

Terrain Characterization for Soil Resource Mapping Using IRS-P6 Data and GIS - A Case Study From Basaltic Terrain of Central India

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Abstract In the present study, landforms and soils have been characterized in Borgaon Manju watershed of basaltic terrain located in Akola district, Maharashtra, Central India. Terrain characterization using Shuttle Radar Topography Mission (SRTM) elevation data (90 m) and IRS-P6 LISS IV data in conjunction with adequate field surveys shows nine distinct landforms. Soil resource inventory shows fourteen soil series in the study area. Soils formed on gently sloping (3–8 %) subdued plateau are very shallow (23 cm), moderately well drained, moderate (15–40 %) surface stoniness, severely eroded, clayey and slightly alkaline in reaction, whereas, the soils formed on level to nearly level (0–1 %) slope in the main valley are very deep (>150 cm), well drained, very slight (<3 %) surface stoniness, moderately eroded with clayey surface and moderately alkaline in reaction. Soils in the watershed are grouped into Lithic Ustorthents, Vertic Haplustepts, Calcic Haplustepts, Typic Haplustepts, Typic Haplusterts and Sodic Calcisterts. The study demonstrates that the analysis of SRTM elevation data and IRS P6–IV data in Geographic Information System (GIS) with

adequate field surveys helps in characterization of landforms and soils in analysis of landscape-soil relationship.

Keywords Terrain characterization · Landforms · Soils resource mapping · GIS · Satellite remote sensing

Introduction

Soil is the base for every production system and knowledge on their properties, extent and spatial distribution at watershed level is extremely important for developing land use (Sarkar et al. 2006). Relationship between the landform position and pedological processes determine the soil attributes in a toposequence (Birkeland 1990; Moore et al. 1993 and Reddy et al. 1999). The geomorphic position on a toposequence plays a vital role for classification of landforms and characterization of soils. Landform units have been used as basic landform descriptors in soil resource mapping (Speight 1990). Soil-landform units are expected to be relatively homogeneous in terms of the main factors including parent material to identify dominant soil-geomorphic processes (Hengl and Reuter 2008). Landform maps are suitable predictors of soil types because soil development often occurs in response to the underlying lithology and water movement in the landscape (McKenzie and Ryan 1999; Ballantine et al. 2005). Terrain characterization and landform analysis of a terrain are essential to develop landscape-soil

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relationship for precise soil resource mapping, land degradation mapping and other environmental applications (Reddy et al. 1999; 2002). Guth (2003) have used SRTM (90 m) data in topography and geomorphological characterization. The soils develop in an organized manner on any given landform and a very close association exists between the different slope units of the landforms (Birkeland 1990). Wright (1993) carried out detailed geomorphological site analysis for natural resource inventories, clearly brought out the importance of such analysis in predicting the processes for precise mapping of an area. Reddy and Maji (2003) reported that analysis of IRS-ID LISS-III data in conjunction with distinct lithological units, drainage pattern and contour information improves the capability in delineation and characterization of geomorphological units.

Satellite remote sensing and GIS techniques are being effectively used in recent times in determining the quantitative description of the terrain features and geomorphological mapping (Reddy and Maji 2003). Although, individual images often show tremendous amount of spatial detail, the use of multi-temporal remote sensing databases complemented with terrain information was found to be very essential for deriving reliable soil categorization (Dobos et al. 2000; McBratney et al. 2000). Several authors have reported that the satellite remote sensing and GIS are proved as promising tools in soil resource mapping with visual interpretation of remotely sensed data (Srivastava and Saxena 2004; Reddy et al. 2008). In the interpretation of satellite image for soil resource mapping proper identification of land type, drainage pattern, vegetation, land use, slope and relief is very essential (Dwivedi 2001). The surface features reflected on satellite image provide enough information to accurately delineate the boundaries, which is accomplished effectively through systematic interpretation of satellite imageries (Velmurugan and Carlos 2009). The present study was undertaken to characterize the terrain, delineation of distinct landform units and inventory of soil resources to establish landform-soil relationship in Borgaon Manju watershed of basaltic terrain, Central India.

