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Geospatial and Analytical Hierarchical Process approach for potential sites of water harvesting in lower Kulsi basin, India

Gitika Thakuriah[1]

[1]Cotton University, Guwahati, India
✉ *gitika.thakuria@cottonuniversity.ac.in*

Abstract

Water crisis issues are common in rural and urban areas, which can be tackled honestly by planning and managing existing water resources. The site suitability map is the principal footstep of planning practice for a region's sustainable surface and groundwater resource development. The paper aims to delineate and suggest suitable sites for water harvesting for sustainable water resource development by taking the lower Kulsi watershed as a study area. Analytical Hierarchical Process (AHP) and Geographical Information System (GIS) techniques are used in the multi-criteria decision-making process to identify a suitability map of water harvesting structures like percolation tanks, check dams, and surface farm ponds on the basin of the specific key factor of each design. About one hundred ninety-six sites are detected from the most suitable category of suitability based on particular criteria and suggestions for sustainable water conservation in the study area.

Highlights for public administration, management and planning:

- GIS-based AHP model is a simple and widely applicable multi-criteria decision-making model for delineating a water harvesting site.
- Water conservation by harvesting rain and river water can mitigate floods in humid tropical regions and drinking water scarcity in the arid and semi-arid regions.

Keywords

Analytical Hierarchical Process (AHP),
Weighted overlay,
Geographical Information System (GIS),
Soil Conservation Service Curve Number (SCS-CN),
Water conservation

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1 Introduction

Water is one of the prime essentials for day-to-day life. As freshwater availability becomes scarce due to ever-increasing population pressure in developing nations, water resource conservation and management have grown immensely for environmental sustainability. Rainwater harvesting is a simple and popular method of obtaining water worldwide for agricultural and drinking purposes. Suitable rainwater harvesting sites better utilize water resources and alter or minimize the excellent use, enabling groundwater levels to be further sustained. RS and GIS provide information on natural resources (Durbude & Venkatesh 2004). A bundle of research work has been done on the identification and delineation of a suitable site for potential water harvesting using geospatial techniques in different climatic conditions, such as the Western Desert of Iraq Adham et al. (2018), Sau-Fransisco, and Nile catchment (Weerasinghe et al. 2011); Sina catchment of Ahmednagar, (Badhe et al. 2020); Sedam taluk, Gulbarga district, Karnataka (Dasog et al. 2011; Gowda 2011); Soankhar watershed of Punjab (Singh et al. 2009); Karson watershed of Hazaribagh (Pandey et al. 2011); Chinnar watershed of Tamilnadu (Lohar et al. 2018); Small watershed of Lormi block of Chattisgarh, (Kumar et al. 2017); Sivganga watershed of Western Ghat (Kadam et al. 2017); Sasti watershed of Maharastra (Rokade et al. 2004, 2011) in India. Different methods and tools have been applied to identify suitable sites for water harvesting structures in the past literature, such as hydrological modelling with GIS and remote sensing (Mahmoud & Alazba 2014); multi-criteria analysis integrated with GIS (Sayl et al. 2017; Ammar et al. 2016); the multi-

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criteria analysis combined with hydrological modelling and GIS/remote sensing (Krois & Schulte 2014). Multi-criterion analysis using an analytical hierarchical process (AHP) integrated with GIS has successfully delineated water harvesting sites, especially in the limited data region (Ammar et al. 2016). The AHP method is flexible, allowing the revision of the weights and rating of the factors to be suitable for other regions according to their specific characteristics (Oikonomidis et al. 2015). It is a method for organizing and analyzing complex decision-making, comparing the importance of two criteria at a time through pair-wise comparison, which Thomas L. Saaty introduced in 1980. It is a suitable technique for evaluating the consistency of the result and reducing discrimination in the decision-making process (Saaty 2008).

People of the lower Kulsi watershed primarily depend on groundwater resources for domestic and agricultural purposes. The suitability map for water conservation structure is essential for regulating groundwater recharge and the region's sustainable land and water resource level. Therefore, the study aims to focus on the combination of AHP and GIS technologies for the identification of potential sites of water harvesting in the lower Kulsi basin by the integration of influencing input parameters such as geomorphology, soil texture, soil depth, geology & lineament density, slope, drainage density, stream order, land use/land cover, road density, and distribution of rainfall. Water harvesting structures like farm ponds in the watershed, percolation tanks, bolder check dams, and stop dams across the stream are considered for water resource management. The suitability map can help the decision-makers, local government, and localities utilize alternate water resources by harvesting rainwater for sustainable development.

2 Materials and methods

2.1 Geographical background

The Kulsi is a left-bank tributary of the Brahmaputra River. On the northern front of the Shillong Plateau, a northward-flowing river drains Assam's plain region into the Brahmaputra River. The stream flow from the southern Meghalaya Plateau as the Khri River flows towards the west, then the north direction forms a narrow valley and descends to the Kulsi River. It developed a dendritic pattern of drainage system in the upper catchment area. Umkrisinya, Um Siri, and Um Ngi, Boko, Singra, Singua, Deosila are left bank tributary of Kulsi River. Batha and Umshru are the only tributaries on the right bank. The 1956 km^2 area drains over Kamrup rural and Goalpara district part of Assam (India) and is taken as the study area, namely the lower Kulsi river basin for water resource development. Geographically its latitude and longitudinal extension are 25˚31′ 58.8′′ N to 26˚75′ 3.33′′ N and 91˚E to 91˚48′ 30′′ E, as shown in Fig 1. The upstream of the study area is composed of moderate to highly dissected structural hills and valleys, which depict the surface runoff of the rugged hilltop and are affected by soil erosion. Low to moderately dissected denudation hills are isolated hills in the pediment complex. The low-lying area is an alluvial plain. The geomorphic subunits of the plain are young alluvial plain, old alluvial plain, active flood plain, and old flood plain. The pediment complex is another crucial geomorphic basin unit with a moderate slope sustaining natural vegetation and grassland. The debris slopes are moderate to severely eroded with the high acceleration of finer alluvial soil.

The upper catchment of the Kulsi basin is composed of fine texture, and the parent material is Gneiss. The downstream section of the river is mainly covered by alluvium. The upper catchment area belongs to the age of the Proterozoic structure, and the downstream belongs to the age of Meghalaya and is formed during the Barpeta-I, Sorbhog, and Hauli formations. White to greyish sand, silt, pebble, and clay formed during the Barpeta-I formation and oxidized to feebly oxidized sand silt and clay formed during the Sarbhog formation, and feebly oxidized sand, silt, and clay formed during the Hauli formation.

It is in a humid sub-tropical monsoon climatic zone with highly seasonal rainfall characterized by wet summer and dry winter. Ten years' average annual rainfall was recorded in Boko station as 1956.67 mm. About 306.52 mm of average monthly rainfall occurs in summer (May to September). Average monthly rainfall was 4.43 mm for winter (December to February) and 102.68 mm for transitional months (October–November and March–April). More than 78% of rain occurs only in summer, causing surface runoff in summer and dry winter. On the other hand, people of the lower Kulsi basin depend more on groundwater resources in dry winter for domestic and agricultural purposes. Therefore, the area needs an artificial recharge structure to reduce surface runoff, regulate groundwater recharge, and increase crop productivity for sustainable land and water resource management.

