structures especially the check dams, percolation tanks, contour trenches with the help of drainage, rainfall, physiographic and socio-economic conditions etc. (Kumar and Vishwanadh, 2012).The key to the successful application of geospatial and multicriteria decision analysis techniques in identifying rainwater harvesting potential and suitable sites for water harvesting structures are selection of suitable thematic layers, proper

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*Corresponding author: gyurembam@gmail.com assignment of weights, suitable analysis of weights, proper use of multicriteria decision analysis techniques, and the adoption of realistic suitability criteria (Jha *et al*., 2014). Analytic Hierarchy Process is a decision method that treats planning criteria and criteria weighting in an open and explicit manner (De Steiguer *et al*., 2003) and has superior performance than the Catastrophe technique (Singh *et al*., 2018).The GIS based suitability analysis refers to the appropriateness of a given area for a particular use such that each aspect of the landscape has intrinsic characteristics that are in some degree either suitable or unsuitable for the activities being planned (Javadian *et al*., 2011).

The study was undertaken to select the suitable location for construction of check dams and contour trenches in Sumbuk watershed based on the AHP overlay analysis of the generated stream network, slope map, soil map, and land use/land cover map.

Description of Study Area:

Sikkim lies between Nepal and Bhutan and is a state of India renowned for its natural beauty, rich biological diversity bestowed by diverse eco-climatic conditions and wide altitudinal variation from 300 to 8,598 m. Mount Khangchendzonga (8,598 m), which is the third highest peak in the world, strongly influences the relief features of the state and it has a total geographical area of 7,096 km^2. Most of Sikkim experiences an average annual temperature of about 18 °C (Sikkimtourism, 2020). Although Sikkim receives 2500 mm of annual rainfall with high variation over short physical distances, the natural ground water recharge is low and most of the rainfall is lost as surface runoff (Tambe *et al.,* 2012). Rainfall is intense and well distributed from the month of May to early October (Das *et al*., 2017).The topographical features of the state consist of mostly steep slopes with 47. 08 % forest covers (Forest Survey of India, 2021). Having an average annual rainfall of 2084 mm, South Sikkim is the most drought prone district of Sikkim (Government of Sikkim, 2014; Sathyanathan *et al*., 2020).

2. Materials and Methodology

ArcGIS was used for the generation of various thematic maps. The flowchart of the methodology is presented in Figure 2.

Description of the thematic maps:

The Digital Elevation Model (DEM) used for the study has been prepared based on CartoDEM Version-2 R1 Sumbuk watershed is located in Sumbuk Tehsil in South District of Sikkim State, India and lies between 27° 05´ 48.53´´ N to 27° 10´ 19.89´´ N latitude and 88° 22´ 48.52´´ E to 88° 22´ 45.73´´ E longitude (Figure 1). The Sumbuk watershed lies towards the South-East of Namchi, which is 63 km from District headquarters. The watershed has a total area of 3707.08 ha with an elevation varies from 231 to 2216 m above mean sea level (MSL) where rainwater drains off straight from the steep slope of hilly terrain into the Rangeet river.

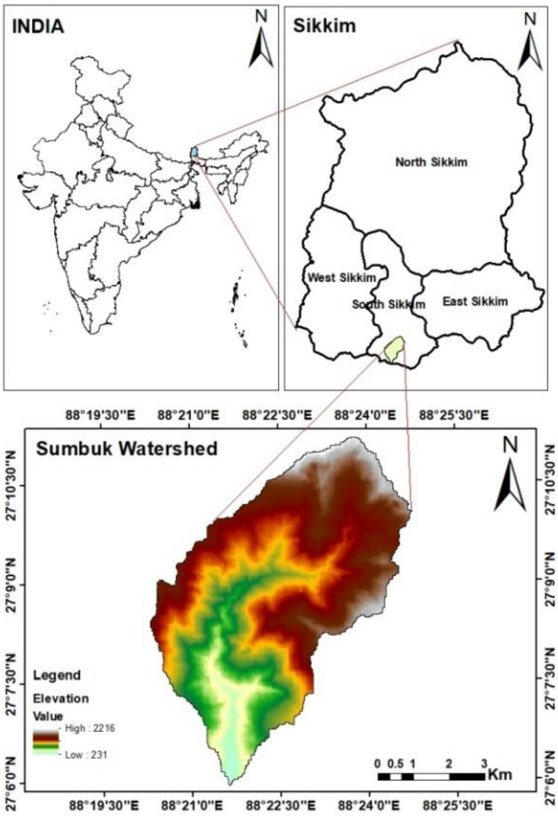

Figure 1. Index map of Sumbuk Watershed

(C1_DEM_16b_2005-2014_V2R1_88E27N_G45E) having a spatial resolution of 30 m × 30 m, downloaded from Bhuvan (http://bhuvan.nrsc.gov.in) which is a freely available **source** operated by the Indian Space Research Organisation (ISRO).

