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Spatial distribution of soil hydro-physical properties and morphometric analysis of a rainfed watershed as a tool for sustainable land use planning

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ABSTRACT

In this study, high resolution (5.8 m) multi-spectral satellite data (IRS-P6, LISS IV) along with extensive ground information were used for sustainable land use planning of a rainfed watershed in eastern India (Bahasuni watershed, Dhenkanal, Orissa). Pedo-transfer functions were developed to predict soil water constants using easily measured parameters such as cation exchange capacity, organic carbon, oven-dry bulk density, soil texture, calcium carbonate etc. Different morphometric parameters like drainage density, stream frequency, form factor, circulatory ratio, elongation ratio, bifurcation ratio, relief ratio, relative relief, etc., were analyzed in relation to the development of water resources in the watershed. A circulatory ratio of 0.56 indicated that the shape of the basin was fairly elongated and suggested that the area was not prone to flood. The elongated shape, together with a moderate bifurcation ratio (3.01), indicates moderate flow, moderate runoff and moderate sediment yield. A low drainage density (2.7 km/km^2) furthermore implies the presence of permeable strata with high groundwater prospects and supports the assumption of moderate runoff and sediment yield. After studying potentials and prospects of soil hydro-physical properties and morphometric parameters, a suggested land use alternative was implemented in representative, rainfed rice areas of the watershed and was found to be more productive and more profitable.

1. Introduction

Presently, all types of arable land ecologies in eastern India are dominated by rice cultivation, irrigated and rainfed. Nevertheless productivity is low (Kar et al., 2004). Sustainable, alternative land use planning based on potentials of soil hydro-physical properties of land are essential to enhance productivity in the region. Land use planning on watershed basis has already proven highly beneficial as well as economical and ecologically protective in different parts of the world to enhance crop production because it relates to the development of all types of land (up, medium and low) ecosystems (Wilkin and Hebel, 1982; Mellerowicz et al., 1994). With the advent of advanced tools such as satellite remote sensing, Geographic Information System (GIS), Global Positioning System (GPS), which were used in many earlier works (Allewijn, 1988; Kite and Kouwen, 1992; Chakravorty, 1993; Krishnamurty et al., 1996), appraisal and assessment of the potentials of existing natural resources of a watershed have become much easier. Remote sensing technology provides a reliable, near real time base line information on existing land use and is relatively faster and more economical for gross estimations of soil and land resources as compared to any other method of surveying. The GIS is useful to develop action plans on alternative land use planning based on the potential of existing natural resources. In this study, an alternative, sustainable land use planning for the watershed was developed based on potential and prospects of soil hydro-physical properties, using remote sensing and GIS techniques. The morphometric parameters were directly related to fluvial characteristics of the basin (Horton, 1945; Longbein, 1949) and provided information on the lithology, structure, relative infiltration, runoff and erosion aspects of the basin, which have a marked influence on the occurrence and distribution of groundwater (Swamy et al., 2002). In this study, morphometric parameters were also analyzed to assess the potential of the watershed to implement an alternative land use planning.

After studying potential and prospects of soil hydro-physical properties and morphometric parameters, the proposed land use alternative was validated in rainfed rice areas representative for the watershed.

Soil water retention and available water capacity are the main determining factors for characterizing sustainable cropping system and crop growing period (Otriz et al., 1997). These soil

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properties may be determined directly, using laboratory methods (by measuring soil water content over a range of matric pressure heads), or indirectly by relating water retention functions (pedo-transfer functions) to some easily measured soil physico-chemical parameter such as soil texture, oven-dry bulk density, organic carbon, cation exchange capacity, etc. (Pachepsky et al., 1996; Elsenbeer, 2001; Tomasella et al., 2003). Thus, estimating soil hydraulic properties through pedo-transfer functions can be an alternative to troublesome and expensive measurements (Cornelis et al., 2001; Nemes et al., 2003; Romano and Santini, 1997; Romano and Palladino, 2002; Kern, 1995; Minasny et al., 1999). In this research paper pedo-transfer functions of agricultural field were likewise developed to predict soil water constants using easily measured parameters such as cation exchange capacity, organic carbon, oven-dry bulk density, soil texture, calcium carbonate, etc.

2. Materials and methods

2.1. Study watershed

The study was undertaken in Bahasuni watershed [20° 35′ to 20° 39′ N latitude and 85° 32′ to 85° 35′ E longitude] of Dhenkanal district, Orissa, India (12.85 km^2 area). The climate of the area was characterized by a hot and sub-humid climate with a mean monthly maximum temperature of 44 °C in May and a mean monthly minimum temperature of 9.3 °C in December. The highest flood level at the outlet was 85 m above mean sea level (msl). Highest and lowest topographic elevations were 440 and 82 m msl, respectively, and the majority of the slopes varied from very gently (1–3%) to gently sloping (3–5%). For the studied watershed, area, perimeter and stream length were computed as 12.85 km^2, 16.41 and 4.99 km, respectively,

2.2. Analysis of existing land use/land cover of the watershed

To develop an alternative and sustainable land use plan, the existing land use pattern of the watershed was first studied (Table 1). Based on the spectral signature and radiometric resolution of satellite imagery, different categories of the existing land use pattern were identified by using a supervised classification. The supervised classification was carried out in a stratified manner for both winter (dry) and rainy (wet/*kharif*) seasons, using IRS-P6, LISS-IV MX (October 2004, January 2005) satellite imagery, through a maximum likelihood classifier. In supervised classification, a prior knowledge of the land use/land cover characteristics is gathered through *ground truthing* before classification. Ground truthing refers to the acquisition of knowledge about the study area from fieldwork analysis, aerial photography, or personal experience. Additionally, global positioning system (GPS) receivers were used to collect training sites and ground information. The resolution of the satellite data was 5.8 m.

Table 1
The existing land use pattern in the watershed.

Serial no.	Land use type	Area (ha)	% of total area
01	Water body	11.65	0.90
02	Upland rice	178.89	13.91
03	Lowland rice	48.57	3.77
04	Forest plantation	148.93	13.60
05	Built up area	2.65	0.20
06	Barren rocky	15.11	1.17
07	Current fallow	154.36	12.00
08	Grazing land	147.69	11.48
09	Reserve forest	288.78	22.46
10	Degraded or scrub land	224.65	18.79
11	Ravenous land	19.4	1.50
12	Rubber plantation	2.02	0.15

Total area 1285.7.

2.3. Determining spatial distribution of existing soil hydro-physical properties

Soil hydro-physical properties along with the topography are the main determining factors to develop optimal crop planning. In this study, grid profile sampling (250 m × 250 m) was done during field campaigns to assess soil hydro-physical properties in different parts of the watershed. Water retention at field capacity and at wilting point and available water capacity was estimated by using a pressure plate apparatus. The processed soil samples (<2 mm size) were analyzed for their mechanical composition (soil texture analysis) following the international pipette method. The spatial distribution of soil texture was derived from IRS-P6 (LISS-IV) satellite imagery based on the basic elements of image characteristics like tone, texture, shape, size, pattern, association, etc., along with extensive ground truth observations and textural analyses (International Pipette method). The organic carbon content of the soil was determined by following standard procedures. Organic carbon, soil water constants, soil texture, oven-dry bulk density, cation exchange capacity (CEC) and calcium carbonate at 0.15, 0.15–0.30, 0.30–0.60, 0.60–0.90 and 0.90–1.2 m soil depths of agricultural land were used to develop pedo-transfer functions. Soil oven-dry bulk density was estimated on undisturbed samples collected with metal cores of 4.2 cm diameter and 5.8 cm height.