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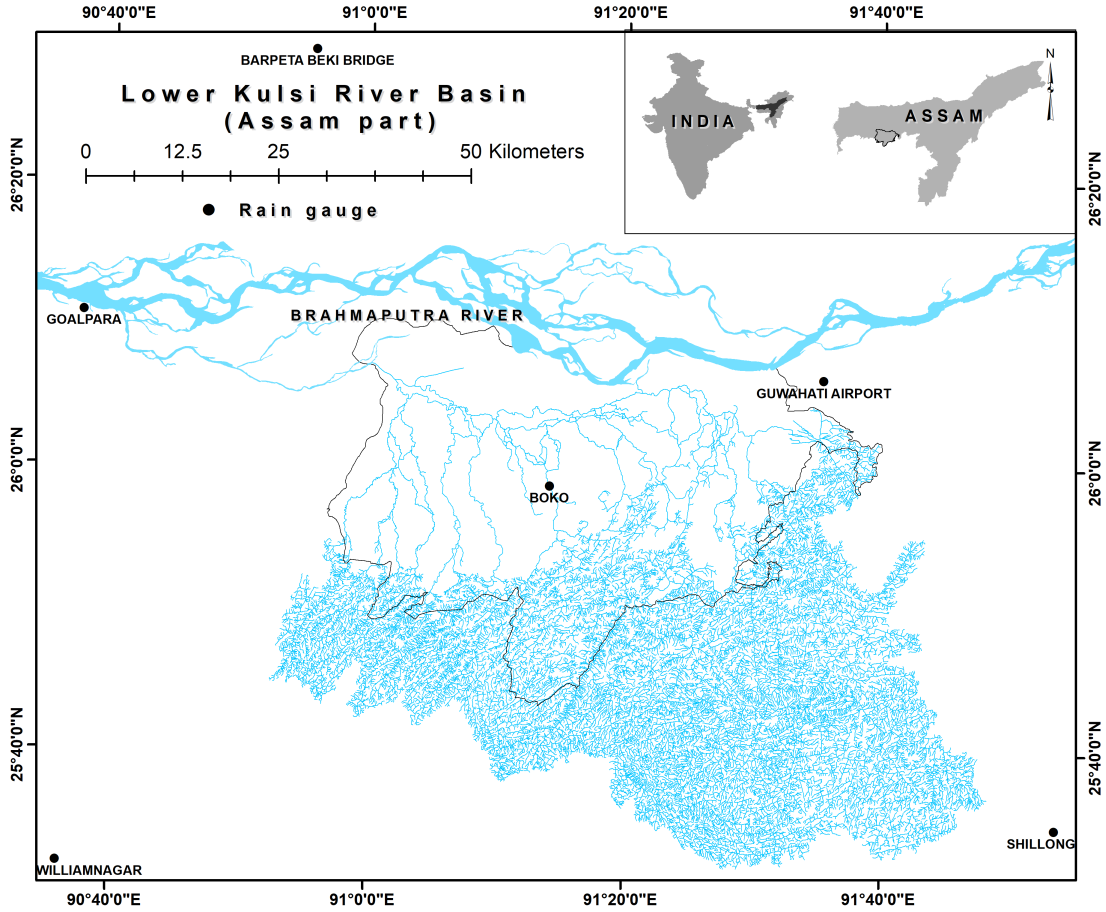


Fig. 1 Location map of the lower Kulsi River basin (Assam part) (Thakuriah 2023)

2.2 Database

Data from primary and secondary sources have been used to fulfil the study's objectives. The details of the most authenticated governmental data are listed below.

1. The watershed of Kulsi has been prepared from the survey of India's topographical sheets at a 1: 50,000 scale. (Sheet no. 78 N/4, 78 N/8, 78 O/1, 78 O/2, 78 O/5, 78 O/6, 78 O/9, 78 O/10, and 78 O/14)
2. The geomorphic and geological data were collected from the Geological Survey of India (www.gsi.gov.in) at a 1:50000 scale.
3. The soil map and its attribute information were collected from the National Bureau of Soil Survey and Land-use Planning 1999 (NBSS & LUP, www.nbsp.in) at a 1:250.000 scale.
4. The rainfall data were collected from Regional Meteorological Centre, Guwahati, India (RMC), Guwahati, and Regional Sericulture Research Institute (RSRS), Boko, for 2009–2018.
5. The land use and land cover (LULC) of the study area is delineated from the satellite data (IRS LISS IV, DOP 26/01/2018) of the National Remote Sensing Center, Hyderabad (India).

3 Methods

3.1 Data preparation

Base map preparation: The watershed boundary is delineated after carefully digitizing the stream network in Arc GIS 10.6 software from topographic sheets covings 4135 km^2 area. Topographical sheets are registered in the WGS_1984_UTM_Zone_46N projection system before digitizing linear features like streams network and contour lines.

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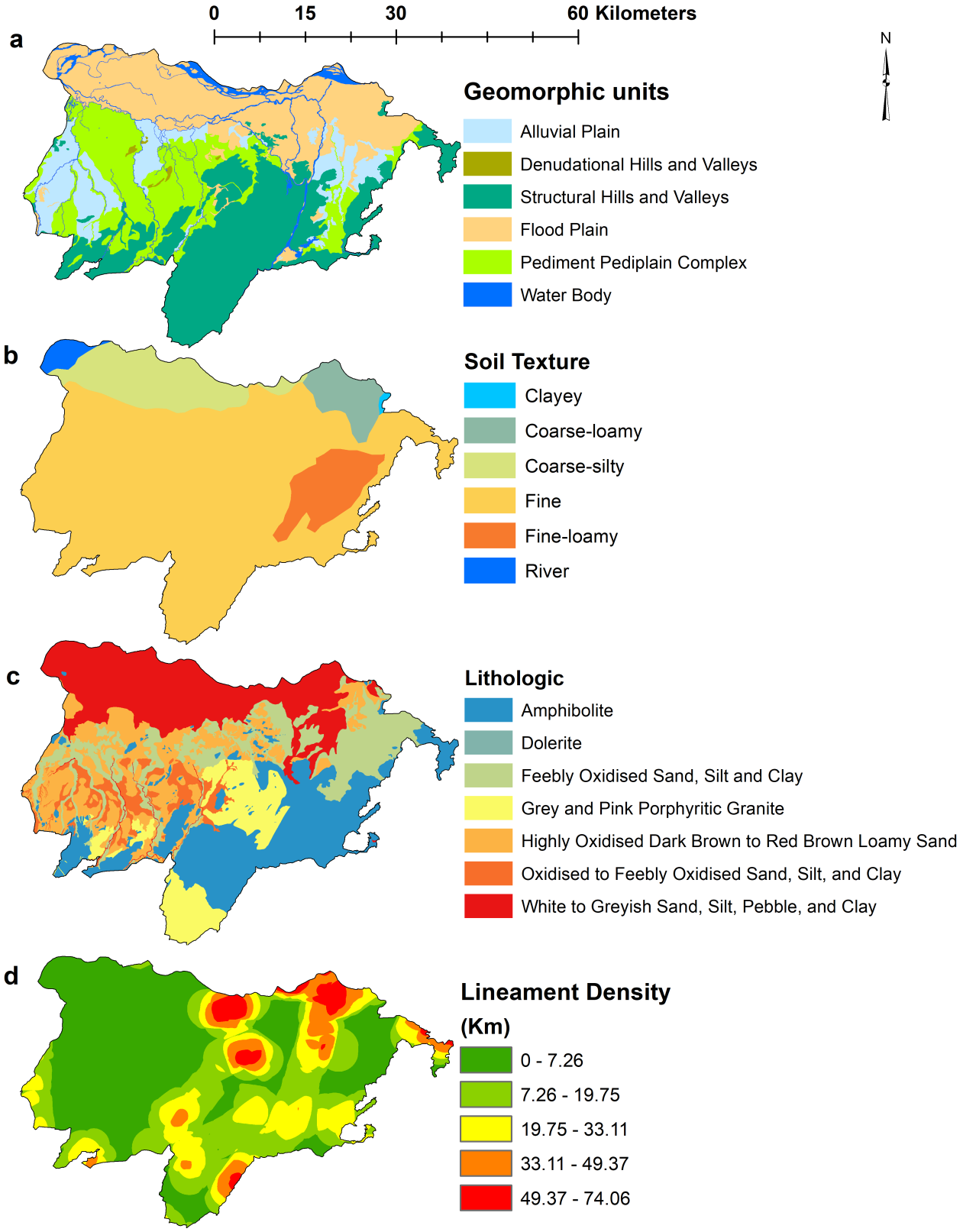