- The textural analysis and water holding capacity for South Sikkim based on the collected soil samples from 16 locations has been carried out by Kusre *et al.* (2017) where the soil map of Sumbuk watershed was obtained.
- The Land use/ Land cover (LULC) map was prepared by using latest satellite images. Freely available Sentinel-2 image obtained from Copernicus portal (https://scihub.copernicus.eu/) was used for preparation of LULC layer.
- The runoff, recharge, and movement of surface water depend on the slope of the area making it an important criterion for the site selection of water harvesting structures. For generating the slope map, the DEM was used as an input in ArcGIS environment as below:

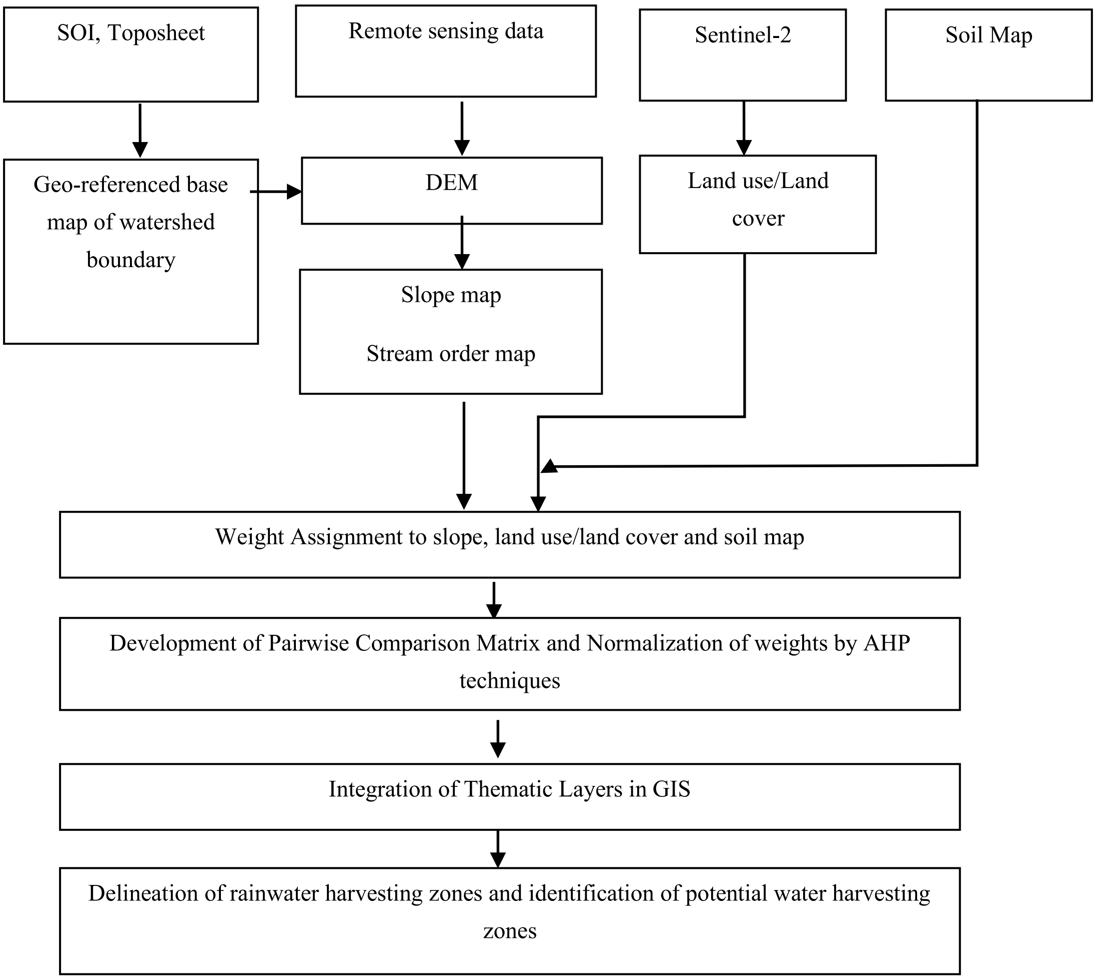

Figure 2. Flowchart for selection of water harvesting structures

Spatial Analyst Tool ⟶Surface ⟶Slope

The slope map was then reclassified into six numbers of classes using the reclassify toolbox where the slopes are classified into <5 %, 6 - 10 %, 11- 25 %, 26-30 %, 31-50 %, > 50 %.

- Flow direction, flow accumulation and a default stream definition threshold value of 36.90 ha was considered for the preparation of Stream order map using Strahler's stream order method as below.

  Spatial Analyst Tools ⟶ Hydrology ⟶ Fill⟶ Flow Direction⟶ Flow Accumulation ⟶ Stream order.

Criteria for Suitable Area Selection:

For the study, the Analytic Hierarchy Process (AHP) multi-criteria decision-making technique originally developed by Prof. Thomas L. Saaty (Saaty, 1987) was adopted. The suitability criteria for identification of potential zone were used following the guidelines as suggested by Jha *et al.* (2014) and Rejani *et al.* (2017) as shown in Table 1. The suitable water harvesting zones were demarcated by integrating thematic layers of slope map, soil map and land use map (Adham *et al.*, 2018) where determination of the percentage importance of the parameters in accordance with the guidelines was used. The criteria involved were prioritized by judging the importance of one criterion over another and each criterion was assigned suitable numerical values on the Saaty (1990) scale to express the comparative importance (Table 2). When using the AHP, pairwise comparisons are fundamentals since it is necessary to first determine the relative relevance of the primary criteria by evaluating them in pairs, which creates a pairwise comparison matrix (Satty, 1987). The resulting pairwise comparison matrix was used to obtain the Eigen-Value of each criterion, which represents the importance weight (Saaty, 1990). Weights of themes and their classes were combined by using Raster Calculator tool following a weighted linear combination technique, given as follows (Malczewski, 1999):

