Land resources evaluation and drainage network analysis of watershed for site specific crop planning using GIS

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To meet the demand of food, fodder, fuel and fibre for the ever-increasing population of the world, achieving higher land and water productivity of a parcel of land is a major challenge. For this, site-specific cropping system plan and land-use system based on basic soil and terrain information are a prerequisite. With the advent of remote sensing and geospatial technique, collection of point data and their spatial interpolation on watershed basis is possible in quick time, which can be used for site-specific cropping system planning. In this study, site-specific cropping system and profitable land-use plan were prepared for a watershed of eastern India (Darpanarayanpur, Nayagarh district, Odisha) using geospatial technique. Drainage analysis revealed that prominent drainage pattern was dendritic with low drainage density which indicates that the watershed region has subsoil with high permeability and low relief and, accordingly, rainwater harvesting structures have been suggested in the watershed.

Keywords: Crop diversification, drainage, land resources, precision farming, remote sensing, watershed.

ANTHROPOGENIC factors like rise in population, economic activities, consumption patterns, social behaviour, energy resource utilization, urbanization, industrialization, over-utilization of underground water, large-scale deforestation, etc. have resulted in ever-increasing demand on land and water, and caused enormous degradation of land and environment. Therefore, conservation of basic natural resources through site-specific cropping and land-use system is the most important task now in hand to obtain higher land and water productivity in future. Natural resources management on watershed basis has already been proved successful for optimal and site-specific sustainable production with the minimum negative impact to natural resources and the environment[1–8].

Precise knowledge on spatial variation of basic natural resources with potentials and limitations is the pre-requisite for formulating cropping system plan on a sustainable basis. The collection of precise information on soil, available water capacity, land use, slope, elevation, soil fertility, etc. at quick pace is possible only with the advent GIS and remote sensing technology. The space technology and geoinformatics have revolutionized the mapping and management of voluminous spatial and non-spatial natural resource information, which helps develop sound, scientific plans for achieving sustainable cropping and land-use system[3–5,9–11]. Considering the above, a study was undertaken to assess the soil and other key natural resources of Darpanaranpur watershed, Nayagarh district, Odisha, India for land-use planning using space technology and GIS. Different input thematic maps of natural resources were integrated into a composite map and based on decision rule alternative cropping and land-use system plan in the watershed were developed by multi-criteria decision analysis[8,12–15].

In this study GIS platform was used for quantitative drainage network analysis of the watershed to assess infiltrability, permeability and run-off potential of the ground parcel.

Materials and methods

Study area

The study watershed lies between lat. 20.098–20.050°N and long. 85.785–85.239°E (Figure 1). Mean maximum and minimum temperatures are 40.82°C and 10.1°C respectively. The region receives an average annual rainfall of 1450 mm. The length of the growing period, which indicates the availability of water for plant growth, is about 140–150 days in a year. It starts from the middle June and continues up to December. The study watershed has an area of 18.14 sq. km with crop cultivated area of 10.63 sq. km only. The elevation of the watershed varies from 76 m amsl at the outlet to 292 m amsl in the northern and southern sides. A check dam and some small ponds in the watershed are the main sources of irrigation.

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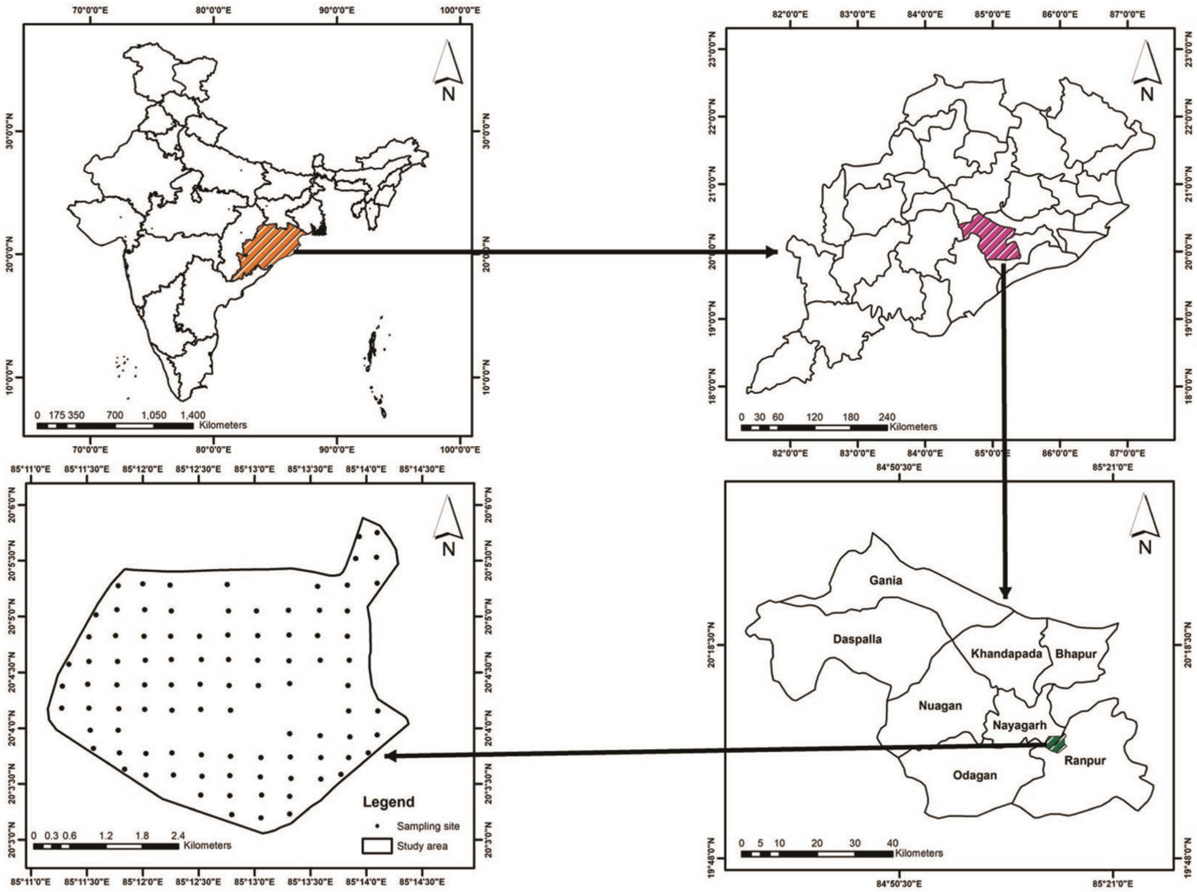