Study Area

Borgaon Manju watershed is located in hot semi-arid agro-ecological region of Deccan plateau and lies between 20°37' 00" to 20°49' 45" North latitudes and

77°03' 30" to 77°10' 15" East longitudes in Akola district of Maharashtra with a total geographical area (TGA) of 18,455.6 ha (Fig. 1). Except during the south-west monsoon season period, the climate of watershed area is characterized by hot summer and general dryness. In May, the mean daily maximum and minimum temperatures are 42.4°C and 27.5°C, respectively. In the month of December, the mean daily maximum and minimum temperatures are 29.3°C and 11.9°C, respectively. The mean annual rainfall of the study area is 833.7 mm, of which 90 % of annual rainfall received during the southwest monsoon (June–October). Geologically, the study area covers with basaltic lava Pahohoe flows of Karanja formations belongs to Upper cretaceous to Paleocene age (GSI 2000). The major crops grown in the watershed are cotton (*Gossypium spp.*), sorghum (*Sorghum bicolor*), pigeonpea (*Cajanus cajan*), bengal gram (*Cicer arietinum*), safflower (*Carthamus tinctorius L.*) and sunflower (*Helianthus annuus L.*).

Materials and Methods

The methodology of present study includes interpretation of SRTM DEM (90 m), IRS P6-LISS IV satellite data in conjunction with the drainage and contours obtained from topographical maps on 1:50,000 scale, delineation of distinct landform units using ArcGIS (ESRI 2010), finalization of landform boundaries with adequate field traverses, soil resource inventory, laboratory analysis of soil samples, soil classification, mapping and soil resource database generation in GIS environment for Borgaon Manju watershed on 1:50,000 scale.

Data Used

SRTM 3-arc second DEM (Fig. 2a) has been used in conjunction with topographic information to identify the broad landform units in the study area. Sinks in the input SRTM dataset have been removed using standard procedures prior to DEM processing (Grimaldi et al. 2007). The slope map of the study area has been generated from SRTM data using standard methods in ArcGIS. The base maps of the study area have been generated based on the Survey of India (SOI) toposheets 55 H/1 and 55 H/2. IRS-P6 LISS IV digital data acquired (Path 102 and Row 73) on 30th October