$$S = \sum W_i \times X_i \qquad \text{... (1)}$$

where, S = Suitability of runoff potential; W_i = Weight of theme i; and X_i = Score of class i.

In addition, the consistency of the assigned weights was evaluated by computing consistency ratio (CR) as given below:

$$CR = \frac{\lambda_{max} - n/(n-1)}{RI} \quad \ldots (2)$$

Where, λ_{max} = maximum Eigen value of the matrix; n = number of themes/factors compared, and RI = random consistency index (a value that depends on the number of elements that are being compared). The judgement is considered acceptable if the value of CR is less than 0.1 (Saaty, 1987).

Overlay analysis:

Overlaying of three thematic layers generated over ArcGIS platform was done using the weighted overlay tool (Spatial Analyst tool⟶ overlay⟶ weighted overlay) where the three thematic layers of different scale values at different fields is overlaid i.e., the Land use/land cover, soil, and slope map were used for this purpose. An integrated suitability map was produced by combining the three thematic maps as the criterion layers using a raster calculator. The stream order map was superimposed with the integrated suitability map to find out the best suitable sites for the water harvesting structures.

3. Results and Discussion

Thematic Layers:

Five thematic maps were generated i.e., DEM, slope map, stream order map, soil map, and land use/ land cover map. The DEM of the study area was divided into equal elevation interval to have a better visualization as shown in Figure 3, having the lowest and highest elevations of 231 and 2216 m, respectively.

Slope Map

The slope map of the study area as shown in the Figure 4 was divided into 6 classes as (i) gentle (< 5 %), (ii) moderately gentle (6-10 %), (iii) steep (11-25 %), (iv) moderately steep (26-30 %), (v) very steep (31-50 %) and (vi) highly steep (>50 %). The slope map gives us the idea that structures like farm ponds and percolation tanks are not ideal in the watershed since it is usually constructed on lower sloping area of less than 3 % (Jha *et al.*, 2014). Therefore, in the Sumbuk watershed construction of check dams and contour trenches would be feasible.