Figure 1. Index map of the study watershed, Darpanarayanpur, Odisha, India.

Soil sampling and interpolation

Soil for analysis was collected from 93 points from the watershed and the coordinates of each point were identified using a portable GPS (Figure 2). The various soil parameters like bulk density, soil texture, field capacity (33 kPa) and permanent wilting point (1500 kPa) at different points were measured using standard laboratory procedures. Available water capacity (AWC) was determined by subtracting water content at permanent wilting point (1500 kPa) from the water content at field capacity (33 kPa). Inverse distance weighted (IDW) method was used for interpolation of point data into surface. For the IDW interpolation method, the value of variable Z at the unsampled location x_0, $Z^*(x_0)$ was estimated based on the data from the surrounding locations, $Z(x_i)$, as follows

$$Z^*(x_0) - \sum_{i=1}^{n} w_i Z(x_i),$$

where w_i is the weight assigned to each $Z(x_i)$ value and n is the number of the closest neighbouring sampled data points used for estimation.

$$w_i = \frac{1/d_i^2}{\sum_{i=1}^{n} 1/d_i^2},$$

where d_i is the distance between the estimated point and the observed point. IDW interpolation uses weight function w_i given by

$$w_i = \frac{h_i^{-p}}{\sum_{j=0}^{n} h_j^{-p}}, \tag{1}$$

where P is the called power parameter (p). It is an arbitrary, positive, real number. To calculate the interpolation of IDW method, first the value of power p which has the least error RMS for interpolation was determined (Table 1).

Drainage network parameters

In this study, drainage network-related parameters like linear parameters (stream number, order, stream length,

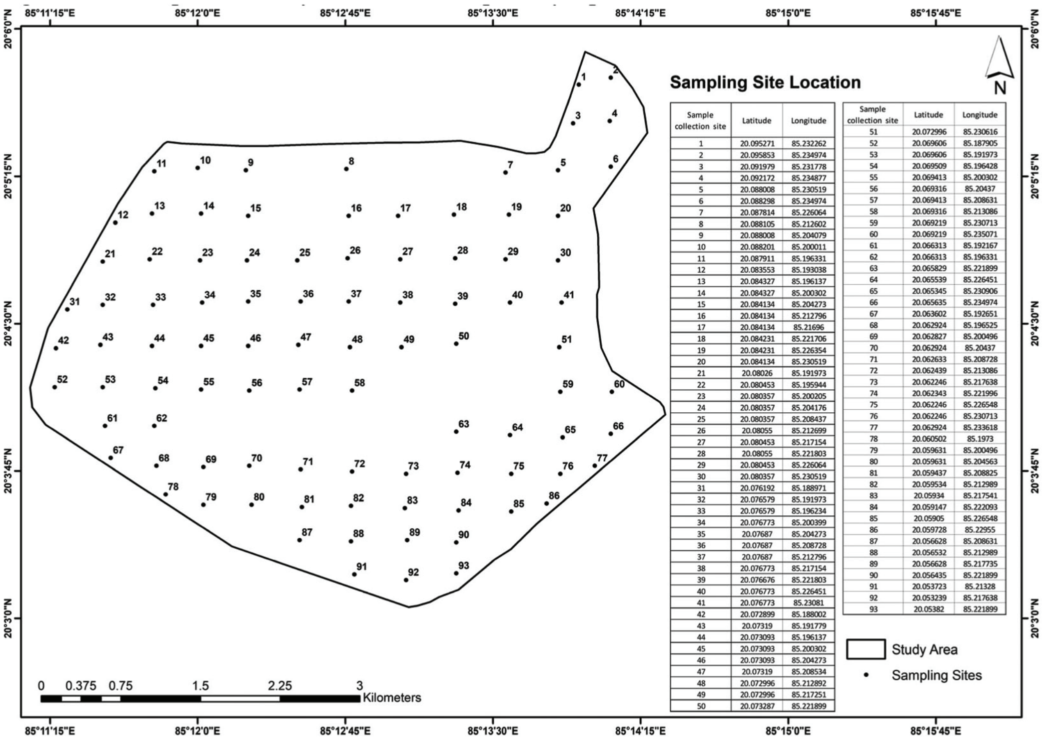

Figure 2. Soil sampling sites in the watershed.