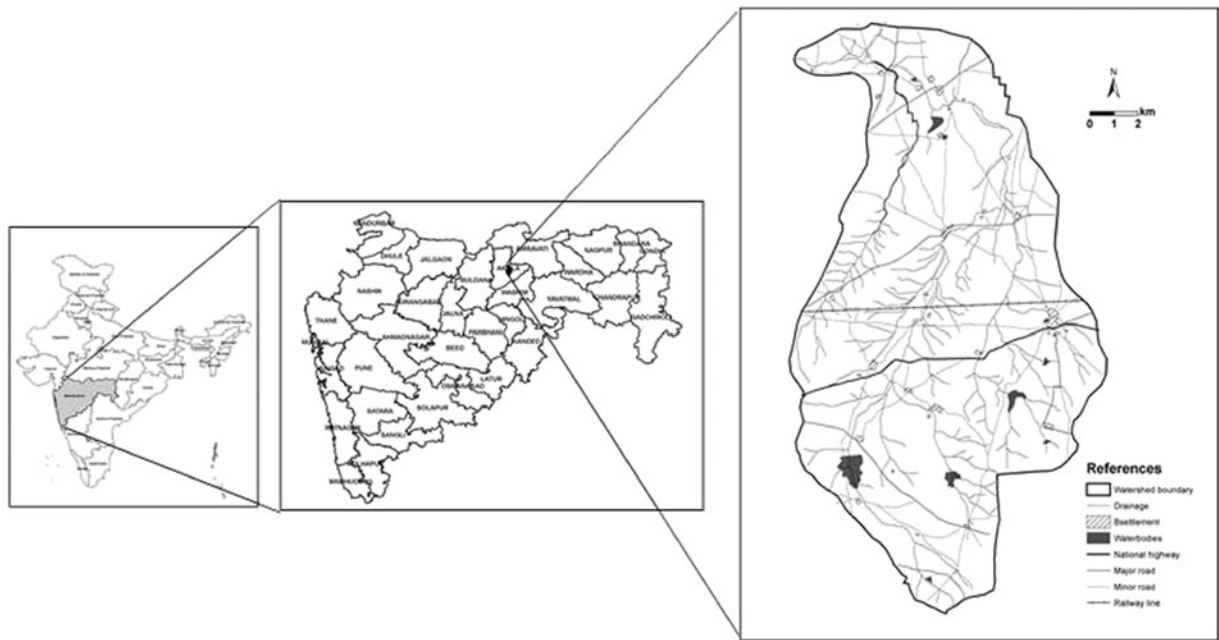


Fig. 1 Location map of the study area

2005 (Fig. 2b) has been geo-referenced at sub pixel accuracy using Geomatica image analysis software *ver* 9.3 (PCI 2007) with adequate ground control points and mosaic has been generated at watershed level. The standard false color composite (FCC) was generated from green, red and near infrared (NIR) spectral bands for onscreen visual interpretation in GIS to analyze the terrain features in characterization of distinct

landforms for soil resource inventory and mapping in the watershed.

Terrain Characterization

The terrain characteristics and the topography of the watershed were analyzed in conjunction with contours, drainage, slope, and vegetation parameters using

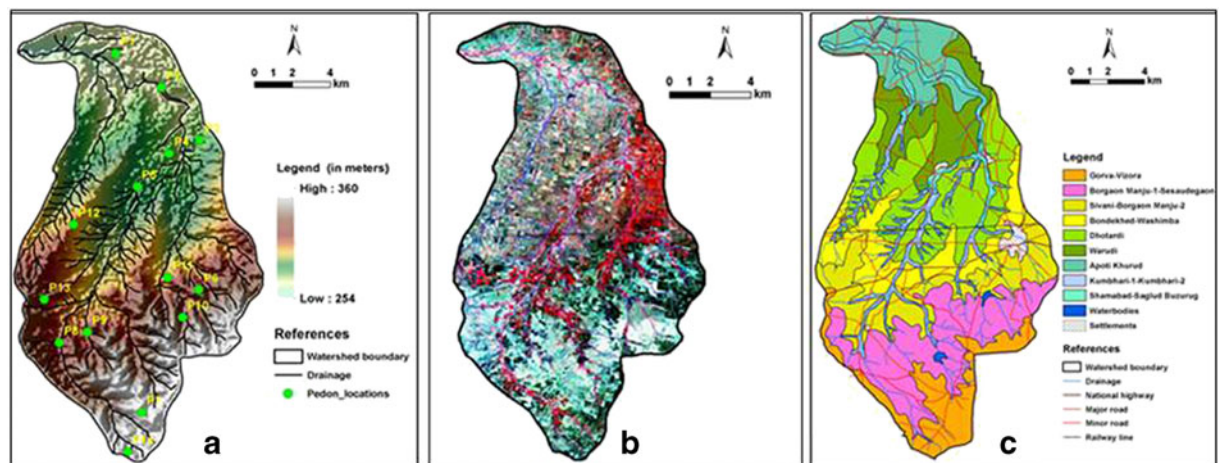


Fig. 2 a: SRTM Digital Elevation Model (90m), b: IRS-P6 LISS-IV standard FCC (30th October 2005) and c: Soil map of the study area depicting soil series associations