Fig. 2 a Spatial extent of the geomorphic unit (GSI), 2b Soil texture classification (NBSS&LUP), 2c Geological structure, and 2d lineament density map

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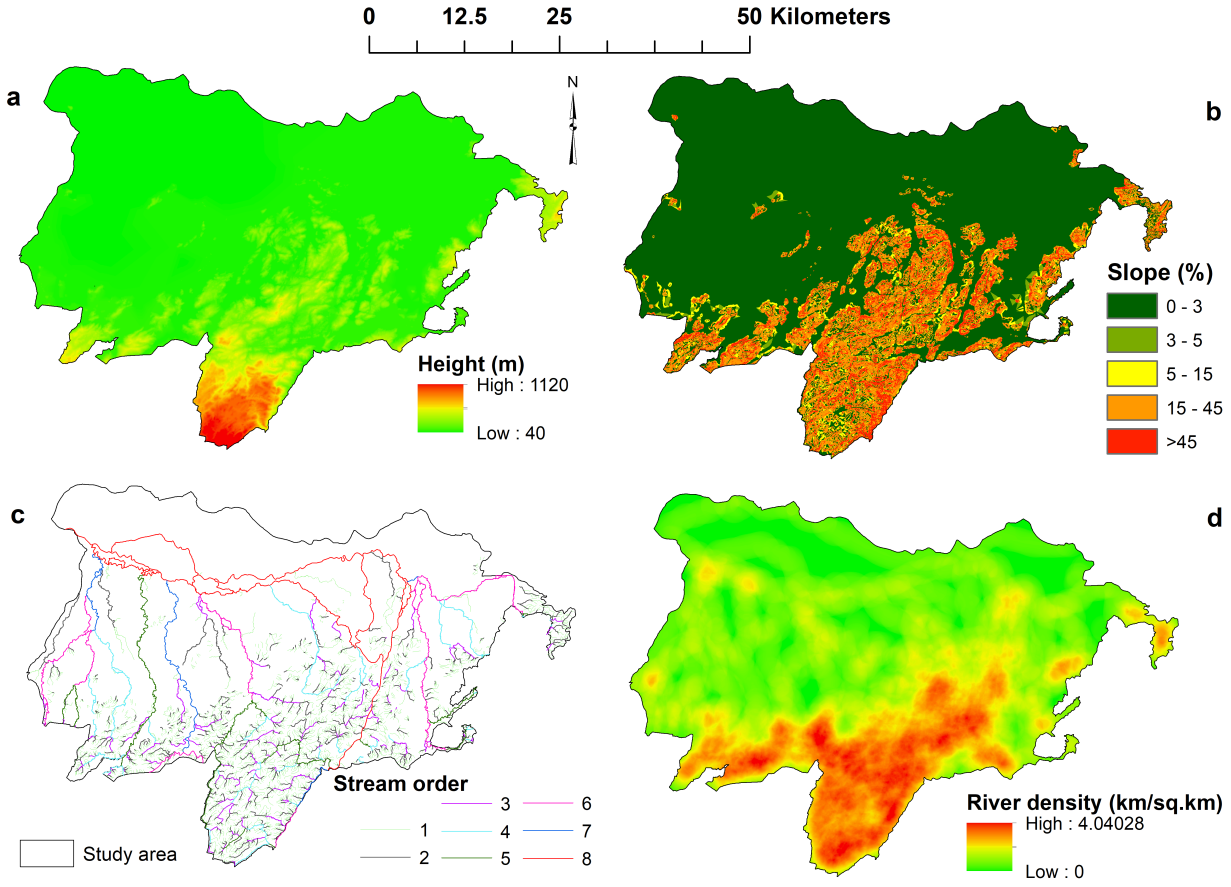


Fig. 3 a Digital elevation model prepared from SOI, contour, 3b slope map prepared from DEM, 3c Strahler's stream ordering map, 3d drainage density map of the study area

The downstream of the basin in the Assam part is extracted as a study area, namely the lower Kulsi River basin covering a 1956 km^2 area.

Geomorphology and Geology: Geomorphology represents an area's landform and topographic setting and plays the most crucial role in water resource management plans. Geologic conditions control the distribution of structural belts, which influence groundwater movement. The geomorphic features control the surface and sub-surface movement of water. It helps to evaluate the groundwater potential and prospects (Kumar et al. 2008). Therefore, the geomorphic features and geology of the basin collected from the Geological Survey of India are extracted using ArcGIS software. The geological lineament features data was used to prepare a lineament density map using the line density arc tools in GIS software.

Soil is the most critical input for selecting a suitable site for a water-harvesting structure. The soil plays a significant role in the amount of water infiltrated into the subsurface and contributes to groundwater recharge (Ibrahim-Bathis & A 2016; Das 2017). The soil map and its attribute information are extracted from the soil map prepared by NBSS & LUP.

Slope: The slope measures the steepness or inclination relative to the horizontal plane. It gives necessary information on the nature of the structure and geodynamic processes at the regional level (Riley 1999). The digital elevation model (DEM) is the primary input for the generation of topographic information. It was prepared from contours of the Survey of India toposheets with 20-meter contour intervals to generate a slope map of the basin using spatial analysis tools of Arc GIS 10.6 software.

Drainage: The order of the stream plays a significant role in the proper site delineation of water harvesting structures. The drainage network map was prepared from topographical sheets registered in the WGS_1984_UTM_Zone_46N projection system before digitizing the linear features of streams. Further ordering the stream network of the basin using Strahler's method Fig 3c. The study area's stream order map was extracted from the order

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of the complete basin using the arc tool of GIS software. The drainage density is obtained by dividing the total length of the channel in the basin by the basin's total area. The drainage density map was prepared using line density arc tools of GIS software and shown in Fig 3d.