Table 1. RMS values for calculation of optimum power for inverse distance weighted (IDW) interpolation method

Value (p)	1	2	3	4	5	6
Digital elevation model (DEM, m)	18.81407	14.62203	13.01164	12.43695	12.29755	12.3304
Organic carbon (%)	0.08224	0.08079	0.08077	0.08147	0.08238	0.08328
Bulk density (mg m^{-3})	00.06159	0.0589	0.0593	0.06084	0.0623	0.0635
Available water capacity (AWC, m^3 m^{-3})	0.0255	0.0228	0.02224	0.02274	0.0234	0.02404

$p = 3$ was suitable for interpolation by IDW method.

mean stream length, bifurcation ratio), aerial category parameters (drainage density, elongation ratio, form factor, circulatory ratio, compactness coefficient) and relief parameters (basin relief, relief ratio, ruggedness number, slope, relative relief, shape factor) were determined using GIS (Table 2).

Generation of thematic maps

The elevation points at different locations of the watershed were randomly collected from the Google Earth images. The IDW interpolation technique was then used to convert elevation points into continuous surface data and thus digital elevation map (DEM) was generated (Figure 3). The contour map of the study area was derived from DEM using GIS software and superimposed. The derived DEM was also further used to generate the slope map (Figure 4).

Land use/land cover mapping

The Landsat ETM+ satellite imagery (acquisition date: 16.01.2017; sensor: ETM+; coordinates: UTM; datum: WGS 84 and zone: 45), acquired from the website https://earthexplorer.usgs.gov/ was used to prepare cropping and land-use system map employing supervised classification, which was then updated with visual interpretation of Google Earth image and limited ground truthing. Table 3 gives the existing cropping system and land-use plan for Darpanarayanpur watershed. The major land-use/land-cover classes identified were upland and lowland cultivated areas (single crop and double crop), plantation, scrubland, and forest. The study indicates that 1063.60 ha (58.6%) area within the watershed is under cultivation (Figure 5), of which 113 ha (6.23% of total watershed area) has provision of supplemental irrigation from a checkdam. The watershed was dominated by traditional land-use system. So we introduced a sustainable, profitable

Table 2. Formulae of different morphometric parameters

Morphometric parameters	Definition	Formula	Reference
Linear aspects			
Stream order (U)	–	Hierarchical rank	17
Stream length (L_u)	–	Length of the stream	18
Mean stream length (L_{sm})	–	$L_{sm} = L_u/N_u$, where L_u is the total stream length of order u; N_u is the total no. of stream segments of order u	17
Stream length ratio (R_L)	It is the ratio of mean of segments of order (L_u) to mean of segments of the next lower order ($L_u - 1$)	$R_L = L_u/L_u - 1$, where L_u is the total stream length of the order u and $L_u - 1$ is the total stream length of the next lower order	18
Stream frequency (F_s)	Total number of stream segments of all orders per unit area	Total number of stream segments of all orders per unit area	19
Bifurcation ratio (R_b)	Ratio between the total number of stream segments of one order to that of the next higher order in a drainage basin	$R_b = N_u/N_u + 1$, where N_u is the total no. of stream segments of order u, $N_u + 1$ is the no. of segments of the next higher order	20
Aerial aspects			
Drainage density (D_d)	Stream length per unit area in a region	$D_d = L_u/A$, where L_u is the total stream length of all the orders and A is the area of the basin (sq. km)	19
Elongation ratio (R_e)	Ratio between diameter of the circle of the same area as the drainage basin and maximum length of the basin	$R_e = (2/L_b) * (A/\pi)0.5$, where, A is the area of the basin (sq. km) and L_b is the basin length	20
Form factor (R_f)	Ratio of basin area to the square of the basin length	$R_f = A/Lb^2$, A is the area of the basin (sq. km) and Lb^2 is the square of basin length	19
Circulatory ratio (R_c)	Ratio of basin area to the area of a circle having circumference equal to the perimeter of the basin	$R_c = 4 * \pi * A/P^2$, where A is the area of the basin (sq. km) and P is the square of the perimeter (km)	21
Compactness coefficient (C_c)	Basin perimeter divided by the circumference of a circle to the same area of the basin	$C_c = 0.2821P/A\ 0.5$, where P is the basin perimeter and A is the area of the basin	22
Relief aspects			
Basin relief (H)	Elevation difference between the reference points	Maximum vertical distance between the highest and lowest points of the watershed	18
Relief ratio (R_h)	Ratio of basin relief to the horizontal distance on which relief was measured	$R_h = H/L_b$, where R_h is the relief ratio; H the total relief (relative relief) of the basin (km) and L_b is the basin length	20
Ruggedness number (R_n)	Product of drainage density (D_d) and basin relief (H)	Product of drainage density (D_d) and basin relief (H)	20
Relative relief (R_r)	Ratio of relief (H) to the perimeter of the basin	Ratio of relief (H) to the perimeter of the basin	20
Shape factor	Ratio of the square of the basin length to the area of the basin	$B_s = L_b^2/A$	18