ArcGIS software (ESRI 2010). In conjunction with the DEM generated based on the contours at 20 m interval, SRTM digital elevation model (90 m) data was used to delineate distinct landforms and slope map of the watershed. The geo-coded terrain information in GIS has been generated and broad landform units were delineated based on the SRTM data and physiographic variations. Landform units were further sub divided based visual interpretation techniques like tone, texture, shape, drainage pattern, colour and differential erosion characteristics derived from IRS-P6 LISS-IV data. The drainage, contour, geological units and land use/land cover types derived from toposheets and satellite imagery were also considered in delineation of different landform units. The standard image enhancement techniques have been followed for better interpretation of the landform units for their delineation and characterization. A rapid reconnaissance survey of the study area was undertaken prior to soil survey to understand the landform units and their processes, land use/land cover and their relationship with soils. It helps to derive information on landform units to establish the relationship between the image elements and landform characteristics. The boundary delineation of landform units has been carried out based on the changes in topographic slopes, relief patterns, crest type, drainage and image characteristics of the area. Landform processes have been analyzed to understand their erosional and depositional processes.

Soil Resource Inventory and Mapping

Soil resources inventory has been carried out in the study area with the help of landform units generated from analysis of SRTM data, high resolution IRS-P6 LISS-IV data and adequate field checks. The watershed area was traversed to identify the representative sites for the soil profile studies. Depending upon the complexity of the terrain and land use/land cover conditions, the representative sites on different landform units in the watershed have been identified for detailed soil profile study. The representative soil profiles were located with the help of hand held Global Positioning System (GPS) and examined for various morphological properties as suggested in the USDA Soil Survey Manual (Soil Survey Division Staff 2000). Various site and soil characteristics like slope, erosion, surface stoniness, colour, surface texture and structure were studied in the standard format. The

location details of profiles collected based on the GPS were transferred as GIS layer and developed profile information. The soil-physiographic relationship has been developed to understand the landform processes and soil properties. From the typifying pedons, horizon-wise soil samples were collected, processed and analysed for different physical and chemical properties following standard procedures (Black 1965; Jackson 1967) and soils were classified as per the Soil Survey Staff (2010). Based on the soil site, physical and chemical analysis, soil resource database for Borgaon Manju watershed has been generated in the GIS (ESRI 2010).

Results and Discussion

Characterization of Landforms

The elevation of Borgaon Manju watershed ranges from 260 m to 360 m above mean sea level. Nearly level to level (0–1 %), very gentle (1–3 %), gentle (3–8 %), moderate (8–15 %), moderately steep (15–30 %) slopes occupy with an area of 80.4 %, 14.4 %, 4.9 %, 0.3 %, and 0.01 % of TGA of watershed, respectively. Terrain characterization through analysis of SRTM data shows five major landforms namely subdued plateau, foot slopes, interfluvial slopes, narrow valleys and main valley. Through visual interpretation of IRS-P6 LISS-IV digital data, the major landforms were further subdivided and nine distinct landform units namely subdued plateau, upper and lower foot slopes, upper, middle and lower interfluvial slopes, entrenched valley floor, narrow valleys and main valley were delineated in the watershed (Table 1). Subdued plateau (9.2 % of TGA) is associated with Karanja formations with rill and gully erosion. Upper foot slopes (17.2 % of TGA) are characterized by various fluvio-erosional activities and show gray to light white tone and irregular shape on the satellite imagery. Lower foot slopes (8.2 % of TGA) are associated with moderate slopes and are susceptible to moderate to severe erosion hazards. Upper interfluvial slopes (10.8 % of TGA) are characterized by concave and convex slopes, which are associated with sheet erosion. Middle interfluvial slopes (18.2 % of TGA) are characterized by low level convex slopes and are associated with sheet erosion. Lower interfluvial slopes (9.9 % of TGA) are characterized by convex and concave slopes. Convex slopes are