A slope map was prepared from the contours of the Survey of India Toposheet. The slope percentage was calculated as,

$$\frac{\text{vertical drop}}{\text{horizontal distance in between contours}} \times 100$$

After preparing individual thematic maps of available water capacity, soil texture, organic carbon, land use, and slope from different sources, they were scanned and on-screen digitized using Raster to Vector (R2 V) software to form ARC INFO GIS coverage. The digitized map, i.e. vector layers of different thematic coverage, was then cleaned and checked for errors like dangles and pseudonodes. After removing the errors, a layer was built for topology by using commands in the PC ARC/INFO 4.0 GIS package. Each coverage was projected using a 'Polyconic Projection' and 'Spheroid Everest' geoid system in order to estimate the area of different classes for a particular theme. Arc View (Version 3.8.1) GIS software was used for spatial analysis through query building tools after integrating all individual thematic coverage into a composite land development unit (CLDU) map.

2.4. Development of an action plan on sustainable land use and cropping systems in the watershed

Based on the potentials of the existing soil hydro-physical properties (soil texture, available water capacity, organic carbon) and the topography, a sustainable and alternative land use plan was developed for different parts of the watershed. The criteria to that purpose are given in Table 2. The entire methodology starting from the preparation of a digital database of soil hydro-physical properties to the development of an action plan is presented in Flowchart 1.

In light textured upland areas, rice was discouraged according to the action plan because of its low and unstable productivity and crop diversification with low water requiring crops (maize, groundnut, blackgram, cowpea, pigeonpea) was suggested through sole or intercropping. Double cropping on such soils was suggested through maize-horsegram/sesamum rotation. The idea of crop diversification in light textured, upland soils emphasizes that these crops can provide an assured income in soils with low water

Table 2
Action plan on alternative proposed sustainable land use system in the watershed.

Present land use system	Texture	Organic matter range (%)	Available water capacity range ($m^3 m^{-3}$)	Slope range (%)	Proposed land use system
Current fallow	Sandy	0.29	0.108–0.128	3–5%, 5–10%	Horticulture (cashew, lemon)
Rainfed rice	Sandy loam	0.29–0.63	0.12–0.139	1–3%, 3–5%	Crop diversification (groundnut, pigeonpea, groundnut + pigeonpea)
Current fallow	Sandy loam/sandy clay loam	0.35–0.65	0.128–0.140	1–3%	Crop diversification (groundnut, pigeonpea, groundnut + pigeonpea)
Grazing land	Sandy loam, loam	0.40–0.68	0.118–0.135	1–3%, 3–5%	Agroforestry
Open forest	Loam, sandy loam	0.62	0.111–0.123	3–5%, 5–10%	Hortipasture/Silvipasture
Rubber plantation	Sandy loam	0.45	0.129–0.139	3–5%	Plantation
Degraded land	Sandy, sand loam	0.29–0.45	0.106–0.145	3–5%	Hortipasture/Silvipasture
Reserve forest land	Sandy loam	0.38–0.52	0.119–0.199	>35	Silvipasture
Residual hills	Sandy loam	0.38–0.42	0.119–0.123	3–5%	Silvipasture
Rice (100 days)—fallow	Sandy loam	0.38–0.45	0.109–0.123	1–3%, 0–1%	Maize (90 days)-horsegram or vegetables (bean, gourd, ladies finger)
Rice (125 days)—fallow or rice (140 days)—fallow with irrigation facilities	Clay loam, loam	0.58–0.75	0.168–0.188	0–1%, 1–3%	Sun flower, potato, tomato, bean, marigold, carrot, radish, groundnut, winter maize
Rice (100 days)—fallow	Clay loam	0.65–0.68	0.220–0.257	3–5%	Maize (90 days)-horsegram or rice + pigeonpea
Rice (125 days)—fallow	Loamy sand	0.52–0.68	0.194–0.239	1–3%, 3–5%	Rice (120 days)-linseed/safflower
Rice (125 days)—fallow	Clay loam	0.45–0.68	0.257–0.285	1–3%, 3–5%	Rice (120 days)-linseed/safflower
Rice (125 days)—fallow	Clay	0.70–0.75	0.257–0.306	0–1%, 1–3%	Rice (120 days)-linseed/safflower
Rice (145 days)—fallow	Clay loam	0.52–0.68	0.227–0.257	1–3%	Rice (150 days)-pea/blackgram
Rice (145 days)—fallow	Sandy loam	0.50–0.52	0.173–0.195	3–5%, 1–3%	Rice (150 days)-pea/blackgram
Built up land	–	–	–	–	Rural settlement

retention capacity or low rainfall because the water requirement of these crops is below that of rice.

On the other hand, in the rainfed rice ecosystem with moderate available water capacity and medium textured soil (represents 25 ha in the watershed), rice of 120 days was suggested during the rainy season. Low water requiring crops like blackgram, linseed or safflower were advocated to grow during the dry season (winter) by utilizing carry-over, residual soil moisture left after the harvesting of rice. In the lowland valley area with heavy textured soil and higher available water capacity, a cropping system based on rainfed rice was suggested and implemented through rice (145 days)-pea/blackgram/chickpea rotation. Agro-forestry, horti-pasture, horticultural plantations like cashewnut (*Anacardium occidentale* L.), pomegranate (*Punica granatum* L.) or ber (*Zizyphus mauritiana* Lamk) plantations were furthermore suggested to grow in upland degraded forest areas where arable crop cultivation was impossible. Grazing lands could be converted into agro-forestry or horti-pasture depending upon the slope and the available water capacity of the soils.

2.5. On-farm implementation of action plan in different rainfed rice areas

As per the developed action plan on alternative land use (Table 3), the proposed land use/cropping system was implemented in rainfed rice areas of the watershed. The suggested cropping system was tested in three types of rainfed land situations viz., unbunded light textured upland, medium textured soil (bunded) and heavy textured lowland.

Table 3
Area under alternative land use system in the watershed.

Alternative land use	Proposed area (ha)	% of total
Agro-forestry	62.8	4.89
Crop diversification	221.8	17.26
Forestry	91.4	7.11
Horti-pasture	225.7	17.56
Plantation crops	15.2	1.18
Rice-based double crops	54.1	4.21
Silvipature	541.3	42.12
Soil conservation	19.4	1.51
Barren rocky	15.1	1.18
Rural settlement	26.7	2.06
Water body	11.6	0.90
Total	1285	