land-use plan in the watershed (Figure 5). For this, various thematic maps like slope map (Figure 4), existing land use (Figure 5), AWC map (Figure 6), organic carbon map (Figure 7), soil texture map (Figure 8) and bulk density map (Figure 9) were generated and overlaid to develop an integrated map by combining them. Based on the multi-criteria analysis on integrated map of basic soil and terrain information, location-specific cropping and land-use system were developed in the watershed.

Results and discussion

Drainage network parameters

Based on DEM, contour map and slope map of the watershed, the drainage map was generated (Figure 10). It shows that the prominent drainage pattern of the study area is dendritic. Most of the watershed area falls under slope categories from 1% to 3%. Total area and perimeter of the watershed are 1814.3 ha and 18.063 km respectively.

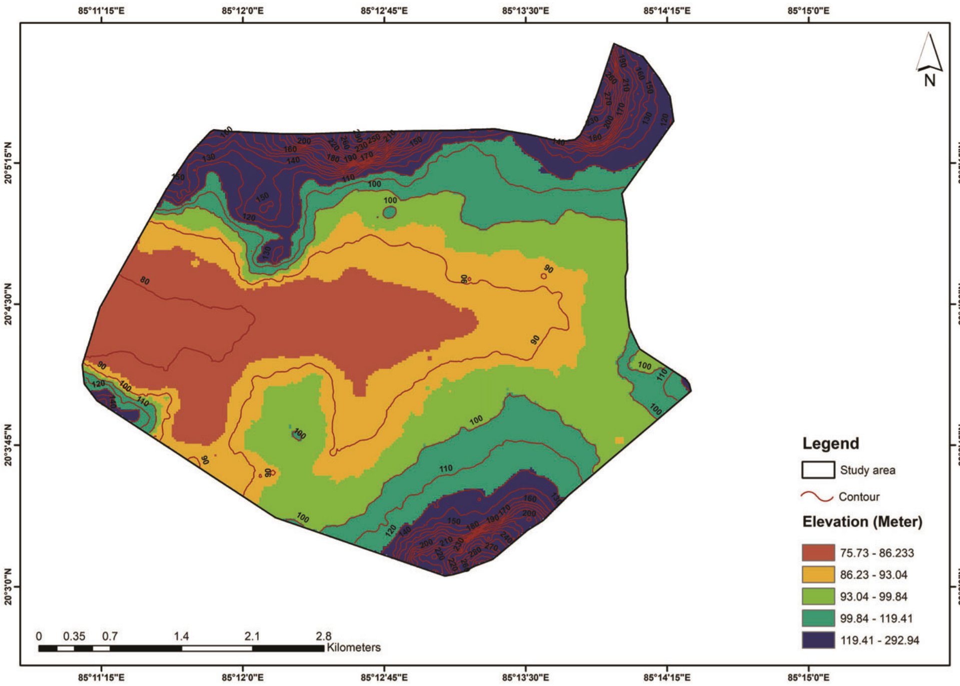

Figure 3. Contour map with digital elevation model (DEM) of the watershed.

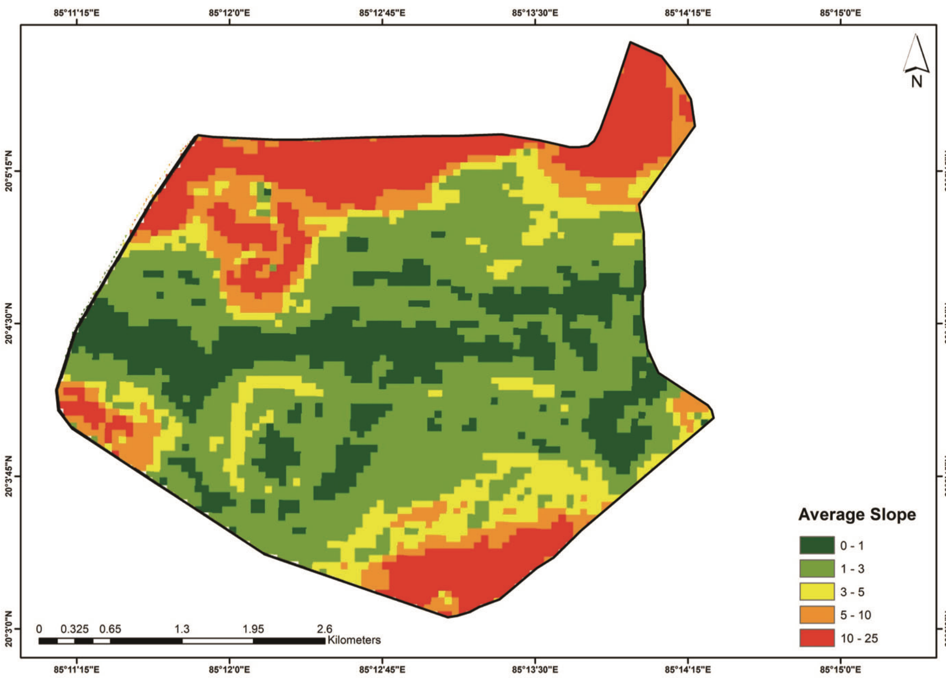

Figure 4. Slope map of the watershed.