Table 1 Image and landforms characteristics of Bargaon Manju watershed

Landform	Geology	Elevation (m)	Slope (%)	Tone/Colour	Texture	Shape and Size	Pattern	Association	Dominant land use/land cover	Area (ha)	Area (%)
Subdued plateau	Pahoehoe flows	320–340	1–3 to 3–8	Light gray to dark red	Coarse	Irregular and elongated	Contiguous	Upper foot slopes	Rainfed crop land, land with scrub and open mixed forest	1692.9	9.2
Upper foot slopes	Pahoehoe flows	300–330	3–8	Light gray to light white	Coarse	Irregular and elongated	Contiguous	Subdued plateau and lower foot slopes	Rainfed crop land, land with scrub and open mixed forest	3173.5	17.2
Lower foot slopes	Pahoehoe flows	290–310	1–3	Light gray to light red	Medium	Irregular and elongated	Contiguous	Upper foot slopes and upper interfluvial slopes	Rainfed crop land, land with scrub	1514.6	8.2
Upper interfluvial slopes	Basaltic alluvium	290–300	1–3	Light gray to light red	Medium	Irregular and elongated	Contiguous	Lower foot slopes and middle interfluvial slopes	Rainfed crop land, land with scrub	2007.7	10.8
Middle interfluvial slopes	Basaltic alluvium	280–290	1–3	Light gray to dark red	Fine	Irregular and elongated	Contiguous	Upper interfluvial slopes and lower interfluvial slopes	Rainfed and limited irrigated crop land	3356.9	18.2
Lower interfluvial slopes	Basaltic alluvium	270–280	0–1	Light gray to dark red	Fine	Irregular and elongated	Contiguous	Middle inter fluvial slopes, entrenched valley floor, narrow valleys and main valley	Rainfed crop land	1824.7	9.9
Entrenched valley floor	Basaltic alluvium	260–270	1–3	Light gray to dark red	Fine	Irregular and linear	Isolated and linear	Lower interfluvial slopes and main valley	Rainfed crop land	1731.9	9.4
Narrow valleys	Basaltic alluvium	280–310	1–3	Light gray to dark red	Fine	Irregular and linear	Isolated and linear	Associated with all units except subdued plateau	Rainfed and limited irrigated crop land	1678.7	9.1
Main valley	Basaltic alluvium	270–280	0–1	Light gray to dark red	Fine	Irregular and linear	Linear	Upper, middle and lower interfluvial slopes, entrenched valley floor and narrow valleys	Rainfed crop land	724.1	3.9
Settlements	–	–	–	–	–	–	–	–	–	562.8	3.1
Water bodies	–	–	–	–	–	–	–	–	–	187.8	1.0
Total	–	–	–	–	–	–	–	–	–	18455.6	100.0

associated with sheet erosion and concave slopes are characterized by depositional alluvium. Entrenched valley floor (9.4 % of TGA) formed on either side of the main valley in the lower reaches and it is associated with the convergent drainage pattern. Narrow valleys (9.1 % of TGA) are well entrenched in the lower elevations and are scooped out by the tributary streams and subsequently filled up by the finer basaltic alluvium. Main valley (3.9 % of TGA) is characterized by narrow strip of low lying zone formed by fluvio-depositional action with semi-stratification of sediments. The settlements and waterbodies occupy 3.1 and 1.0 % of TGA of the watershed, respectively.

Characterization of Soils in a Toposequence

The relationship between the landform position and pedological processes determine the soil attributes in a toposequence (Birkeland 1990; Moore, et al. 1993, and Reddy et al. 1999). The development of soils on a toposequence often follows the way water moves through/over the landscape. Based on the landform-soil relationship, fourteen soil series have been identified and mapped as soil series and associations in the watershed (Fig. 2c). The soils of the watershed have been classified according to the criteria proposed by Soil Taxonomy up to family level. Soil physical and chemical properties are presented in Tables 2 and 3, respectively.