2.5.1. On-farm trial in rainfed upland

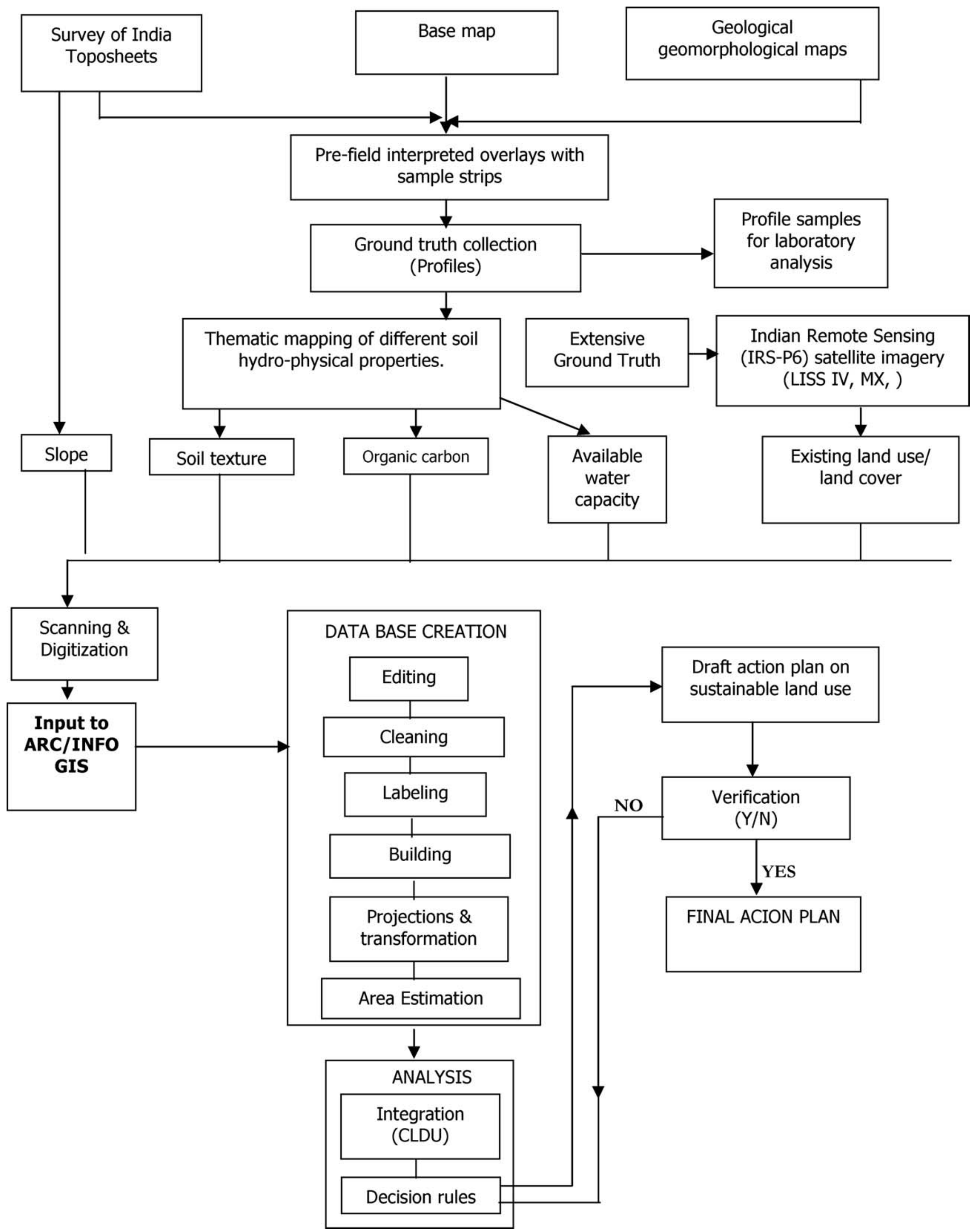
Since rice productivity in rainfed light textured upland was not economical, in the study, emphasis was given to substitute rice with direct seeded, low water requiring, drought tolerant crops. Under this experiment, productivity and net returns of five crop combinations *viz.*, sole pigeonpea (*Cajanas cajan* L. Millsp.), sole groundnut (*Arachis hypogaea* L.), sole blackgram (*Vigna mungo* L. Hepper), groundnut + pigeonpea and groundnut + blackgram were compared with that of sole rice (*Oryza sativa* L.) to explore the possibility of crop diversification in rainfed upland rice soils of eastern India. The treatments were executed in six farmers' field of 2 ha area, considering one farmer as one replication. The crop rows were placed across the slope and excess water was disposed off through grass waterways to avoid breaching of ridges. Rice of 90 days duration (cv. Vandana) was grown as a control.

2.5.2. On-farm trial in lowlands with medium textured soils

As per the action plan, improved rice variety "Lalat" of 120 days duration was grown in medium textured soils (instead of local varieties), during rainy season with improved management. During winter season (dry season), the low water requiring crops safflower (*Carthamus ticntorius* L.), linseed (*Linum usitatissimum* L.) and greengram (*Vigna radiata* L. Wilczek) were advocated and tested in 2 ha area, utilizing winter rainfall and carry-over, residual soil moisture remaining after harvesting the rice. The productivity of double crops (rice-linseed/safflower/greengram) was converted into rice equivalent yield and compared with that of sole rice to visualize the enhancement of yield after introduction of new cropping system.

$$\text{rice equivalent yield (kg/ha)} = \frac{\text{yield of alternative crops (kg/ha)} \times \text{price of the crop (Rs./kg)}}{\text{price of rice (Rs./kg)}}$$

Sole rice of 120 days duration was grown as a control under both improved and farmers' management practices. The treatments were



Flowchart 1. Flowchart of preparing digital database of soil hydro-physical properties and development of action plan.

executed in five farmers' field of 2 ha area, considering one farmer as one replication.

2.5.3. On-farm trials in lowlands with heavy textured soils

In the rainfed rice area with higher available water capacity and heavy textured soils, improved rice variety 'Gayatri' of 150 days duration (cv. Gayatri) was grown during the rainy season with both farmers' and improved management practices. As per the action plan during winter season (dry season), pea (*Pisum sativum* L.), blackgram (*V. mungo* L. Hepper) and chickpea (*Cicer arietinum* L.) were grown after harvesting rice, utilizing carry-over residual soil moisture. The treatments were executed in five farmers' field of 2 ha area, considering one farmer as one replication.

2.6. Morphometric analysis of the watershed

The drainage lines of the watershed were extracted from the Toposheet of 1:50,000 scale and updated with the help of remote sensing satellite imagery (IRS-P6) of October 2004. The updated drainage lines were used as input to ARC/INFO GIS software for analysis of different morphometric parameters of the watershed. Morphometric parameters of the basin like linear aspects and size, shape, relief and texture were determined.

(A) Linear aspects of drainage network

(i) *Stream order*: Stream order, 'w', was determined using Horton–Strahler's stream network classification system. According to this, a first-order stream is the smallest un-branched stream, originating at a source. Two first-order streams join to form a second-order stream. Likewise when two streams of order 'w' join, a stream of order '$w+1$' is created. On the other hand, when two streams of different order, say 'w' and '$w+2$', join, the stream segment immediately downstream retains the higher of the orders of the two combining streams and will consequently have the order '$w+2$'.

(ii) *Stream length* (L_w): Total basin stream length is defined as the sum of the stream lengths of all orders.

(iii) *Bifurcation ratio* (R_b): Bifurcation ratio is the ratio of the number of streams of lower order to the number of streams of the next higher order. This is a dimensionless figure and shows only a small variation from one region to another because watersheds in homogenous material tend to manifest geometric similarity.

(B) Basin size

(i) *Basin area* (A_w) of a watershed of order 'w' is defined as the area of a horizontal projection of the total area contributing overland flow to the stream segment of the given order and all segments of lower order.

(ii) *Basin perimeter* (L_p) represents the length measured along the border or divide of the drainage basin of a given order as projected on to the horizontal plane of the map.

(iii) (iii) *Basin length* (L_b) is defined as the longest dimension of a basin parallel to the principal drainage line.

(C) Basin shape:

(i) *Form factor* (R_{ff}) is a dimensionless parameter defined as the ratio of basin area, 'A_w', to the square of basin length, 'L_b^2'.

$$R_{ff} = \frac{A_w}{L_b^2}$$

(ii) *Circulatory ratio* (R_c) is a dimensionless parameter defined as the ratio of the basin area of a given order, 'A_w', to the area 'A_p' of a circle having a circumference equal to the basin perimeter, 'L_p'.

$$R_c = \frac{A_w}{A_p} = \frac{4\pi A_w}{L_p^2}$$

The value of 'R_c' tends to approach 1 as the shape of the basin approaches a circle.