To assess run-off potential, soil infiltration, agro-climatic condition and vegetation of the basin, drainage pattern of the watershed, different morphometric parameters were computed (Table 4), which would help identify locations for constructing water-harvesting structures (WHS), farm ponds, check dams, etc.

Linear parameters

Stream number and order of any watershed or basin are the most important parameters for selecting sites for WHS within the watershed. According to Horton's law, an unbranched stream is designated as a first order stream.

When two such streams join together, it is called a second order stream. When two second-order streams meet, a third-order stream is formed, and so on. In the study watershed totally, 138 streams were available of which 72 were of first order, 37 of second order, 15 of third order and 14 of fourth order. Total length of the streams of all orders was 46.5 km. Generally, stream length decreases as the stream order increases. The stream length ratio (R_L) which is the ratio of the mean of segments of order (L_u) to the mean of segments of the next lower order ($L_u - 1$), was found to be 0.4117, 0.2799 and 0.8314 for the second, third and fourth order streams respectively. The stream frequency (F_s) for the study watershed was 7.6/sq. km. Generally low stream frequency reflects permeable subsurface material, sparse vegetation, low relief, and high infiltration and permeability of the soil. Another important linear parameter is the bifurcation ratio (R_b) whose mean value was 2.642 for the watershed. This low R_b value reflects branching pattern, i.e. dendritic type of drainage network.

Table 3. Existing land-use statistics for Darpanarayanpur watershed, Odisha, India

	Area	
Land-use category	Hectare	Percentage
Built-up area	99.85	5.5
Forest area	449.21	24.76
Lowland cropped area (rainfed)	506.93	27.94
Lowland cropped area (irrigated)	113.04	6.23
Upland cropped area (rainfed)	443.63	24.45
Plantation area	160.1	8.82
Scrub land	2.28	0.13
Waterbodies, water harvesting structure, Nallah, etc.	39.25	2.16
Total	1814.29	100

Table 4. Morphometric parameters of the watershed

Morphometric parameters	Formula	Value
Linear aspects		
Area (ha)	A	1814.3
Perimeter (km)	P	18.063
No. of streams of order 1 (m)	N_1	72
No. of streams of order 2 (m)	N_2	37
No. of streams of order 3 (m)	N_3	15
No. of streams of order 4 (m)	N_4	14
Mean length of order 1 (m)	L_1	388.0
Mean length of order 2 (m)	L_2	333.0
Mean length of order 3 (m)	L_3	246.0
Mean length of order 4 (m)	L_4	191.0
Stream length (km)	L_u	46.5973
Mean stream length (km)	L_{sm} (first order)	0.4158
	L_{sm} (second order)	0.333
	L_{sm} (third order)	0.2465
	L_{sm} (fourth order)	0.1913
Stream length ratio	R_L (second order)	0.4117
	R_L (third order)	0.2799
	R_L (fourth order)	0.8314
Stream frequency (1/sq. km)	F	7.606
Bifurcation ratio	R_b	2.642
Aerial aspects		
Drainage density (km/sq. km)	D_d	2.568
Elongation ratio	R_e	0.832
Form factor	R_f	0.445
Circulatory ratio	R_c	0.699
Compactness coefficient	C_c	1.196
Relief aspects		
Basin relief (m)	H	216.5
Relief ratio	R_h	0.038
Ruggedness number	R_n	0.556
Relative relief	R_r	0.0119
Shape factor	B_s	1.836

Area-related parameters

The drainage density is the most important area-related parameter which is helpful to study run-off potential, soil infiltration, agro-climatic conditions and vegetation of a basin. Low drainage density value of 2.56 was computed for the study watershed. This low value indicates that the areas have permeable subsoil material and low relief. Elongation ratio of the basin was also computed and found to be 0.832. The elongation ratio varied from 0.6 to 1.0 depending upon the different types of vegetation, agro-climate, geology and hydromorphological features. Generally watersheds having higher elongation ratio possess high infiltration capacity and low run-off. A circular-shaped watershed was found to be more suitable in discharging run-off efficiently than an elongated watershed[16]. Form factor is the another important parameter related to aerial aspects, which was computed as 0.445 for the study watershed. The low form factor reflects that the watershed has the least fluctuated peak run-off flow, which continues for a long duration. It is easier to manage flood flows in an elongated basin than a circular basin. Circulatory ratio of the study area was found to be 0.699, which indicates that the watershed is almost elongated. Another parameter related to aerial aspects, i.e. compactness coefficient (C_c) was computed as 1.196. Compactness coefficient is the indicator of erosion risk. The low value indicates that the study watershed is less prone to erosion risk.