Soils of Subdued Plateau

Gorva and Vizora soils were identified in this unit. Soils of Gorva are formed on gently sloping (3–8 % slope) subdued plateau underlain by weathered basalt. Soils of Gorva are very shallow (23 cm), moderately well drained with very dark brown (10 YR 2/2) in color, clayey texture and slightly alkaline in reaction. They have moderate (15–40 %) surface stoniness and are severely eroded. The available water capacity (AWC) ranged from 14.8 to 16.8 % and organic carbon content is 1.2 % in surface soil. Soils of Vizora are formed on gently sloping (1–3 % slope) subdued plateau underlain by weathered basalt. These soils are very shallow (12 cm), well drained, dark reddish brown (5 YR 3/3) in color with clayey surface and are neutral in reaction. They have strong (>40 %) surface stoniness and are severely eroded. The AWC is 11.9 % and the organic carbon content is 0.8 % in surface soil.

These soils are mainly under cultivation of rainfed cotton/pigeonpea-fallow, cotton/pigeonpea/sorghum-fallow and partly under permanent fallows and open mixed forest systems. These soils occupy about 1692.9 ha (9.2 %) of TGA of the watershed.

Soils of Upper Foot Slopes

Borgaon Manju-1 soils formed on very gently sloping (3–8 % slope) of upper foot slopes underlain by weathered basalt. These soils are very shallow (15 cm), well drained, dark reddish brown (5 YR 2.5/2) in color with clayey surface and are neutral in reaction. These soils have slight (3–15 %) surface stoniness and are moderately eroded. The AWC is 12.6 % and organic carbon content is 0.6 %. They are mainly under permanent fallows and cotton/pigeonpea-fallow system. These soils occupy about 3173.5 ha (17.2 %) of TGA of the watershed.

Soils of Lower Foot Slopes

Sivani and Borgaon Manju-2 soils were identified in this landform unit and are formed on very gently sloping (1–3 % slope) lower footslopes underlain by weathered basalt. Soils of Sivani are shallow (32 cm), well drained, dark brown (7.5 YR 3/2) in color with clayey surface and are neutral in reaction. These soils have slight (3–15 %) surface stoniness and are moderately eroded. The AWC varied from 12.6 to 13.8 % and organic carbon in surface soil is 0.7 %. Soils of Borgaon Manju-2 are very shallow (12 cm), well drained, dark brown (7.5 YR3/2) in color with clayey surface and are neutral in reaction. These soils have moderate (15–40 %) surface stoniness and are moderately eroded. The AWC is 14.0 % and organic carbon content of surface soil is 0.6 %. These soils are under cultivation of cotton-fallow and cotton/pigeonpea-fallow systems. These soils occupy 1514.6 ha (8.2 %) of TGA of the watershed.

Soils of Upper Interfluvial Slopes

Bonderkhed and Washimba soils formed on very gently sloping (1–3 % slope) of upper interfluvial slopes underlain by basaltic alluvium. These soils are very deep (>150 cm), moderately well drained, dark grayish brown (10 YR 3/2) in color with clay surface and are moderately alkaline in reaction. These soils have