(iii) *Elongation ratio* (R_e) of a basin is defined as the ratio of the diameter of a circle, 'D_c', with the same area as that of the basin to the maximum length, 'L_b'.

$$R_c = \frac{D_c}{L_b}$$

(iv) *Basin shape factor* (R_s) is defined as the ratio of the mainstream length, 'L_b', to the diameter, 'D_c', of a circle having the same area as the watershed.

$$R_s = \frac{L_b}{D_c} = L_c\sqrt{\frac{4A_w}{\pi}}$$

(D) Basin relief

(i) *Total basin relief* (H) is the maximum vertical distance between the lowest (outlet) and the highest (divide) points in the watershed.

(ii) *Relief ratio* (R_h) is a dimensionless quantity, defined as the ratio of the basin relief, 'H', to the horizontal distance along the longest dimension of the basin parallel to the principal drainage line, 'L_b'.

$$R_h = \frac{H}{L_b}$$

(iii) *Relative relief* (R_p) is defined as the ratio of basin relief, 'H', to the basin perimeter, 'L_p'.

$$R_p = \frac{H}{L_p}$$

(iv) *Ruggedness number* (R_n) is a dimensionless quantity defined as product of the basin relief, 'H', to the drainage density, 'D', where both terms are in the same units.

$$R_n = H \times D$$

(E) Basin texture

(i) *Drainage density* (D) is defined as the ratio of the total length of all streams within a watershed to the watershed area, 'A_w' (Horton, 1945).

$$D = \frac{\sum_{i=1}^{W}\sum_{j=1}^{Ni} L_{ij}}{A_w}$$

where L_{ij} is the stream length of ith order and jth segment, W is the basin order and N_i is the total number of segments of ith order streams.

(ii) *Fineness ratio* (R_f) is defined as the ratio of the channel lengths to the basin perimeter. This parameter is a measure of topographic fineness.

(iii) *Stream frequency* (C_f) or channel segment frequency is defined as the total number of streams per unit area, or the ratio of the total number of segments to the watershed area, 'A_w' (Horton, 1945).

$$C_f = \frac{\sum_{w=1}^{Ni} N_w}{A_w}$$

where N_w is the number of streams of order w and W is the basin order.

3. Results and discussion

3.1. Existing land use of the watershed

The land use categories of the watershed were analyzed using IRS-P6 data, GPS survey and extensive ground truthing. The area under each land use class is given in Table 1 and their spatial distribution is given in Fig. 1. Altogether 12 classes of land use, i.e. water body, upland rice, low land rice, forest plantation, built-up area, barren rocky, current fallow, grazing land, reserve forest, degraded or scrub land, ravenous land rubber plantation were identified in the watershed with the help of satellite imagery and ground observations. The watershed was mainly dominated by forest, and grazing land. Only 16% of the watershed's area was covered by arable land, namely 149 and 48 ha under 'upland' and 'lowland agricultural field', respectively. There were five small ponds inside the watershed.

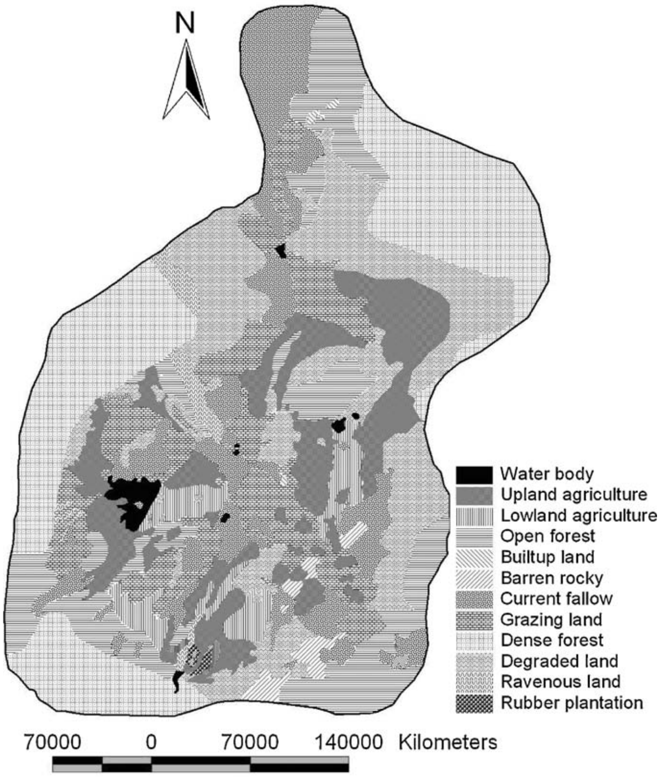


Fig. 1. Existing land use system of the watershed.

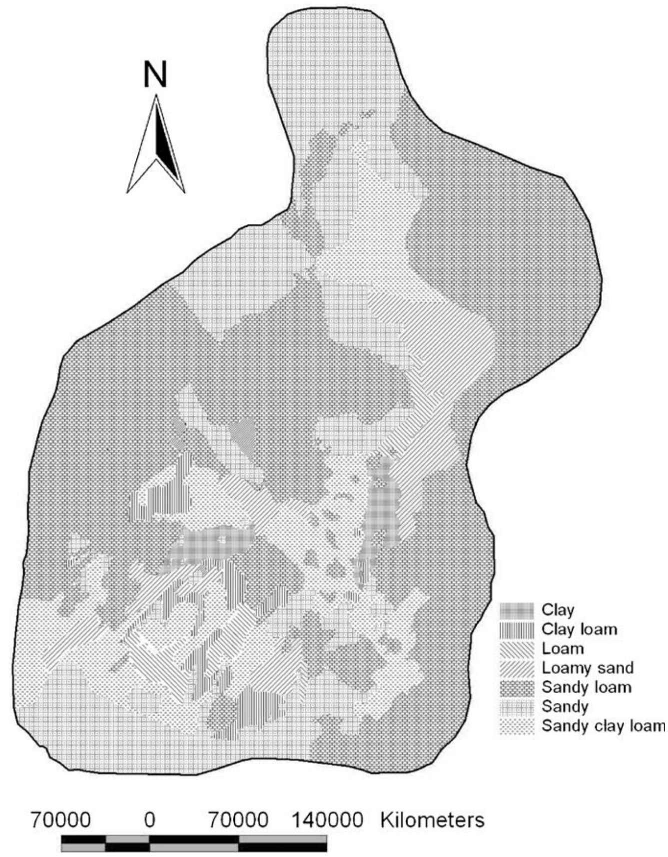


Fig. 2. Spatial distribution of soil texture.

3.2. Spatial variability of soil texture

The soil texture of 0–0.30 m depth was geo-spatially mapped and is presented in Fig. 2. The data indicated that sandy loam was the main soil texture at 0–0.30 m depth, covering an area of 628 ha, followed by sand (298 ha) and sandy clay loam (185 ha). Coarse textured soils were mainly found in unbunded, upland areas, whereas the heavy textured soils occurred in lowland valley fill areas. Clay soils were found in lowland valleys which represented 25 ha in the watershed and in which residual soil water can be expected after harvesting the rainy season rice.

3.3. Spatial distribution of available water capacity of soils

The available water capacity in different parts of the watershed was organized into 6 classes *viz.*, 0.10–0.12, 0.12–0.14, 0.14–0.16, 0.16–0.18, 0.18–0.20 and >0.20 $m^3\ m^{-3}$. Their spatial distribution is presented in Fig. 3. Study revealed that most of the area fell into the category of water storage capacity 0.14–0.16 $m^3\ m^{-3}$, followed by the categories 0.16–0.18 and 0.12–0.14 $m^3\ m^{-3}$.