Land use/land cover (LULC): The variation of LULC of a watershed gives essential information on the variation of infiltration, runoff, surface & groundwater, and soil moisture. The LULC is the most influencing factor in the soil and water management plan. The LULC types of the study area are delineated from the high spatial resolution satellite data based on visual interpretation techniques in the GIS environment. The whole approach for preparing the LULC map of the study area involved visual observation and digitization, preliminary interpretation using SOI topographical map and Google Earth satellite map provided by Landsat/Copernicus 2021, and final interpretation after rigorous field check. The correctness of the LULC information derived from satellite images was assessed using the Kappa coefficient. The Kappa coefficient was 0.828, indicating almost perfect strength of agreement between classified and ground truth data.

Rainfall: Rainfall is the primary input of the hydrological cycle and the most dominating factor in the water resources management study. The rainfall distribution map was prepared using Interpolate Distance Weight (IDW) method in GIS software. IDW is the preferable method for measuring a river basin's smooth rainfall distribution in terms of mean error (Bakis et al. 2021). Seven stations were used to estimate the rainfall distribution map more accurately. Out of which, two stations were located inside the basin, Boko and Guwahati Airport. Tikirikila, Williumnagar, and Shillong rain gauge stations are located in Meghalaya Plateau towards the southern boundary of the basin. Goalpara and Beki River Barpeta rain gauge stations are located in the study area's West and North West boundary Fig 1. The rainfall has been classified using reclassify tools in the GIS software for preparing to run a multi-criteria decision analysis model.

Runoff Depth: The runoff depth is critical for the water resources management plan. The SCS-CN method is applied to estimate the runoff depth of the study area. It is the most popular method for estimating runoff in a watershed for soil and water conservation. This method is suitable for running hydrological modelling using remote sensing data in GIS techniques (Senay & Verdin 2004). The runoff depth for ten years' average rainfall (2009–2018) was estimated at 1336 mm to 2257 mm Fig 4d. Further, it has been classified in the GIS platform to run a multi-criteria decision-making model. The runoff depth for the study area was estimated by equation 1 (Soil Conservation Service 1972) using the map algebra tool in GIS.

$$Q = \frac{(P - Ia)^2}{(P - Ia) + S} \tag{1}$$

Where Q is runoff depth (mm) P is rainfall in mm Ia is an initial abstraction (mm),

$$Ia = 0.2S \tag{2}$$

Where S is the potential maximum retention after runoff start (mm). S can be calculated from CN using equation 3.

$$S = \frac{25400}{CN - 254} \tag{3}$$

CN is the curve number, which is a dimensionless number ranging from 0–100, determined from Supplement 1 based on LULC and hydrological soil group according to antecedent moisture condition (AMC II) (United States Department of Agriculture 1986). A hydrological soil group comprises soils with similar runoff potential under similar storm and cover conditions (Natural Resources Conservation Service Soil Survey Staff)).

Antecedent moisture condition (AMC) indicates watershed wetness and availability of soil storage before a storm event. Three levels of AMC are used based on the availability of rainfall in the study area, AMC I for dry (December to March), AMC II (April & October–November) for normal, and AMC III (May to September) for wet conditions. The CN for AMC I and AMC III is measured by equations 4 and 5 (Soil Conservation Service 1972).

$$CN_1 = CN_2 - \frac{100 - CN_2}{100 - CN_2 + exp\,[2.533 - 0.0636(100 - CN_2)]} \tag{4}$$

$$CN_3 = CN_2 \cdot exp\,[0.00673 \cdot (100 - CN_2)] \tag{5}$$

The mathematical formula for slope adjustment CN is given by Sharpley and Williams (1976) to the CN value of >5% slope. CN2s slope adjusted CN values for AMC II using equation 6.

$$CN_{2s} = \frac{1}{3}[CN_3 - CN_2] \cdot [1 - 2exp^{(-13.86.slope)}] + CN_2 \tag{6}$$

Now to avail the slope-adjusted curve number for AMCI (dry condition), *CN1s*, and AMC III (wet condition), *CN3s* equation 7 and 8 (Chow et al. 1988) was used as follows:

$$CN_{Is} = \frac{4.2CN_{2s}}{(10 - 0.058CN_{2s})} \tag{7}$$

$$CN_{3s} = \frac{23CN_{2s}}{10 + 0.13CN_{2s}} \tag{8}$$

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Table 1 Pair-wise comparison matrix of thematic layers for suitability of farm pond

	Theme	Assign Weight	Geomorphology	Soil	Geology	Slope	River density	LULC	Rainfall	Runoff depth
1	Geomorphology	8	8/8	8/7	8/3	8/7	8/4	8/7	8/5	8/6
2	Soil	7	7/8	7/7	7/3	7/7	7/4	7/7	7/5	7/6
3	Geology	3	3/8	3/7	3/3	3/7	3/4	3/7	3/5	3/6
4	Slope	7	7/8	7/7	7/3	7/7	7/4	7/7	7/5	7/6
5	River density	4	4/8	4/7	4/3	4/7	4/4	4/7	4/5	4/6
6	LULC	7	7/8	7/7	7/3	7/7	7/4	7/7	7/5	7/6
7	Rainfall	5	5/8	5/7	5/3	5/7	5/4	5/7	5/5	5/6
8	Runoff depth	6	6/8	6/7	6/3	6/7	6/4	6/7	6/5	6/6

Consistency Ratio (CR) = 0 (perfectly consistent)

Table 2 Pair-wise comparison matrix of thematic layers for suitability of check dam and other structures

	Theme	Assign Weight	Geomorphology	Soil	Geology	Lineament density	Slope	Drainage order	LULC	Rainfall	Runoff depth
1	Geomorphology	8	8/8	8/6	8/6	8/7	8/6	8/7	8/5	8/4	8/5
2	Soil	6	6/8	6/6	6/6	6/7	6/6	6/7	6/5	6/4	6/5
3	Geology	6	6/8	6/6	6/6	6/7	6/6	6/7	6/5	6/4	6/5
4	Lineament density	7	7/8	7/6	7/6	7/7	7/6	7/7	7/5	7/4	7/5
5	Slope	6	6/8	6/6	6/6	6/7	6/6	6/7	6/5	6/4	6/5
6	Drainage order	7	7/8	7/6	7/6	7/7	7/6	7/7	7/5	7/4	7/5
7	LULC	5	5/8	5/6	5/6	5/7	5/6	5/7	5/5	5/4	5/5
8	Rainfall	4	4/8	4/6	4/6	4/7	4/6	4/7	4/5	4/4	4/5
9	Runoff depth	5	5/8	5/6	5/6	5/7	5/6	5/7	5/5	5/4	5/5

Consistency Ratio (CR) = 0 (perfectly consistent)