Table 2 Physical properties of soils of Borgaon Manju watershed

Horizon	Depth (cm)	Particle size distribution			Bulk density (Mg m ⁻³)	Moisture retention		AWC (%)
		Sand %	Silt	Clay		33 kPa %	1500 kPa	
Gorva series (Clayey, smectitic, hyperthermic Lithic Ustorthents) on Subdued plateau								
Ap	0–11	10.8	23.4	65.8	1.6	35.5	18.7	16.8
AC	11–23	9.7	21.7	68.6	1.8	35.0	20.1	14.8
Cr	23–45	Weathered basalt						
Vizora series (Clayey skeletal, smectitic, hyperthermic Lithic Ustorthents) on Subdued plateau								
Ap	0–12	21.8	26.1	52.1	1.6–	29.1	17.2	11.9
Cr	12–35	Weathered basalt						
Borgaon Manju-1 series (Clayey skeletal, smectitic, hyperthermic Lithic Ustorthents) on Upper footslopes								
A	0–15	7.6	23.2	69.2	1.6	37.4	18.8	12.6
r	15–32	Weathered basalt						
Sivani series (Clayey, smectitic, hyperthermic (Cal)TypicHaplustepts) on Lower footslopes								
A	0–11	13.5	25.4	61.1	1.8	33.5	19.7	13.8
Bw	11–32	13.3	23.4	63.3	1.8	34.9	22.3	12.6
Cr	32–50	Weathered basalt						
Borgaon Manju-2 series (Clayey, smectitic, hyperthermic Lithic Ustorthents) on Lower footslopes								
Ap	0–12	14.8	18.6	66.7	1.6	31.5	17.6	14.0
Cr	12–34	Weathered basalt						
Bonderkhed series (Very fine, smectitichyperthermic (Cal) TypicHaplusterts) on Upper interfluvial plain								
Ap	0–19	8.1	26.6	65.3	1.6	32.3	18.2	14.1
Bw	19–55	6.9	22.4	70.7	1.6	32.6	19.0	13.6
Bss1	55–88	7.4	24.9	67.7	1.8	37.2	20.2	17.0
Bss2	88–121	8.8	25.3	65.9	1.9	39.0	21.3	17.7
Bss3	121–150	9.4	21.3	69.3	1.7	39.5	21.8	17.7
Washimba series (Very fine, smectitichyperthermic (Cal) TypicsHaplustepts) on Upper interfluvial plains								
Ap	0–17	16.0	22.2	61.8	1.6	40.2	21.4	18.8
Bw	17–50	15.3	23.1	61.6	1.5	39.9	19.6	20.3
Cr	50–80	Weathered basalt						
Dhotardi series (Fine, smectitic, hyperthermic (Cal) TypicHaplusterts) on Middle interfluvial slopes								
Ap	0–19	10.5	31.7	57.8	1.5	29.7	16.1	13.6
Bw	19–53	9.5	30.1	60.4	1.6	28.8	16.5	12.3
Bss1	53–82	12.5	33.2	54.3	1.7	32.6	18.1	14.5
Bss2	82–118	9.6	32.3	58.1	1.8	34.7	19.2	15.5
Bss3	118–150	11.1	35.1	53.8	1.8	40.7	21.2	19.5
Warudi series (Very fine, smectitichyperthermic (Cal) TypicHaplusterts) on Lower interfluvial slopes								
Ap	0–17	9.3	28.2	62.5	1.7	35.8	19.9	15.9
Bw	17–47	10.5	24.8	64.7	1.8	35.2	19.9	15.3
Bss1	47–81	8.8	25.0	66.2	1.7	35.3	21.6	13.7
Bss2	81–116	11.4	24.2	64.4	1.7	36.2	21.7	14.5
Bss3	116–150	10.9	24.9	64.2	1.8	35.8	21.1	14.7
Apotikhurud series (Very fine, smectitic, hyperthermic (Cal) TypicHaplusterts) in Entrenched valley floor								
Ap	0–19	12.4	24.2	63.3	1.7	33.8	18.6	15.3
Bw	19–40	17.2	26.6	56.2	1.6	35.4	20.6	14.8

Table 2 (continued)