Stream Order Map

Stream order map of the study area is shown in Figure 5. Numbers of 1st, 2nd and 3rd order streams were 27, 7 and 1, respectively. The length of smallest drains of 1st and 2nd orders were 91.97 m and 858.78 m, respectively and length of longest drains was found to be 2120.30 m, and 1909.2 m, respectively. The mean length of drains was found to be 294.90 m and 392.44 m for 1st and 2nd order, respectively. The total length of the 3rd order streams is 10774.27 m.

Land use/Land Cover map

Figure 6 shows the False Colour Composite (FCC) layer of Sentinel-2 image of the study area. The Land use/Land Cover in the study area has twelve classes presented in Figure 7. It can be seen that the forest occupies the main land use/land cover in the watershed followed by build up, scrub land, agro forest, bare ground, open area, roads, river, tree clad, crop land and water body , respectively. The area under different classes is as under (i) forest (2158.63 ha) (ii) built up (737.38 ha) (iii) scrub land (504.75 ha) (iv) agro forest (91 ha) (v) bare ground (56 ha) (vi) open area (46.8 ha)

Table 1. Suitability criteria for identifying potential water harvesting zones in Sumbuk watershed

Check dam	**Contour trenches**
Land slope:<15 %	**Land slope:** 20-50%
Land use: Agriculture	**Land use:** Agriculture/Open space/Dense forest
Soil: clay loam	**Soil:** excluding sandy loam
Drainage order: 2nd and 3rd orders	

Table 2. Numerical expression of comparative importance scaling

Numerical Value	Comparative importance
1	Equal importance
3	Moderate importance of one over another
5	Strong importance of one over another
7	Very strong importance of one over another
9	Extreme strong importance one over another
2, 4, 6, 8	Intermediate values between two adjacent judgements

Source: Saaty (1990)

(vii) roads (31 ha) (viii) river (30 ha) (ix) tree clad (29.6 ha) (x) crop land (21 ha) and (xi) water body (0.92 ha). While the build-up area was well dispersed toward the western side of the watershed, the forest was concentrated in the northern and eastern regions of the watershed.