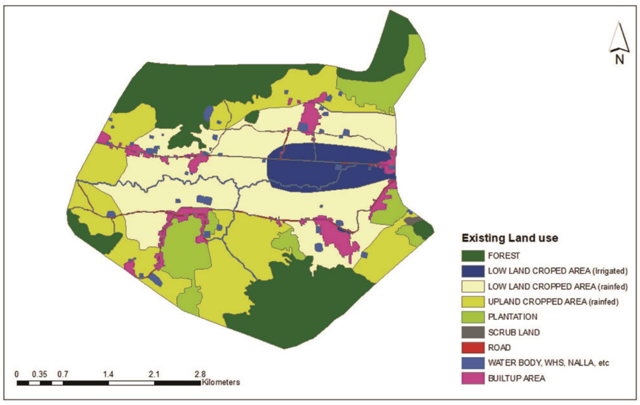

Figure 5. Existing land-use/land-cover map of the study area.

Relief aspects of the watershed

Relief-related parameters like basin relief (*H*), relative relief (R_p), relief ratio (R_h) and ground slope or ruggedness number (R_n) were also determined which will be useful for direction of stream flow, water movement, etc. basin relief is the elevation difference between the reference points, i.e. maximum vertical distance between the highest (divide) and lowest (outlet) reference points located within the watershed. For the watershed, low relief indicates high gravitational water flow as well as infiltration and low run-off with less sediment yield down the slope. The high relief reflects low gravitational water flow as well as low infiltration and high run-off. The degree of slope of the watershed is characterized by relief ratio, which ultimately determines the rate of soil loss and sedimentation within the watershed. The relief ratio for the study watershed was 0.038. The low and high values of relief ratio

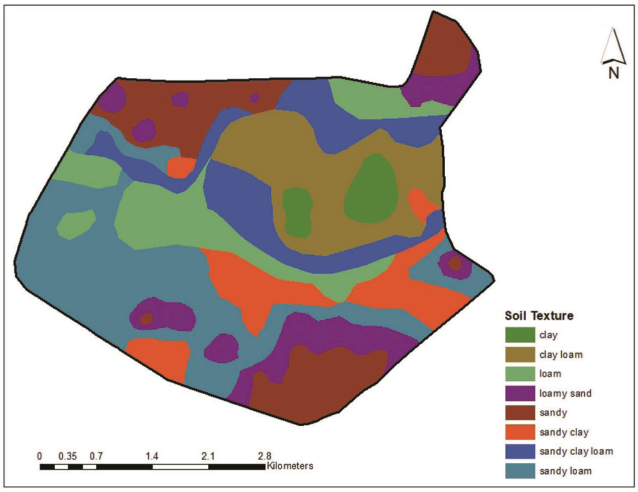

Figure 8. Soil texture map of the watershed.

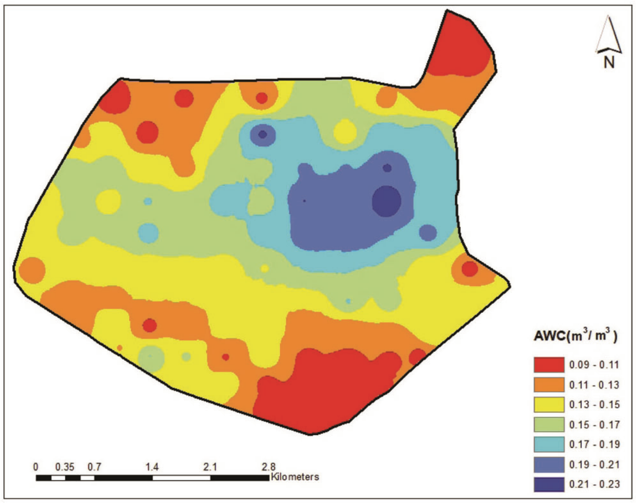

Figure 6. Available water capacity (AWC) map of the study area.

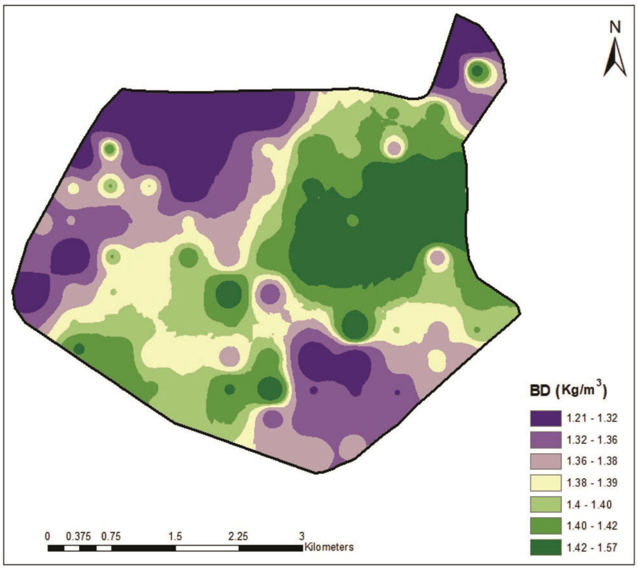

Figure 9. Bulk density map of the watershed.