3.2 GIS-based muti-criteria decision analysis

The study uses GIS-based multi-criteria decision analysis with Analytical Hierarchical Process (AHP) to select a suitable water harvesting site. It is the most common and well-known decision-making method for delineating a suitable site for water resource management. The sustainable water resource management plan of the lower Kulsi watershed is based on the integrated criteria layer such as geomorphology, soil texture, geology, lineament density, slope, drainage density, stream order, land use/land cover, rainfall, runoff depth, road density, groundwater potential. The weight of the criteria layers is assigned according to the importance of the water resource plan structure. The consequences of each parameter are given as per Saaty's scale (1–9) of relative importance value. Saaty's scale of relative importance tells a value of 9 for extreme importance; a value of 8 indicates very strong plus, seven means very strong, six indicates strong plus, 5 indicates Strong preference, four means moderate plus, 3 implies moderate importance, two standards weak or slight and 1 for two activities contribute equally. According to the scale, all the influencing criteria layers have been compared in a pair-wise matrix (Table 1 for farm ponds and Table 2 for other structures). The normalized pair-wise comparison matrix of thematic layers was considered for measuring the consistencies index using the AHP extension module in Arc GIS. Consistency ratio (CR) is the ratio of the consistency index for the matrix to random consistency indices of several criteria used in the model (equation 9, Saaty (2008)).

$$CR = \frac{CI}{RCI} \tag{9}$$

Consistency Ratio, where,

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{10}$$

Largest eigenvalue,

$$\lambda_{max} = \frac{\lambda_1 + \lambda_2 ... n}{n}$$

, n is the number of the factors used in the analysis) *RCI* is random consistency indices for different size matrices (as suggested by Saaty (2008))
According to Saaty, the revision of the preference matrix is recommended if CR is greater than 0.1. If CR is 0.10 or less, it is acceptable for the analysis. The CR is 0, which means a perfect level of consistency in the pair-wise comparison. The threshold value of the assigned weight for each harvest-

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ing structure of the study area is zero (0); therefore, the judgment matrix is perfectly consistent.

Each criteria layer is classified using the reclassify under the spatial analysis toolbox of Arc GIS 10.6 software. Table 3 illustrates the assigned rank and weight of subcategories of each influencing criteria layer as per the consistency result. The criteria layers were integrated with the weighted overlay analysis method in the GIS environment to delineate suitable sites for the water resources plan. Eight criteria layers, namely geomorphology, slope, geology, soil texture, river density, LULC, rainfall distribution, and runoff, were integrated with the weighted overlay method to delineate the farm pond. Criteria layers on geomorphology, slope, geology, lineament density, soil texture, stream order, LULC, rainfall distribution, and runoff were integrated with the weighted overlay method to delineate other structures such as the percolation tank, the check dam, and the stop dam. The site suitability map of each structure was classified into three categories highly suitable, moderately suitable, and less relevant (Fig. 5a, 5b, 5c, and 5d). The final most suitable sites shown in Fig. 5e are identified from the most potential site of suitability map generated after the weighted overlay method based on integrating critical factors of each harvesting structure illustrated in Table 4. The resultant suitability map was validated successfully with the help of the observed harvesting structure of the irrigation and water resource department of the Government of Assam (Image 1–8).

Table 3 Runoff curve number (C.N.) for combinations of LULC and hydrologic soil group of the watershed

LULC		Hydrologic soil group			
Level I	Level II	A	B	C	D
Cultivated land	Cropland	58	72	81	85
	Tea Plantation	30	48	65	73
Vegetation	Forest	30	55	70	77
	Shrubland	35	56	70	79
	Grassland	49	69	79	84
Waterbody	Marshy land	98	98	98	98
	Wetland	98	98	98	98
	River	98	98	98	98
Bare ground	Barren land	77	86	91	94
	Sand bar	77	86	91	94
	Exposed rocky surface	77	86	91	94
Built-up	Road	83	89	90	92
	Railway	72	82	87	89
	Settlement	59	74	82	86

(United States Department of Agriculture 1986; Jaiswal & Amin 2021)

4 Results and Discussion

4.1 Description of the influencing criteria

Geomorphology: The main geomorphic features in the lower Kulsi watershed are Structural & Denudation Hills and Valleys, Pediments, and Alluvial plains (Fig 2a). Structural hills & valleys and pediment complex landforms give more weightage for delineating suitable sites of check dams and percolation tanks. Older alluvial plain areas are selected for the construction of farm ponds.

Soil: Fig 2b shows the soil texture classification of the lower Kulsi basin. Soil with a low infiltration rate is most suitable for farm ponds (Reddy et al. 2012). Highly porous soil is ideal for percolation tanks (Central Groundwater Board 2000). Therefore clayey, coarse loam and fine loam soil of the basin prioritize the construction of surface farm ponds. Fine soil gives high preferences for selecting suitable sites for check dams and percolation tanks. Geology: Fig 2c illustrates that structurally the upper catchment area belongs to the age of the Proterozoic with dolomite, amphibolite, and grey–pink porphyritic granite structure. The percolation tank and check dam are more prevalent in India to recharge the groundwater reservoir in the alluvial and hard rock formations. These structures' efficiency and feasibility are higher in hard rock formation (Central Groundwater Board 2000). Therefore, highly fractured and weathered rock in the upper catchment structure is considered ideal for percolation tanks and check dams in the watershed, and high weight is assigned for such rocks.

Lineament density: O.'Leary et al. (1976) define lineament as 'a mappable linear feature of the earth surfaces whose parts are aligned in a rectilinear or slightly curvilinear relationship and differ from adjacent elements' pattern presumably reflect some subsurface phenomenon. The lineament density of the lower Kulsi watershed varies from 0 to 74 km/sq. km (Fig 2d). The lineament density map was reclassified into five categories. The lineament represents the zone of faulting and fracturing, increasing porosity and permeability (Yeh et al. 2016). It is the best geologic unit that helps to collect and store water at high capacity. It required sufficient thickness of permeable bed or weathered formation to facilitate recharge of stored water within a short period (RWHM). Therefore, high-density lineament surface areas are assigned for the increased weight of the percolation tank and check dam to recharge groundwater.

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Image 1 Farm pond near the Bamunigaon village of the basin



Image 2 Farm pond near the Bandapara village of the basin



Image 3 Farm pond near Dhanubhanga village of the basin



Image 4 Dam and canal on the Kulsi River



Image 5 Dam and canal on the Batha River



Image 6 Dam and canal on the Deosila River



Image 7 Dam on the Singua River



Image 8 Dam and canal on the Singra River

Source: Images 1–4 Collected by the author from the field; Images 5–8 Esri, Maxer, Earthstar Geographics, and the GIS Community

Slope: The elevation of the lower Kulsi watershed varies from 40 m near Nagarbera to 1120 m above mean sea level at Um Tynrai hilltop (Fig 3a). A slope map is shown in Fig 3b. The slope of the basin has been categorized into five classes level (0%–3%), gentle (3%–5%), moderate (5%–15%), high (15%–45%), and very high (>45%). As per the rainwater harvesting manual of PHED, Meghalaya, the percolation tank's location should be 3 to 5%. The gentle sloping area has been prioritized for the structure of the percolation tank and check. The level sloping area has prioritized the suitable site

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Table 4 Adopted specifications for water resource conservation site based on RWHM, PHED, Meghalaya

Type of structure	Geomorphology	Lithology	Soil type	LULC	Order	Slope	Lineament	Rainfall	Runoff potential
Farm pond	Plain	Clay & loam	Low infiltrated soil	Cropland	-	Gentle	Moderate to low	High rainfall	Moderate to high
Percolation tank	Structural Hill	Highly fractured & weathered rock	Light sandy soil, highly permeable soil	Uncultivated shrub	3rd	Moderate	High density	Moderate rainfall	Moderate
Boulder check dam	Hill	All type	Relatively permeable soil	Crop, shrub	2nd & 3rd	Gentle	Moderate to high	Low rainfall	Low
Stop Dam	Alluvial Plain	Alluvial	All type	Cropland	4th & 5th	Gentle	low	Moderate to high	High

selection of water harvesting structures of the farm pond.