3.4. Spatial distribution of soil organic carbon

The organic carbon content was low in several parts of the watershed and was the main cause for the low fertility status of soils. The geo-spatial distribution of the organic carbon (%) for the upper soil profile (0–0.30 m) is depicted in Fig. 4. In different parts of the watershed, it ranged between 0.25% and 0.85%, indication of a low organic carbon content status. Organic carbon was very low in the light textured soil (0.3–0.4%) upland and hence, mono-culture, rice-based agriculture should be avoided. Integrated nutrient management including inclusion of legumes in the cropping system during the rainy season and addition of organic

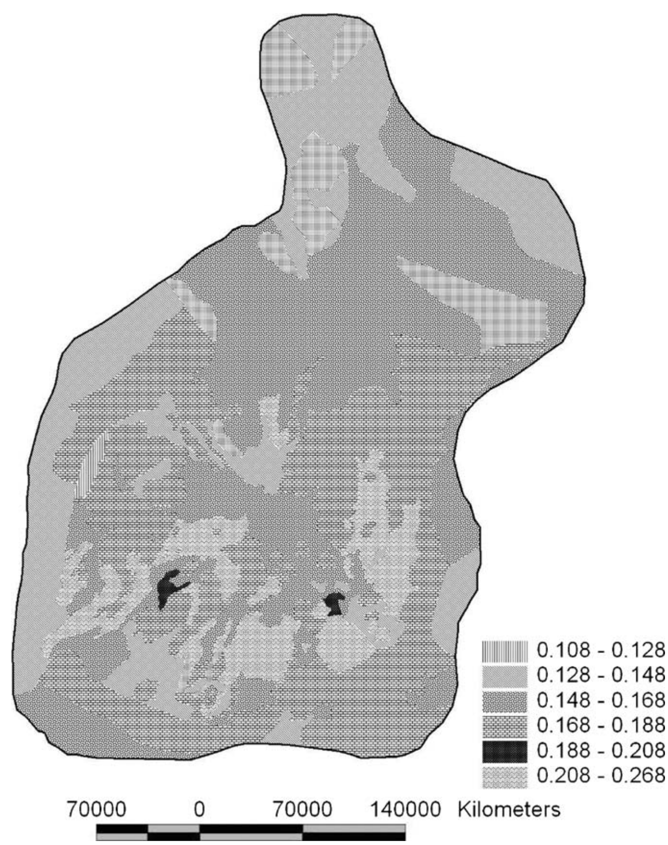


Fig. 3. Spatial distribution of available water capacity ($m^3\ m^{-3}$).

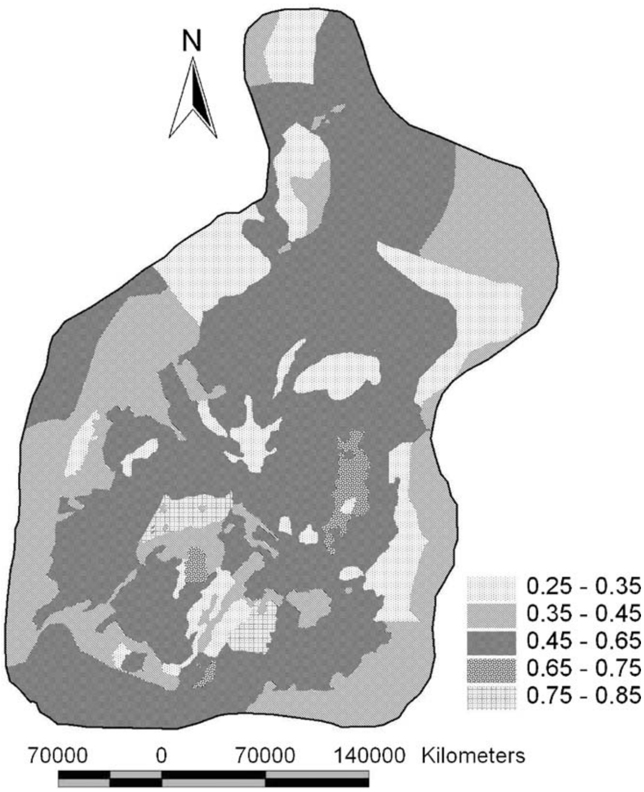


Fig. 4. Distribution of organic carbon (%) through out the watershed.

matter is advocated to sustain the soil fertility of such soils with higher and assured net economic return. In medium to heavy textured soils with lowland topography, a majority of the areas was having an organic carbon content of 0.65–0.75%.

3.5. Slope map

The slope map was derived from the contour map and is presented in Fig. 5. Study revealed that a majority of the slopes fell under 'very gentle slope' (1–3%), the area being 612 ha. Gentle slopes (3–5%) were found in an area of 420 ha where soils were light to medium textured and fields were unbunded or bunded. Higher slopes (>35%) were found in residual hills or degraded forest areas.

3.6. Drainage pattern

The drainage patterns are good indicators of land form and bedrock type and also suggest soil characteristics of the region. Study revealed that the predominant drainage pattern of the watershed was dendritic, indicating the existence of rocks with uniform resistance to erosion. A 'dendritic' pattern is the irregular branching of channels ('tree like') in many directions, common in massive hard rock terrains especially in granite and gneiss rock and flat lying areas. This pattern develops where rocks are devoid of marked structural control, suggesting uniform resistance to erosion in the watershed. The drainage network of the watershed is given in Fig. 5. The drainage lines of the watershed along with the slope have been used for morphometric analyses.

3.6.1. Linear aspects of drainage network

Stream order, stream length and bifurcation ratio are the main linear aspects of a channel system in watersheds. In the selected watershed there were 38 first-order, 13 second-order, 8 third-order and 1 fourth-order channel (Table 4). The mean length of a stream-channel segment of a particular order reveals the characteristic size of components of the drainage network and

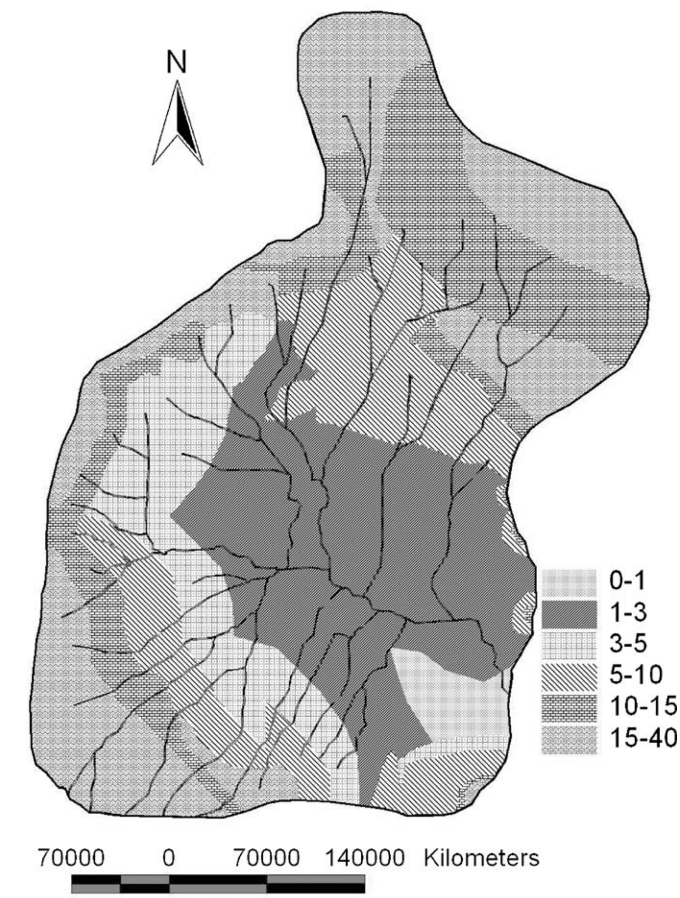


Fig. 5. Slope (%) and drainage map of the watershed.

Table 4
Analyzed morphometric parameters of watershed.