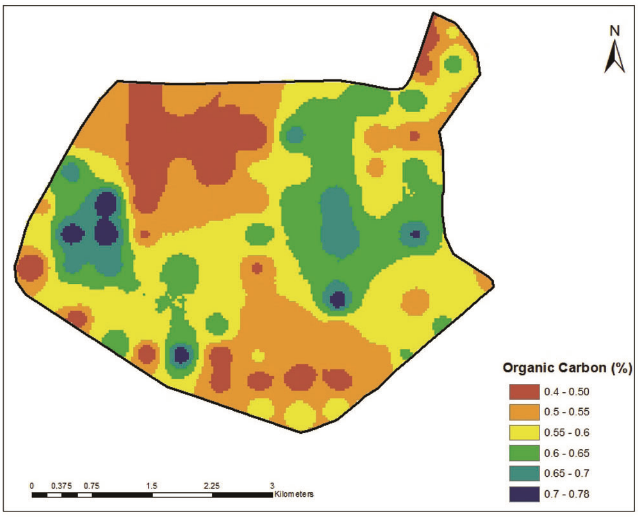

Figure 7. Organic carbon map of the study area.

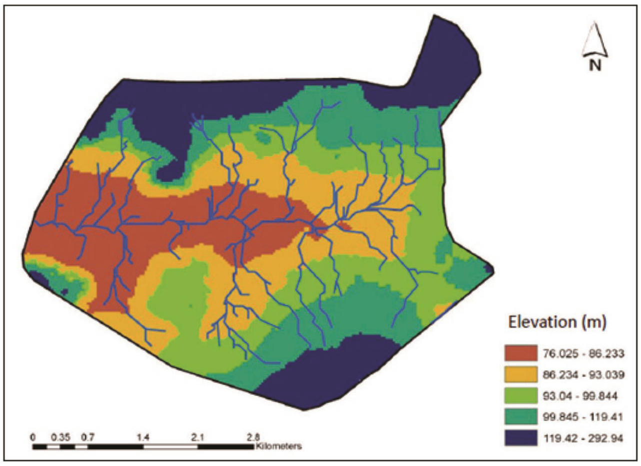

Figure 10. Drainage map and DEM map of the watershed.

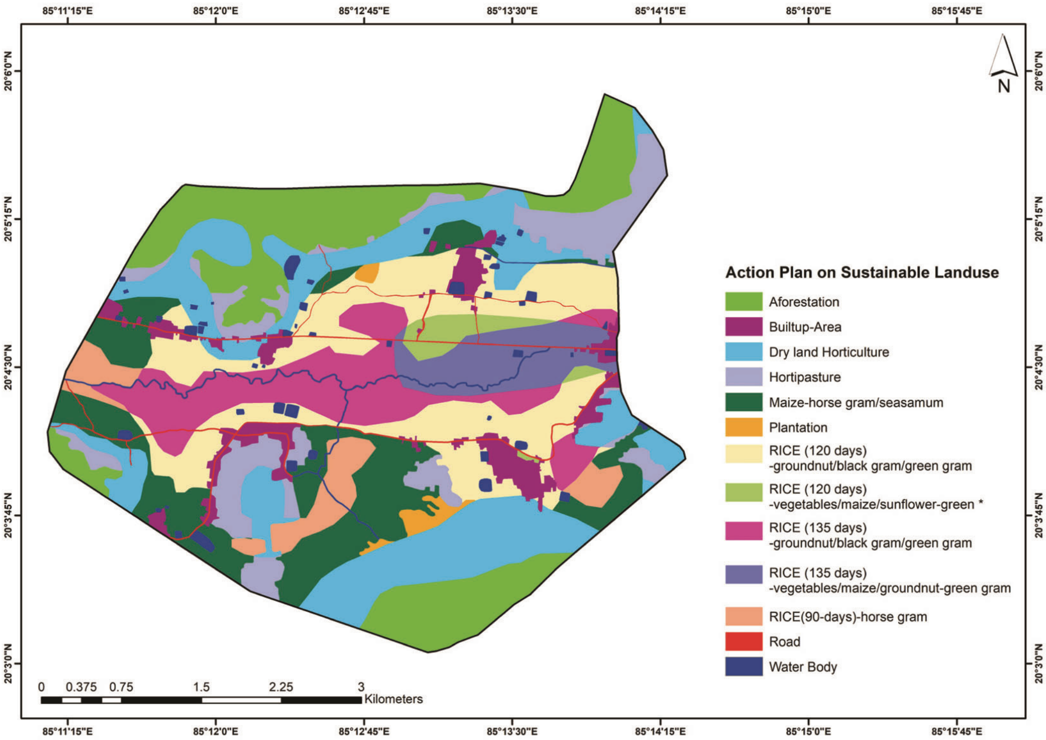

Figure 11. Alternative cropping and land-use system plan map of the watershed.