Drainage: As per Strahler's hierarchy 1964, the Kulsi is an eight-order channel (Fig 3c). 2nd and third-order streams are suitable for percolation tanks and stone check dams, 4th and fifth-order streams are ideal for stop check dams (Central Groundwater Board 2000). The study's drainage density range is 0 to 4 km/sq km (Fig 3d). The drainage networks of a basin depend on the lithology, and it provides an essential index of infiltration rate (Arulbalaji et al. 2019). Farm ponds are suggested in the lower permeable areas of the basin where canal irrigation is not covered. Therefore, the low drainage density with impermeable soil area gives high weight to the farm pond.

Land use/land cover: The lower Kulsi basin was classified into five broad categories of LULC, namely cultivated land, vegetation cover, bare ground, water bodies, and built-up land, and 14 level II types of LULC observed in the watershed. Fig 4a exhibits 14 different types of LULC observed in the watershed. The land downstream of the percolation tank should have irrigable land (Consultancy Services Organization 2002). Streams near the shrub forest and grassland of the high altitudinal area with irrigable cropland downstream give high weight for selecting a percolation tank and bolder check dam. Uncultivable land, scrubland near the settlement, and croplands in plain areas assign a high weight to suitable site detection of a farm pond.

Rainfall and runoff depth: The Kulsi watershed experiences southwest monsoon with high precipitation in the pre-monsoon period. The average annual rainfall varies from 1604.31 mm to 2280.83 mm (Fig 4b). More regional rainfall specifies higher water harvesting possibilities (Al-Adamat et al. 2010). The high weights are assigned for high rainfall to delineate all types of water harvesting structures. The infiltration and surface runoff depends on the rainfall's intensity, and the duration of rain influences surface runoff and less infiltration (Thapa et al. 2017). The annual average runoff varies from 1336.04 mm–2257.04 mm, as shown in Fig 4a, due to the variation of total annual rainfall during the ten years study period.

4.2 Site selection

In the lower Kulsi watershed, water harvest structures like farm ponds, percolation tanks, bolder check dams, and stop dams are suggested for water resource management in the most suitable potential area. Table 4 illustrates the integration of critical factors of different water harvesting structures.

The farm pond is a dug-out structure with a proper inlet and outlet for collecting the surface runoff from the farm area. It is one of the essential rainwater harvesting structures for irrigation on farmland (Reddy et al. 2012). It is constructed in low-lying farmland areas to minimize excavation and build an earthen bund surrounding the water to reduce excess flow. The pond is made in a highly eroded farm area with undulating topography. In the lower Kulsi watershed, soil with a low infiltration rate and more than 1 m soil depth, moderate to low groundwater level, and high annual rainfall and surface runoff is the most suitable condition for constructing a farm pond. Accordingly, 113 most appropriate sites are suggested from the highly relevant area of the farm pond's suitability map, which fulfils almost all required conditions for the structure (Fig 5b).

A percolation tank is a dug-out structure with a proper inlet and outlet for collecting surface runoff for recharge. It is a critical water harvesting structure in soils with a high infiltration rate to recharge

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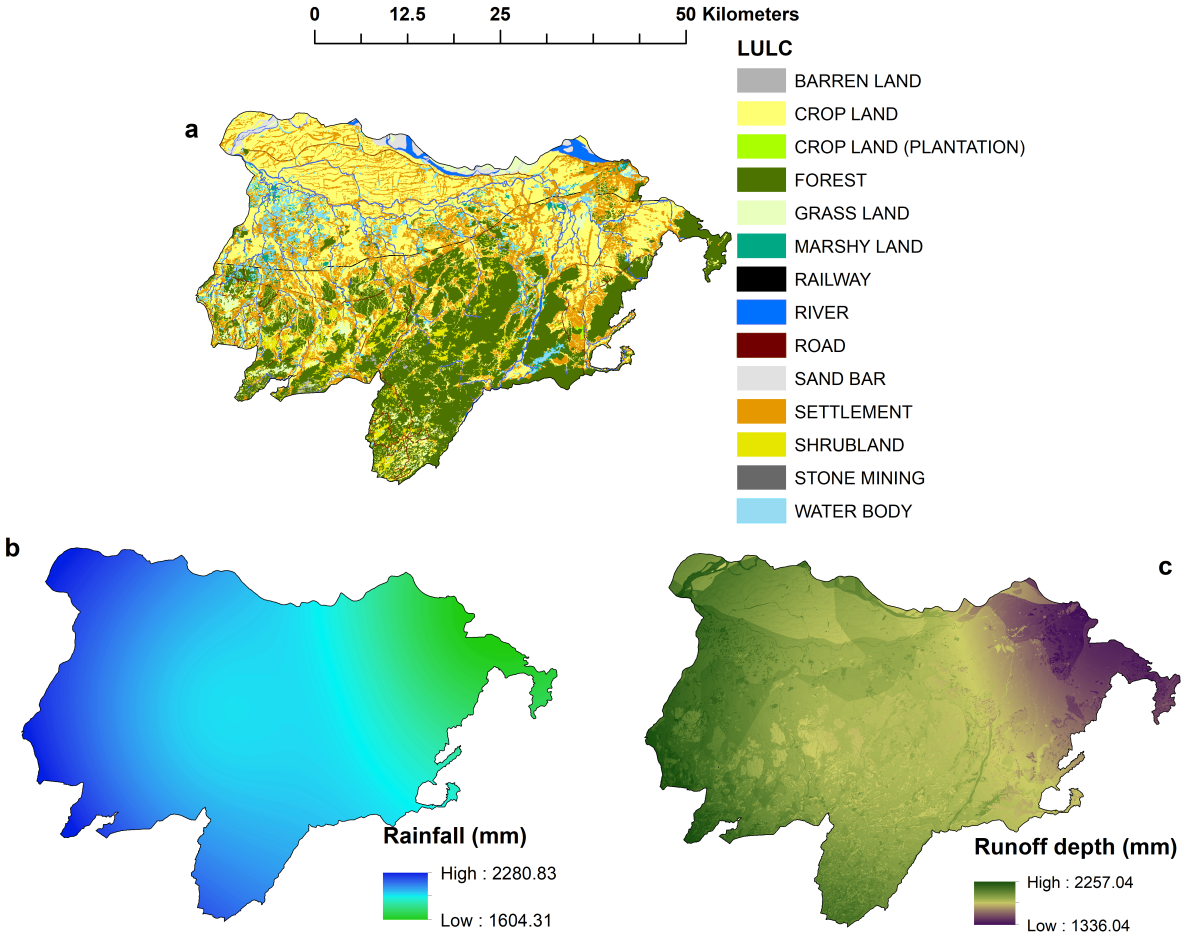