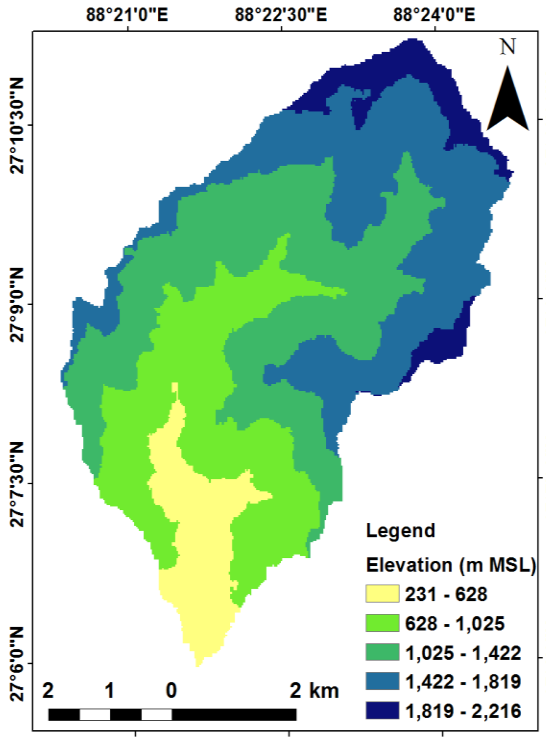

Figure 3. Digital Elevation Model of Sumbuk Watershed

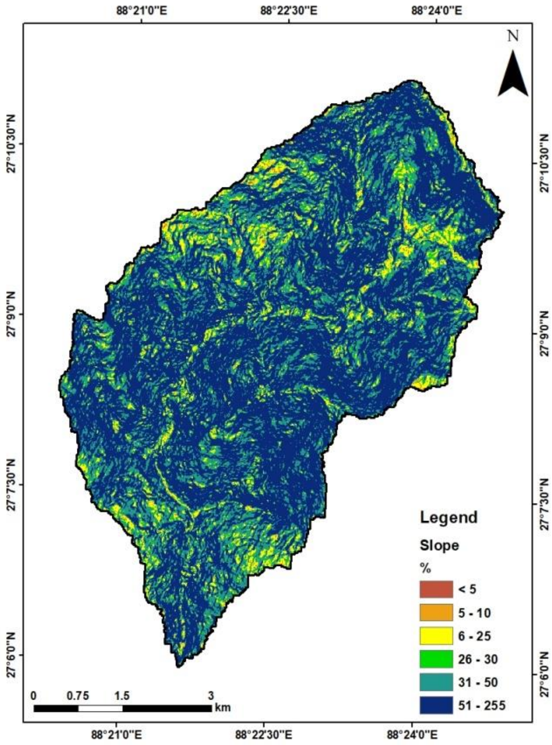

Figure 4. Slope Map of SumbukWatershed

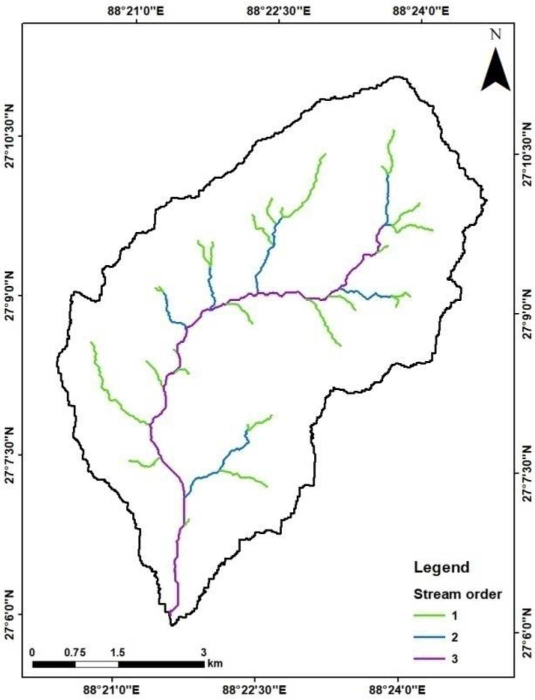

Figure 5. Stream Ordering of the Sumbuk watershed

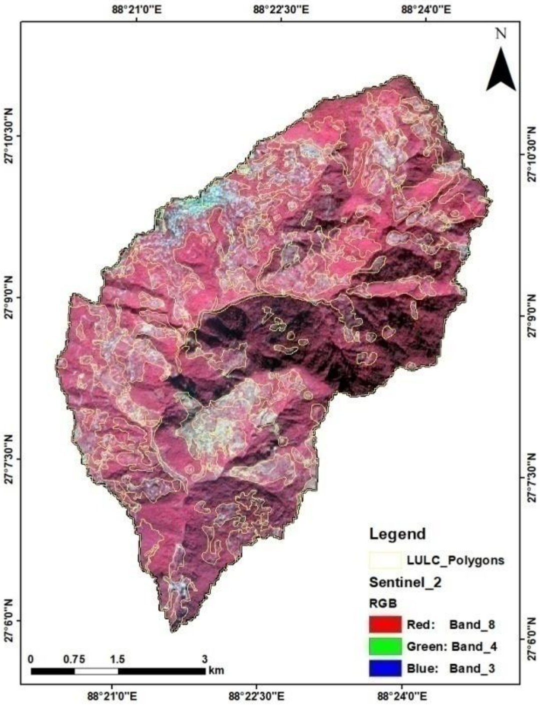

Figure 6. False Colour Composite (FCC) layer of Sentinel-2 image

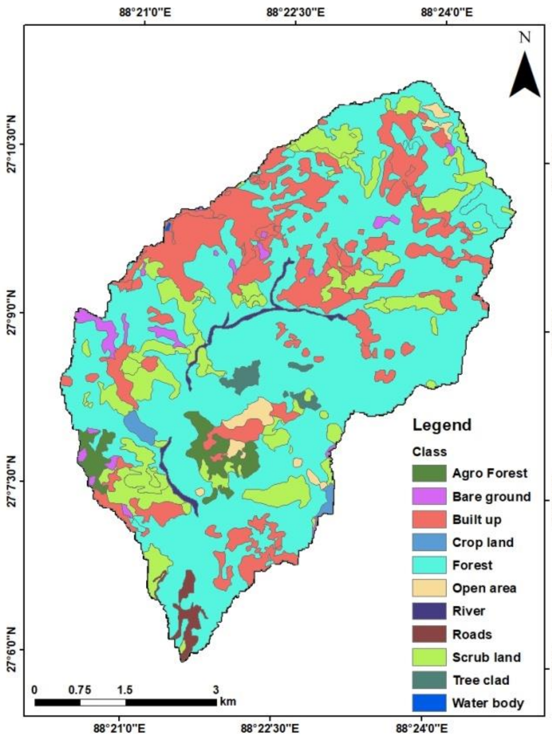

Figure 7. Land use/land cover map of the Sumbuk watershed

Soil map

The Soil map of the study area is presented in Figure 8. The soil map of the study area consisted of three soil classes namely sandy loam, clay loam and silt loam.