Table 5. Suggested land-use statistics for Darpanarayanpur watershed

Land-use category	Area	
	Hectare	Percentage
Afforestation	295.13	16.27
Built-up area	80.93	4.46
Dry land horticulture	336.05	18.52
Horti-pasture	157.82	8.7
Maize–horse gram/sesamum	233.13	12.85
Plantation	14.55	0.8
Rice (120 days)–groundnut/black gram/green gram	279.68	15.42
Rice (120 days)–vegetables/maize/sunflower–green gram	29.36	1.62
Rice (135 days)–groundnut/black gram/green gram	173.44	9.56
Rice (135 days)–vegetables/maize/groundnut-green gram	83.67	4.61
Rice (90-days)–horse gram	72.34	3.99
Road	18.93	1.04
Waterbodies, WHS, nallah, etc.	39.25	2.16
Total	1814.29	100

reflect the presence of both gentle and steep slope respectively[15]. Ruggedness number is the product of drainage density (D_d) and basin relief (H), whose value was estimated as 0.556. The low value of ruggedness number indicates that total basin relief and drainage density values are low for the study watershed.

Relative relief (R_r) is an important relief-related morphometric parameter of the terrain, which was estimated as 0.0119 for the study watershed. The watersheds having low relative relief have low run-off potential and those with high relative relief have high run-off potential.

Thematic maps of soil physical and chemical properties

The point soil samples were analysed and interpolated using IDW method to prepare surface AWC map (Figure 6), organic carbon map (Figure 7), soil texture map (Figure 8) and bulk density map (Figure 9). The water content at permanent wilting point (1500 kPa) was deducted from the water content at field capacity (33 kPa) to derive the AWC map. The value of AWC (%, v/v) varied from 0.09–0.11 to 0.21–0.23 m^3/m^3 for the surface layer of 0.20 m. Maximum water content was found at the middle part of the watershed, where soil texture was mostly clay loam to clay. The soil organic carbon content was low to medium, and varied from 0.35%–0.45% to 0.60%–0.65%. The soil texture of majority of cultivable areas was sandy loam to sandy clay loam (Figure 8). The texture of hilly terrain was mainly fine to coarse sand. Bulk density of the surface soil ranged from 1.21 to 1.54 kg/m^3.

Developing alternative cropping system and land-use plan using GIS

A comparison between the present vegetation cover and the proposed action plan reflects considerable amount of growth in the vegetative cover (Figure 11 and Table 5). There is scope for diversification of the cultivable area through profitable cropping system with short-duration field crops and vegetables. The moderately dense/degraded forest areas have been recommended under afforestation. Fast-growing tree species well adopted to climate change, like Australian teak (*Aacia mangium*) should be planted in the area. The highland sandy and stony area needs to be covered with silvipasture, i.e. a combination of trees and grasses, like *Cenchrus ciliaris*, *Dichanthium annulatum*, etc. can be grown along with these forest trees.

In the arable part of the watershed, rice in the upland area needs to be diversified with short-duration, low water requiring crops like maize, groundnut, green gram and black gram. By adjusting sowing dates, two crops through maize–cowpea/horse gram can be grown in rainfed upland area. The upland with higher slope can be used for growing short-duration crops like mungbean, urdbean, sesame and fodder sorghum under suitable soil water conservation practices. Also, plantations of timber/fruit and medicinal plants (lemon grass, palmarose, khus) and flowers like marigold have great potential on these lands.

The low-lying areas which are presently under single, long-duration rice cropping can be profitably converted to double/triple cropping, particularly in areas where supplementary irrigation is possible. The rainfed rice lowlands with higher available water capacity have greater residual soil moisture, where low water requiring legume crops like green gram, black gram, etc. can be grown after rice following conservation agriculture. The irrigated lowland can also be utilized by incorporating one legume crop like green gram into the cropping system after rice and one short-duration vegetable crop. Long-duration rice of 150 days needs to be avoided to convert mono-cropping to double-cropping. Since soil organic carbon was low to medium in range, emphasis has been for increasing organic carbon content in the cultivable soil through conservation tillage and legume-based cropping system. Certain management practices like minimum tillage, cover crops and crop rotation are advocated to improve organic carbon content of the topsoil. The sloping areas and wastelands, in general, need urgent soil conservation measures, like contour bunding, contour trenching and small check dams. Very gently sloping plateau are needed under vegetative cover of fast-growing trees/crops to minimize the risk of soil erosion. It must be emphasized here that to grow double/triple crops successfully, additional farm ponds/storage tanks must be constructed at suitable sites.

Conclusion

This study demonstrates the capability of GIS-based spatial interpolation technique for developing sustainable land-use system on watershed basis. There are enough opportunities for diversification of the rainfed upland area with short-duration field crops and vegetables for higher land and water productivity. The valley soils, which are presently under single cropping, could be converted to double/triple cropping, particularly in areas where irrigation is possible. The rainfed lowlands with higher AWC have greater residual soil moisture which could be utilized to grow low-duty crops like green gram, black gram, etc. after rice. Since soil organic carbon is low to medium, emphasis is given to organic carbon sequestration in the cultivable soil through conservation tillage. Morphometric analysis of drainage network revealed that the prominent drainage pattern of the watershed was dendritic with low drainage density. Thus, the region has subsoil with high permeability and low relief.

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