Fig. 4 a Land use/land cover map prepared high-resolution satellite data, 4b Spatial rainfall distribution during 2009–2018, and 4c Estimating surface runoff using the SCS-CN method.

groundwater. These are usually constructed across streams and more prominent gullies to impound a part of the runoff water. In the lower Kulsi watershed, the most suitable sites for the construction of percolation tanks are suggested in the area where land is not utilized for agriculture, moderate slope, highly permeable soils, structural hills with high-density lineament, areas with medium to low groundwater potential zones across the second & third order streams. Thirty-five (35) most suitable sites are suggested for constructing a percolation tank along the streams in the study area. These sites fulfil all the required conditions for making a percolation tank, improving groundwater recharge, reducing surface runoff, and resulting flooding downstream.

Check dams are small structures constructed of stone, sand, gravel bagged, or other durable material across the stream to reduce erosion in a drainage channel by restricting the flow velocity. Soil having a sufficient thickness of permeable bed or weathered formation to recharge stored water, small streams in the gently sloping area, and feasible both in hard rock and alluvial formations are desirable conditions for constructing a check dam. Depending on the materials and purpose of the building, two types of check dams are suggested in the lower Kulsi river basin. The bolder or stone check dams are specified in second and third-order streams with gentle sloping and scrub forested areas. They can be built with cheap, locally available materials for gully control and stabilizing vegetation to reduce upstream soil erosion and bed gradient. Ninety-five segments of streams are identified in the lower Kulsi watershed as the most potential sites for checking dams in the catchment area. Thirty-four Stop dams are proposed across fourth and fifth-order streams with gentle sloping near agricultural and settlement areas for irrigation and domestic.

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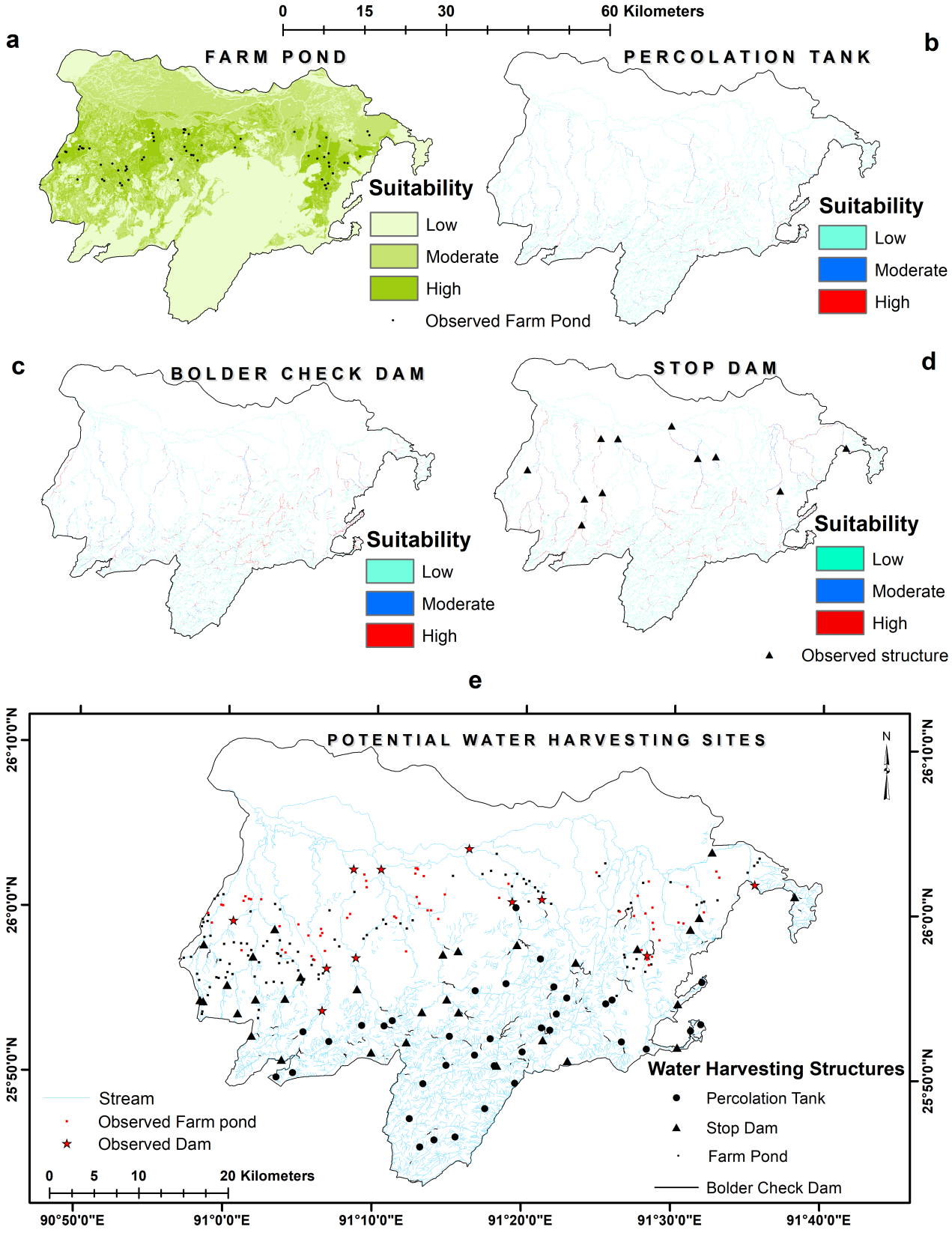


Fig. 5 a Site suitability map of farm pond, 5b suitability map of percolation tank, 5c river segments suitable for bolder check dam, 5d suitability map of stop dam, and 5e Suggested most potential water harvesting sites with observed water harvesting structure.

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These ravine reclamation structures help impound water, catch sediment flow, lower the risk of floods downstream, and reduce channel erosion and flow velocity across fourth and fifth-order streams with gentle slope scrub and barren land areas (Fig 5e). The past works of literature show that rain and river water harvesting is a promising tool to overcome water shortage and regulate groundwater flow in arid and semi-arid climates (Singh et al. 2009; Weerasinghe et al. 2011; Mahmoud & Alazba 2014; Al-Shaheeb 2016; Adham et al. 2018; Badhe et al. 2020; Alwan et al. 2020). Rain and river water harvesting is an alternate measure of water problems in the cities and rural areas of the tropical region too, including the high rainfall region of Kenya (Mugo & Odera 2018); Chinnar watershed of Tamilnadu (Lohar et al. 2018), the small watershed of Lormi block of Chattisgarh, (Kumar et al. 2017), Sivganga watershed of Western Ghat (Kadam et al. 2017) in India. The Kulsi basin of North-East India needs research on rain and river water harvesting. As already discussed, the study area is located in the undulating topography with highly seasonal rainfall in summer and dry winter, which is required for a water harvesting structure, especially a bolder check dam to control gully erosion and a percolation tank for regulating groundwater recharge in the upper catchment, and a farm pond for irrigation in farmland to increase crop productivity where canal irrigation is not covered.