Serial no.	Parameter	Value
1	No. of stream of order 1 (w_1)	38
2	No. of stream of order 1 (w_2)	13
3	No. of stream of order 1 (w_3)	08
4	No. of stream of order 1 (w_4)	01
5	Mean length of order 1 (11) (m)	87.4
6	Mean length of order 1 (12) (m)	484
7	Mean length of order 1 (13) (m)	1142
8	Mean length of order 1 (14) (m)	1784
9	Total watershed area (A_w) (km^2)	12.85
10	Watershed perimeter (L_p) (km)	16.41
11	Basin length (L_p) (km)	4.99
12	Total length of streams of all order ($w_1 + w_2 + w_3 + w_4$) (m)	34074.2
13	Drainage density (D) (km/km^2)	2.7
14	Stream frequency (C_f) (km^{-2})	0.032
15	Fineness ratio (R_f)	2.07
16	Form factor (R_{ff})	0.498
17	Circularity ratio (R_c)	0.579
18	Elongation ratio (R_e)	0.398
19	Basin shape factor (R_s)	12.78
20	Bifurcation ratio (R_b)	3.05
21	Total relief (H) (m)	358
22	Relief ratio (R_h)	0.0716
23	Relative relief (R_p)	0.0218
24	Ruggedness number (R_n)	0.716
25	Hypsometric integral (Hy)	0.45

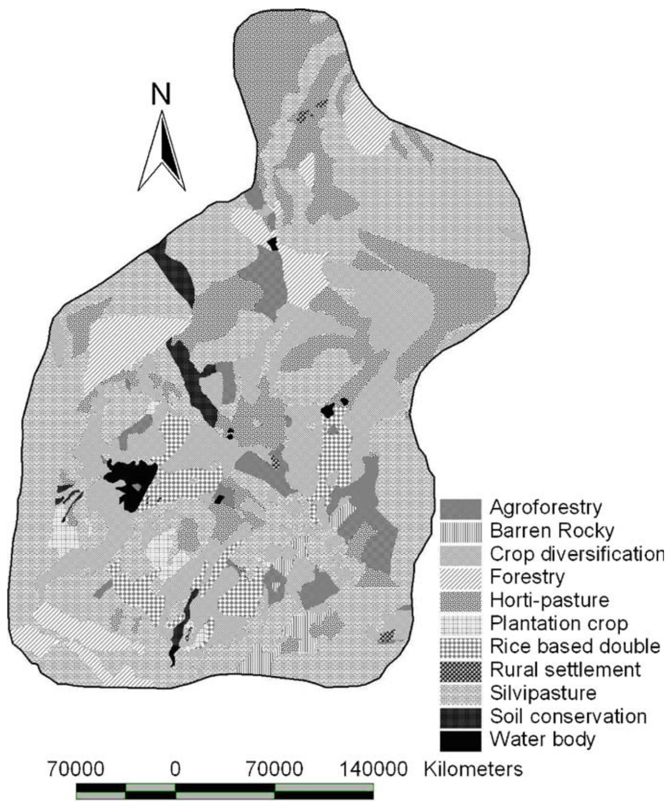


Fig. 6. Proposed alternative land use system in the watershed.

its contributing basin surfaces. It was found that the mean length of first-order channels was 873.8 m, the length of second-order channels was 483.6 m, while the length of third- and fourth-order channels were 1142 and 1784 m, respectively. Bifurcation ratio of the watershed was 3.05, which is a moderate one. With such a bifurcation ratio, the studied watershed is elongated in north to south direction, suggesting that the basin experiences neither extended steep flows nor sharp peak flows but moderate ones. The higher the bifurcation ratio, the more numerous lower order streams are and, as a result, the larger will be the sediment yield. Generally, when geometrical similarity is not maintained by drainage channels in the basin, a minimum value of 2.0 may occur. On the other hand, a high bifurcation ratio can be observed in a basin with steep dipping rock strata.

3.6.2. Basin size

Watershed area (A_w), perimeter (L_p) and basin length (L_b) are the three parameters which determine basin size. For the studied watershed, area, perimeter and stream length were computed as 12.42 km^2, 16.41 and 4.99 km, respectively, which are moderate values (Table 4). With increase in basin length and basin area, sediment yield increases.

3.6.3. Basin shape

The circulatory ratio and elongation ratio are the main basin shape parameters which determine intensity of erosion and occurrence of floods in the basin. The value of these parameters ranged between 0 and 1. Low values reflect an elongated shape of the basin. The circulatory ratio of the present watershed was calculated as 0.56 indicating the shape of the basin is fairly elongated and the area is not prone to flood. On the other hand, an elongation ratio of 0.398 was computed for the watershed, indicating a strong relief as well as a wide variety of soils and geologic type features.

3.6.4. Basin relief features

Total relief of the basin is the difference in the elevation of the highest point (upper reach) and lowest point (basin outlet), which determines the intensity of erosion and floods. The total relief of the watershed was 358 m and the relief ratio was 0.0716, which indicates moderate erosive force and sediment yield. The relative relief is the ratio of the relief of the basin to the perimeter of the basin and is an indicator of potential energy available in the drainage basins for the soil erosion process. In the studied watershed, relative relief was computed as 0.0218, indicating that, in the drainage basin, the potential energy for the soil to erode is low.

3.6.5. Basin texture

Main factors that determine basin texture are drainage density, fineness ratio and stream frequency. The drainage density of the basin affects runoff. The higher the drainage density, the greater will be the runoff. Lower drainage densities indicate the presence of permeable formations in the sub-surface, which can be found in regions of high resistance or highly permeable sub-soil materials, under dense vegetation cover. High drainage densities occur in regions of weak or permeable sub-surface materials, sparse vegetation and mountainous relief. In the study area, the drainage density was computed as 2.7 km per square km, which is relatively low. It indicates that the watershed has a low relief, permeable strata and moderate runoff. The fineness ratio and stream frequency were computed as 2.07 and 0.032 km^{-2} respectively, which also indicate low surface runoff and sediment yield. The larger the stream frequency, the larger the surface runoff, consequently the more sediment yield.

From the morphometric analyses, it can be concluded that the watershed is elongated and not prone to flood neither to erosion. The drainage density of the watershed was relatively, indicating permeable strata and moderate runoff. This is promising for groundwater recharge, thus pointing to potential areas for groundwater development, which is further confirmed by the low value of the circulatory ratio. The moderate bifurcation ratio indicates a strong relief and a wide variety of soils and geologic features. Circulatory ratio of 0.57 is an indication of a higher order basin in quartzites.

3.7. Pedo-transfer functions for prediction of soil water constants and available water capacity from agricultural land

Since direct measurements of water retention characteristics over large areas are expensive, burdensome and tedious, in this investigation some of the more easily measured soil physical and chemical properties of agricultural land were determined. From these, pedo-transfer functions were derived through regression equations in order to predict available water capacity and water content at field capacity and permanent wilting point. The correlation matrix for different hydro-physical properties viz., sand, silt and clay fraction, bulk density, organic carbon, calcium carbonate and cation exchange capacity on water content at field capacity, wilting point and available water was computed and the result is presented in Table 5. Study revealed that moisture retention at field capacity, wilting point and available water in these soils was influenced by two sets of factors which had effects in opposite direction. One set of factors *viz.*, silt, clay, organic carbon, calcium carbonate and cation exchange capacity, had a positive influence, while sand and bulk density a negative one. The available water content was also influenced by the same set of factors and in a similar manner.

Water content at field capacity and wilting point had a good correlation with clay ($r = 0.83^{*}$ and 0.90^{*}, respectively) and cation exchange capacity ($r = 0.76^{**}$ and 0.79^{**}, for field capacity and

Table 5
Correlation matrix of different soil hydro-physical parameters.