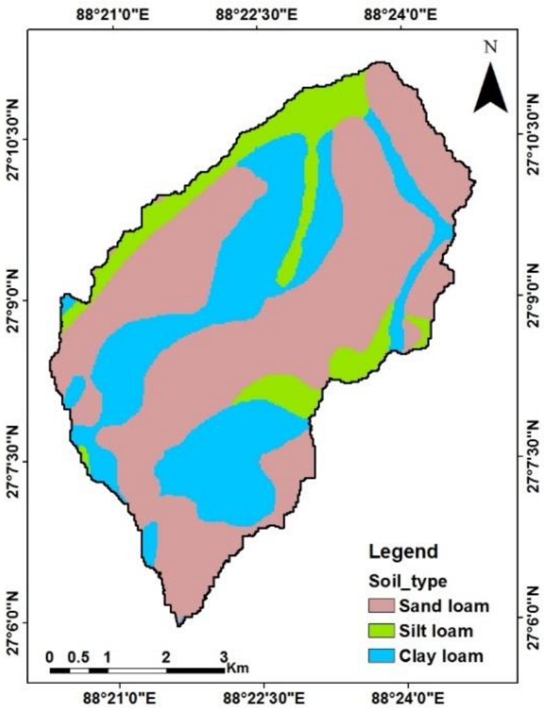

Figure 8. Soil map of the Sumbuk watershed

Water Harvesting Potential Zones:

Suitability of the area for construction of rainwater harvesting structure greatly depends on the topography, soil type and LULC of the study area. Different classes of slope, soil texture and LULC are classified based on their suitability for construction of the water harvesting structures as shown in the table below (Table 3 & Table 4).

Table 3. Normalized theme weights assigned to different thematic layers for identification off suitable zones for construction of check dam.

Sl. No.	**Characteristic**	**Theme weight**	**Class**	**Suitability**
1	Slope (%)	0.70	< 5	Low
			6 - 10	Very High
			11 - 15	High
			16-100	Low
			>100	Very Low
2.	Soil Texture	0.18	Clay loam	High
			Silt loam	Medium
			Sandy loam	Low
3.	Land use/ land cover (LULC)	0.11	Agro Forest	Very High
			Bare ground	High
			Built up	Very Low
			Crop land	Very High
			Forest	Low
			Open area	High
			River	Very Low
			Roads	Very Low
			Scrub land	Low
			Tree clad	Very Low
			Water bodies	Very Low

Table 4. Normalized theme weights assigned to different thematic layers for identification off suitable zones for construction

Sl. No.	**Characteristic**	**Theme weight**	**Class**	**Suitability**
1s	Slope (%)	0.65	< 5	Very Low
			6-10	High
			11-25	Very High
			26-30	High
			31 -50	Low
			>50	Very Low
2.	Soil Texture	0.23	Clay loam	High
			Silt loam	Medium
			Sandy loam	Low
3.	Land use/ land cover (LULC)	0.12	Agro Forest	Very High
			Bare ground	High
			Built up	Very Low
			Crop land	Very High
			Forest	Low
			Open area	High
			River	Very Low
			Roads	Very Low
			Scrub land	Low
			Tree clad	Very Low
			Water bodies	Very Low

A pair-wise comparison matrix between the thematic layers was constructed arbitrarily based on expert judgement. The layer which is having more influence on identification of the potential zones for rainwater harvesting was given higher value as compared to other layers. The pair-wise matrix was normalized by dividing each cell value in a column by the sum of the cell values in that column. The normalised pairwise matrix for identification of check dams and contour trenches are shown in the table below (Table 5 & Table 6) where the weights of each layer were calculated by taking the row-wise average of each thematic layer. These weights were utilised to derive the suitable maps for the rainwater harvesting structure in the GIS environment using the weighted overlay analysis. The consistency ratio of the AHP was found to be less than 0.1 (i.e. CR=0.052 for check dam and CR=0.004 for contour trench), thus indicating that the judgement on weight and score assignments was acceptable (Satty, 1987).