4.3 Results validation

The combined AHP and GIS-based model output of the potential site suitability map of water harvesting were validated by analyzing the observed authenticated governmental record of the farm pond and stop dam structure for irrigation. Fig 5a illustrates the location of the observed farm pond with a suitability map of the farm pond. Fig 5d displays the location of the observed water harvesting structure with a suitability map of the stop dam. Out of the 63 observed farm ponds, 52 numbers of farm ponds are located in a highly suitable area, and 11 observed farm ponds are located in a moderate zone. No observed farm ponds are recorded in low categories of the suitable zone. From the result, 82.53% of farm ponds fall in a highly suitable area and 17.46% fall in a moderately suitable area. None of the farm ponds falls in a low suitable and unsuitable area. There are 11 water harvesting structures (stop dams) recognized downstream of the Kulsi River and its tributaries constructed under the Department of irrigation, Govt of Assam. Out of the 11 structures, eight (8) are located in a high suitability stream segment to construct a stop dam. Two structures are found in the moderate category of suitability segments, and only one is located in the low suitability segment of the stream for the stop dam. It is observed that 72.72% of stop dam falls in a highly suitable area, 18.18% fall in a moderate zone, and only 9% fall in the low category of suitable area. None of the observed stop dams falls in an unsuitable area. The overall accuracy assessment shows 82.53% for the farm pond and 72.752% for the stop dam in the model. The delineation of suitable water harvesting sites, especially farm ponds and stop dams, using AHP and GIS techniques based on nine contributing layers – geomorphology, soil, geology & lineament density, slope, drainage density and stream order, land use/land cover, distribution of rainfall pattern, and runoff depth are validated successfully.

4.4 Strength and limitations

The paper focused primarily on physical criteria per the general guidelines of the Public Health Engineering Department, Government of Meghalaya, India, for selecting a suitable water harvesting site. In this research, the potential water harvesting site was delineated using high-resolution satellite data (5.8m) for the first time with reasonable accuracy of the LULC map; seven observed gauge rainfall was used for calculating rainfall distribution, and 20 m contour DEM for calculating topographic factor. The combined AHP and GIS-based method offer multi-criterion decision-making to suitable water harvesting sites and water resources management of the lower Kulsi basin using ten input criteria that directly and indirectly influence water resource management. The suitable water harvesting sites are proposed in the most convenient area per the general guidelines of the Public Health Engineering Department, Government of Meghalaya, Central Ground Water Board and Rain Water Harvesting and Conservation Manual, Government of India.
There is limited availability of authenticated observed data for analysis of runoff depth. However, surface runoff is estimated using the SCS-CN method, applicable in an ungauged watershed and from available data on rainfall, soil, LULC, and slope. No observed percolation tanks and bolder check dam are recognized in the study area to assess the percolation tanks and bolder check dam results.

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5 Conclusions

Based on some selected physical criteria, the paper focused on combining GIS and AHP methods to generate a water harvesting suitability map of the lower Kulsi basin, India. The suitable sites are proposed on the most suitable water harvesting areas per the guidelines of RWHM, PHED, Meghalaya, CGWB, and CPWD, Government of India. In the watershed, 113 surface farm ponds, 35 percolation tanks across streams, 34 stop dams, and 95 gullies sites for bolder checks are suggested for sustainable water resource development. It will help to improve irrigation facilities and crop productivity, regulate groundwater recharge, reduce erosion of gullies, and control flooding downstream of the study area. The resultant output of the model was validated successfully and applied for identification and suggests a suitable location for water harvesting from the most potential site based on key factors of each harvesting structure. Therefore, the research will contribute to developing countries' local governments and communities' water resource departments if the suggested sites are used for water harvesting.

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Supplement 1 - Assigned weight and rank for suitable site selection of water harvesting

Sl No.	Thematic layer	Classes	Farm pond		Other structures			
			Weight influence (%)	Rank Farm pond	Weight influence (%)	Rank Percolation tank	Bolder Check Dam	Stop Dam
1	Geomorphology	Alluvial Plain	17	7	15	3	3	3
		Flood Plain		3		-	2	-
		Structural Hills		-		8	8	8
		Denudation Hills		-		5	5	7
		Pediment Complex		5		4	7	5
		Water bodies		-		2	2	3
2	Soil	Coarse-silty	15	2	11	-	3	3
		Fine-loamy		5		5	5	5
		Coarse-loamy		3		3	3	3
		Fine		5		7	7	7
		Clayey		7		2	3	3
		River		-		-	-	-
3	Geology	W-G SSPC	6	3	11	3	3	3
		O-F OSSC		5		5	5	5
		FOSSC		7		5	5	5
		Dolerite		-		6	6	6
		Amphibolite		2		7	7	7
		GPPG		-		6	6	6
		HODB-RBLS		7		5	5	5
4	Lineament density (km/km2)	0-7.26	-	-	13	2	2	2
		7.26-19.75				5	5	5
		19.75-33.11				7	7	7
		33.11- 49.37				7	7	7
		49.37-74.06				8	8	8
5	Drainage order	1st	-	-	14	-	-	-
		2nd				3	5	-
		3rd				8	7	3
		4th				7	5	8
		5th				5	-	7
		6th				3	-	5
		7th				3	-	3
		8th				-	-	-
	River density (km/km2)	0-0.90	8	7	-	-	-	-
		0.90-2.10		5				
		2.10-4.04		2				
6	Slope (in %)	0-3	15	8	11	5	7	7
		3-5		5		8	5	5
		5-15		3		2	3	2
		15-45		-		-	-	-
		>45		-		-	-	-
7	Land use/ Landcover	Barren Land	15	5	9	5	7	5
		Crop Land		7		3	7	5
		Tea Plantation		2		2	6	2
		Forest		2		2	5	2
		Grass Land		1		5	2	3
		Marshy Land		2		-	3	2
		Railway		-		-	-	-
		River		-		7	7	7
		Road		-		-	-	-
		Sand Bar		-		5	5	5
		Settlement		3		-	2	5
		Shrubland		5		7	7	3
		Stone mining		-		-	-	-
		Water Body		-		-	-	-
8	Rainfall (in cm)	160.4-184.8	11	5	7	5	5	5
		184.8-204.7		7		7	7	7
		204.7-228.1		7		5	7	7
9	Runoff depth (in mm)	1336-1657	13	3	9	3	3	3
		1657-1805		5		3	3	3
		1805-1903		5		5	5	5
		1903-2004		7		7	7	7
		2004-2257		7		7	7	7

W-G SSPC -White to Greyish Sand, Silt, Pebble, and Clay; O-F OSSC -Oxidized to Feebly Oxidized Sand Silt and Clay; FOSSC -Feebly Oxidized Sand, Silt, and Clay; GPPG -Grey and pink Porphyritic Granite; HODB-RBLS-Highly Oxidized dark brown to Rd brown Loamy Sand.

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