Sand (%)	Silt (%)	Clay (%)	Bulk density carbon (%) (Mg/m^3)	Organic (%)	$CaCO_3$ (me/100 g)	CEC θ (F.C) (m^3 m^{-3})	θ (PWP) (m^3 m^{-3})	θ (AWC) (m^3 m^{-3})		
Sand (%)	1									
Silt (%)	−0.83*	1								
Clay (%)	−0.46*	0.51*	1							
Bulk density (Mg/m^3)	0.63*	−0.60*	−0.62*	1						
Organic carbon (%)	−0.12	0.18	−0.13	−0.53*	1					
$CaCO_3$ (%)	−0.53*	0.49*	0.53*	−0.59*	0.11	1				
CEC (me/100 g)	−0.68*	0.51*	0.85*	−0.61*	0.12	0.53*	1			
θ (F.C) (m^3 m^{-3})	−0.80*	0.63*	0.83*	−0.59*	0.13	0.54*	0.76*	1		
θ (PWP) (m^3 m^{-3})	−0.72*	0.59*	0.90*	−0.59*	0.14	0.56*	0.79*	0.89*	1	
θ (AWC) (m^3 m^{-3})	−0.73*	0.75*	0.60*	−0.64*	0.196	0.58*	0.63*	0.90*	0.78*	1

CEC, Cation exchange capacity; PWP, permanent wilting point; FC, field capacity, AWC = available water capacity.
* $P < 0.05$.

wilting point, respectively). They were also significantly but negatively associated with sand and bulk density indicating that with increase in value of either sand or bulk density or with decrease in magnitude of clay, silt or cation exchange capacity, water content, θ (m^3 m^{-3}), of these soils at field capacity and wilting point, decreased. Available water showed positive correlation coefficient values with silt, clay, calcium carbonate and cation exchange capacity and negative values with sand and bulk density. These results were in good agreement with those of studies earlier under Indian conditions (Das and Dutta, 1997; Kar et al., 2004). Stepwise regression equations were also developed to predict field capacity, wilting point and available water capacity from measured soil physico-chemical properties. This is presented in Table 6.

3.8. Results of implementation of action plan

As per the action plan (Fig. 6) discussed in Section 2, alternative cropping system was implemented in rainfed rice areas for validation of plan. Based on the results of an implementation lasting for 2 years (2005 and 2006), the alternative cropping system was found to be productive and profitable (Figs. 7–9).

3.8.1. Enhancement of productivity in light textured unbunded upland

As per the action plan, in the rainfed upland, rice was substituted with diversified low water requiring crops like groundnut, pigeonpea or blackgram through sole crop or intercropping. The idea of crop diversification in light textured, upland, rainfed rice soils is based on the fact that the water requirement of these crops is lower then that of rice. Hence, these crops can provide an assured income on soils with low water retention capacity or in areas with low rainfall.

The productivity of different crops/crop combinations grown on light textured soils was converted into rice equivalent yield for better comparison. Study revealed that (average of 2 years of pooled data) (Fig. 7a) highest rice equivalent yield (6839 kg ha^{-1}) was obtained from groundnut + pigeonpea followed by sole

Table 6
Linear regressions ($y = bx + a$) for predicting soil water constants and available water.

a			*b*					R^2
Sand (%)	Silt (%)	Clay (%)	Bulk density (Mg/m^3)		Organic carbon (%)	$CaCO_3$	CEC (me/100 g)	
For field capacity (θ, m^3 m^{-3})								
1.51	−0.013	−0.103	−0.023	0.049	−0.003	0.019	0.012	0.81
−5.314	0.053	0.093	0.032	−0.113	−0.003	0.019	–	0.79
−9.314	0.111	0.115	0.119	−0.312	−0.063	–	–	0.87
−9.308	0.093	0.132	0.103	−0.192	–	–	–	0.78
−4.210	0.049	0.058	0.069	–	–	–	–	0.78
−0.708	−0.018	0.114	–	–	–	–	–	0.81
0.499	−0.014	–	–	–	–	–	–	0.82
0.501	−0.016	0.012	–	–	–	–	0.007	0.864
For wilting point (θ, m^3 m^{-3})								
8.798	−0.009	−0.098	−0.094	0.049	−0.019	0.019	0.003	0.76
6.83	−0.063	−0.071	−0.0712	−0.023	−0.019	0.017	–	0.83
3.59	−0.035	−0.039	−0.039	−0.089	−0.023	–	–	0.83
5.31	−0.057	−0.049	0.047	−0.041	–	–	–	0.84
5.99	−0.069	−0.069	−0.049	–	–	–	–	0.88
0.48	−0.009	0.0065	–	–	–	–	–	0.73
0.39	−0.006	–	–	–	–	–	–	0.76
0.38	−0.004	−0.006	–	–	–	–	0.002	0.79
For available water (θ, m^3 m^{-3})								
−7.91	0.084	0.089	0.083	0.0043	0.015	0.005	0.004	0.69
−11.41	0.129	0.132	0.129	−0.087	−0.017	0.006	–	0.71
−12.79	0.133	0.151	0.143	−0.119	−0.014	–	–	0.69
−13.89	0.157	0.149	−0.157	−0.141	–	–	–	0.63
−10.32	0.113	0.119	0.107	–	–	–	–	0.68
0.29	−0.013	0.004	–	–	–	–	–	0.64
0.31	−0.012	–	–	–	–	–	–	0.63
0.13	−0.003	0.004	–	–	–	–	0.003	0.60

y = Output (FC/PWP/AWC). x = inputs (soil physical and physico-chemical properties), a = constant, b = slope.

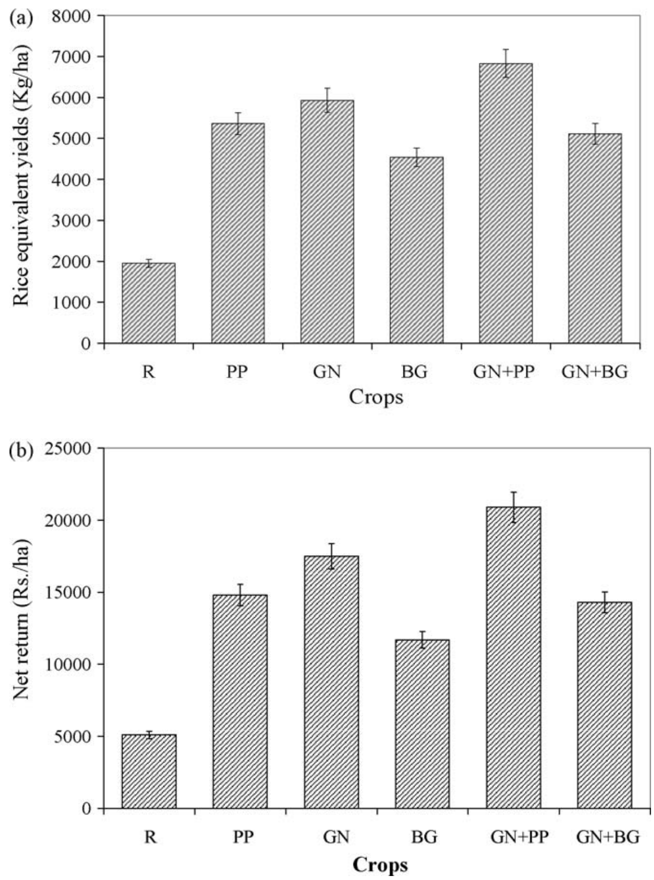


Fig. 7. (a) Rice equivalent yield from diversified crops in unbunded light textured upland. (b) Net return (Rs. ha^{-1}) from diversified crops in unbunded light textured upland.