Table 5. Normalized pair-wise matrix for check dam

Check Dam	**Slope (%)**	**Soil texture**	**LULC**	**Normalized Weights**
Slope (%)	0.71	0.77	0.63	0.70
Soil texture	0.14	0.15	0.25	0.18
LULC	0.14	0.07	0.13	0.11

Table 6. Normalized pair-wise matrix for contour trenches

Contour Trenches	**Slope (%)**	**Soil texture**	**LULC**	**Normalized Weights**
Slope (%)	0.65	0.67	0.63	0.65
Soil texture	0.22	0.22	0.25	0.23
LULC	0.13	0.11	0.13	0.12

The suitability map for the check dams and contour trenches were derived by using overlay analysis in GIS environment. Weights of the corresponding layers were applied to generate the suitability maps. The final map produced by integrating all the thematic layers was classified into three zones of suitable, moderately suitable and least suitable. The suitable zones for check dams are those which satisfied the criteria i.e. slope between 6-15%, clay loam soil and LULC which falls under agro-forest, bare ground, crop land or open space. Similarly, those zone having slope between 6-30%, clay loam soil and LULC which falls under agro-forest, bare ground, crop land or open space are considered suitable for contour trenches. Least suitable zones for check dams are those which have slope >16 %, sandy loam soil and LULC consisting of forest, build up and roads. Similarly the least suitable zones for contour trenches are those which have slope >31 %, sandy loam soil and consisting mostly of forest, build up and roads.

Check dam:

The suitable area for construction of check dam is presented in Figure 9. The potential water harvesting area under Suitable zone for check dam covers about 85.49 ha (2.3 %) area. Likewise, the coverage area of moderately suitable and least suitable was found to be 92.13 ha (2.48 %) and 3529.46 ha (95.2 %), respectively.

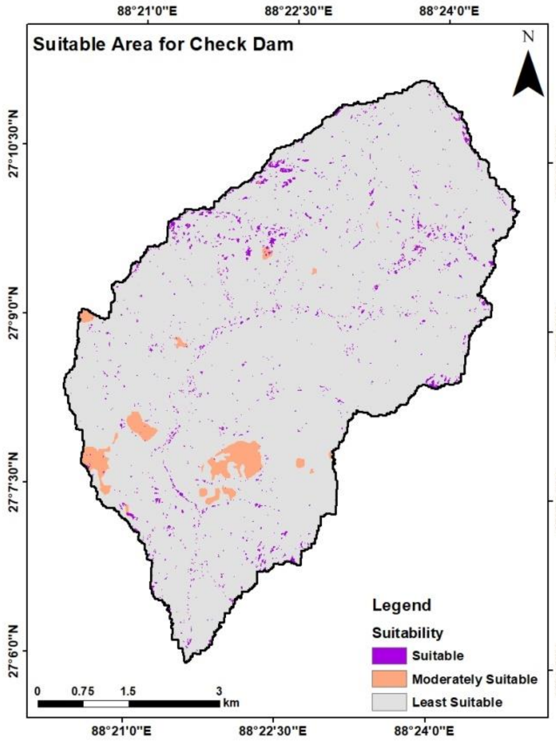

Figure 9. Potential water harvesting zone map for check dams

Contour trenches:

The suitability area for construction of contour trench is presented in Figure 10. The potential water harvesting area under Suitable zone for contour trench covers about 794.23 ha (21.42 %) area. Likewise, the coverage area of moderately suitable and least suitable was found to be 1228.13 ha (33.12 %) and 1684.72 ha (45.44 %), respectively.