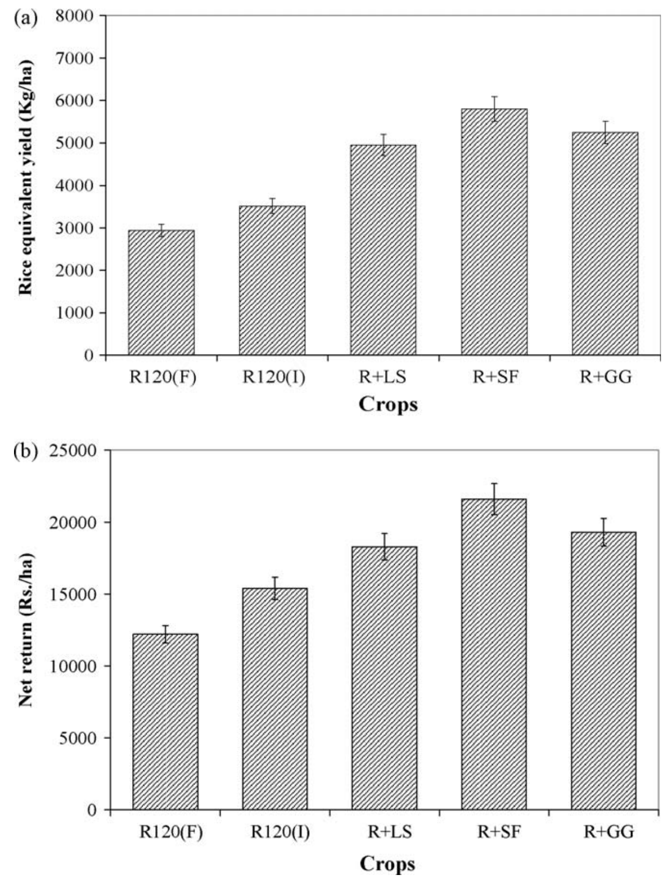


Fig. 8. (a) Rice equivalent yield of alternative cropping system in rainfed medium textured soils. (b) Net return (Rs. ha^{-1}) from alternative cropping system in rainfed medium textured soils.

groundnut (5940 kg ha^{-1}) and sole pigeonpea (5315 kg ha^{-1}) while sole rice produced only 1930 kg ha^{-1}. Higher net economic return per annum was also obtained from groundnut + pigeonpea followed by sole groundnut and sole pigeonpea (Fig. 7b). Study revealed that, through crop diversification in light textured upland rice soils, productivity and profitability were enhanced by 3–4 times that of sole rice or preceding farmers' practices.

3.8.2. Increasing productivity, profitability and cropping intensity in lowlands with medium textured soils

As per the action plan, improved rice variety ''Lalat'' of 120 days duration was grown in medium textured soils, instead of local varieties, during rainy season with improved management. During winter season (dry season), the low water requiring crops sunflower, linseed and greengram were advocated and tested in farmers' fields of 2 ha, utilizing winter rainfall and carry-over, residual soil moisture remaining after harvesting the rice. The productivity of double crops (rice-linseed/safflower/greengram) was converted into rice equivalent yield and compared with that of sole rice to visualize the enhancement of yield after introduction of new cropping system. Sole rice of 120 days duration was grown as a control under both improved and farmers' management practices. Rice equivalent yields of 5028, 5861 and 5307 kg ha^{-1} were obtained from rice-linseed, rice-safflower and rice-greengram cropping system, respectively (from the 2004–2005 and 2005–2006 pooled data), whereas sole rice produced only 3540 and 2870 kg ha^{-1} yield under improved and farmers' management, respectively (Fig. 8a). Study revealed that the productivity, cropping intensity and profitability of a medium textured, rainfed rice area can be improved through changing the cropping system and an effective utilization of residual soil moisture by second crops after rice (Fig. 8b).

3.8.3. Enhancement of productivity and profitability in lowlands with heavy textured soils and rainfed rice

In the rainfed rice area with higher available water capacity and heavy textured soils, improved rice variety 'Gayatri' of 150 days duration (cv. Gayatri) was grown during the rainy season with both farmers' and improved management practices. During winter season (dry season), pea, blackgram and chickpea were grown after harvesting rice, utilizing carry-over residual soil moisture.

The productivity of double crops (rice–pea/blackgram/chickpea) was converted into rice equivalent yield and study revealed that rice equivalent yields of 6458, 6378 and 5089 kg ha^{-1} were obtained from rice-pea, rice-blackgram and rice-chickpea, respectively (2 years of pooled data), whereas sole rice produced 3240 and 4050 kg ha^{-1} yield with farmers' and improved management, respectively (Fig. 9a). The net returns increased in the following order: sole rice (farmers' management), sole rice (improved management), rice-chickpea, rice-blackgram and rice-pea (Fig. 9b).

After implementing the alternative sustainable cropping system in representative, rainfed rice areas of the watershed, it was revealed that the suggested cropping plan was more productive, more profitable and more sustainable than before.

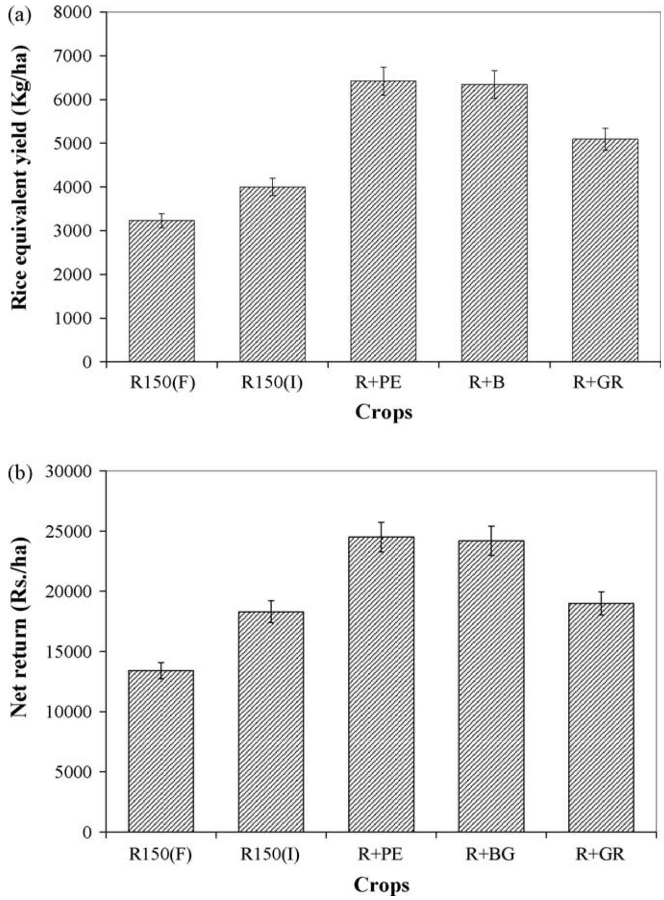


Fig. 9. (a) Rice equivalent yield from double crops in lowland with heavy textured soils. (b) Net return (Rs. ha^{-1}) from double crops in lowland with heavy textured soils.

4. Conclusion

This paper illustrates the application of satellite remote sensing and GIS for soil and other natural resources mapping of a watershed to develop alternative land use plans. Furthermore, the integration of SRS and GIS was found to be a very useful technique for land suitability classifications and in planning new alternative land use options. Pedo-transfer functions were developed, which will be useful in algorithms of simulation models for predicting soil water constants for large rainfed ecosystems of eastern India. After studying potentials and prospects of soil hydro-physical properties and morphometric parameters, a suggested land use alternative was implemented in representative, rainfed rice areas of the watershed and it was found to be more productive and more profitable.

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