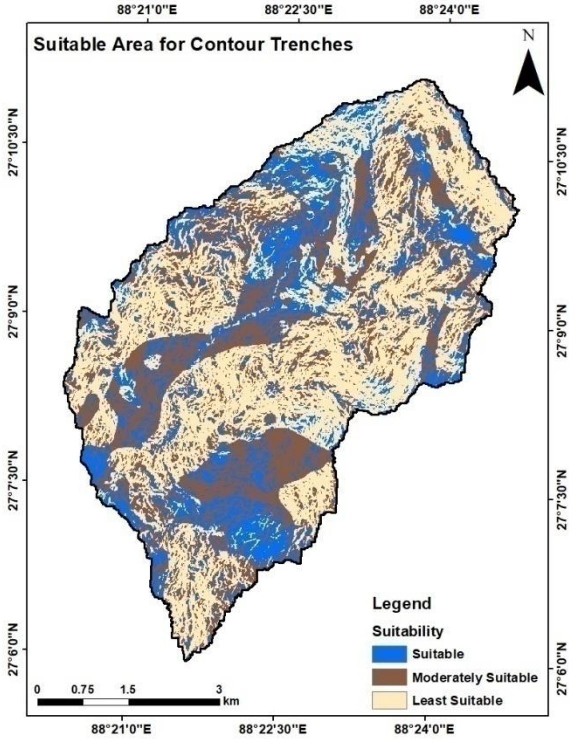

Figure 10. Potential water harvesting zone map for contour trench

Best Suitable Sites Selected for Water Harvesting Structures:

The best suitable sites were selected for check dam and contour trenching by overlaying the AHP results with the stream order and contour lines. Stream having order of 2nd and 3rd order are considered to be suitable for construction of check dams. Therefore, the locations falling in these stream orders were identified. Similarly, the locations of contour trenches were identified by overlaying the AHP results with the contour lines. Figure 11 shows the best suitable sites selected for developing these structures within the natural watershed boundary of the watershed. A total of 73 numbers of suitable sites for construction of water harvesting structures (i.e., 45 numbers for check dams and 28 numbers for contour trenches) were identified in the Sumbuk watershed. The upstream end of the watershed was discovered to have a higher distribution of suitable sites for the construction of check dams and contour trenches.

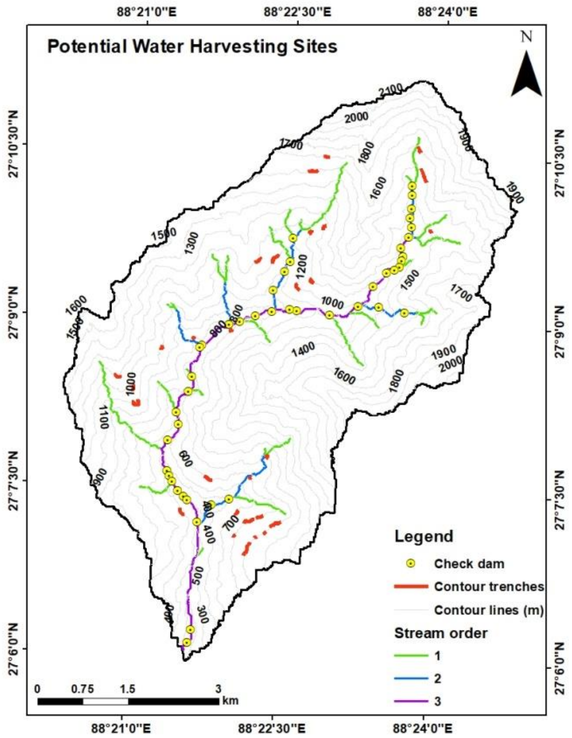

Figure 11. Best suitable sites selected for check dam and contour trenches

4. Conclusions:

With the increasing pressure on water resources, the importance of water harvesting is noticeable. The main objective of this study was to identify the most suitable sites for the construction of water harvesting structures in Sumbuk watershed of South Sikkim using remote sensing and GIS. The Land use/ Land cover map was prepared from Sentinel-2 image. The three thematic layers of slope, soil and land use/ land cover map were integrated to identify the potential zones of rain water harvesting using AHP multi-criteria decision analysis approaches in ArcGIS. The delineated zones were classified into three suitability classes of suitable, moderately suitable and least suitable in the watershed boundary. In terms of the water harvesting potential zone for the check dam, areas of 85.49 ha (2.3 %), 92.13 ha (2.48 %), and 3529.46 ha (95.2 %) were found to be suitable, moderately suitable, and least suitable, respectively. Likewise, suitable, moderately suitable and least suitable water harvesting potential zone for contour trenches covers an area of about 794.23 ha (21.42 %), 1228.13 ha (33.12 %) and 1684.72 ha (45.44 %), respectively. Correspondingly, a total of 73 sites suitable for water harvesting structures were identified within the boundary of Sumbuk watershed.

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