Horizon	Depth (cm)	Particle size distribution			Bulk density (Mg m ⁻³)	Moisture retention		AWC (%)
		Sand %	Silt	Clay		33 kPa %	1500 kPa	
Bss1	40–74	13.2	29.3	57.5	1.6	40.5	24.4	16.1
Bss2	74–104	11.2	28.4	60.4	1.5	43.8	24.7	19.1
Bss3	104–150	12.6	23.2	64.2	1.7	48.3	27.0	21.3
Kumbhari-1 series (Very fine, smectitic, hyperthermic (Cal) TypicHaplusterts) in Narrow valleys								
Ap	0–18	14.1	22.3	63.6	1.7	32.5	23.2	9.3
Bw	18–43	12.9	22.8	64.3	1.7	33.2	25.0	8.2
Bss1	43–77	11.7	19.7	68.6	1.9	34.4	25.7	8.7
Bss2	77–107	13.7	20.3	65.9	1.9	37.1	27.3	9.9
BCK	107–142	13.8	19.4	66.8	1.3	37.4	24.8	12.6
Crk	142+	Soft powdery lime						
Kumbhari-2 series (Fine, smectitic, hyperthermic (Cal) Vertic Haplustepts) in Narrow valleys								
Ap	0–15	14.5	31.2	54.3	1.7	32.0	18.8	13.2
Bw1	15–35	21.5	24.3	54.2	1.5	32.7	19.9	12.8
Bw2	35–55	20.8	19.7	59.5	1.7	34.6	20.9	13.7
Bw3	55–82	21.2	20.9	57.9	1.7	36.2	24.1	12.6
Crk	82–140	Weathered CaCO ₃ layer						
Shamabad series (Clayey, smectitic, hyperthermic Calcic Haplustepts) in Main valley								
Ap	0–21	55.9	18.2	25.8	1.6	20.2	10.5	9.6
Bw1	21–68	48.0	14.2	37.8	1.6	17.2	9.4	7.8
Bw2	68–115	8.1	34.2	57.7	1.7	34.1	19.5	14.6
Bw3	115–150	11.5	32.2	56.3	1.7	32.5	18.5	14.0
SangludBuzurug series (Very fine, smectitic, hyperthermic Sodic Calcicusterts) in Main valley								
Ap	0–17	8.2	29.4	62.4	1.6	31.1	17.1	14.0
Bw	17–53	10.2	27.7	62.1	1.7	34.6	19.8	14.8
Bss1	53–89	10.9	28.1	61.0	1.6	39.3	20.3	19.0
Bss2	89–118	12.2	26.3	61.5	1.8	43.4	21.0	22.4
Bss3	118–150	10.9	26.6	62.5	2.0	42.9	21.9	21.0

slight (3–15 %) surface stoniness and are moderately eroded. The AWC ranges from 13.6 % to 17.7 % and organic carbon content in the surface soil is 0.7 % and decreased with depth. Soils of Washimba are moderately shallow (50 cm), well drained, very dark brown (10 YR 2/2) in color with clayey surface and are slightly alkaline in reaction. These soils have very slight (<3 %) surface stoniness and are moderately eroded. The AWC ranges from 18.8 to 20.3 % and organic carbon content in the surface soil is 0.8 %. They are mainly under cultivation of cotton-fallow and cotton/pigeonpea-fallow system with an area of 2007.7 ha (10.8 %) of TGA of the watershed.

Soils of Middle Interfluvial Slopes

Dhotardi soils were identified in this unit and are formed on very gently sloping (1–3 % slope) middle interfluvial slopes underlain by basaltic alluvium. These soils are very deep (>150 cm), moderately well drained, very dark grayish brown (10 YR 3/2) in color with clayey surface and are moderately alkaline in reaction. These soils have very slight (<3 %) surface stoniness and are moderately eroded. The AWC ranges from 12.3 to 19.5 % in the profile cm and organic carbon content in the surface soil is 0.4 %. These soils are under cultivation of cotton/pigeonpea-fallow and

Table 3 Chemical properties of soils of Borgaon Manju watershed

Horizon	Depth (cm)	pH (1:2.5)	EC (1:2.5) (dSm ⁻¹)	OC	CaCO ₃ (%)	Exchangeable cations				Sum of cations	CEC	ESP (%)	BS (%)
						Ca ⁺⁺	Mg ⁺⁺	Na ⁺	K ⁺				
Gorva series (Clayey- smectitic, hyperthermic Lithic Ustorthents) on Subdued plateau													
Ap	0–11	7.8	0.2	1.2	0.4	51.9	8.7	0.1	0.6	61.3	66.1	0.2	92.8
AC	11–23	7.4	0.4	1.0	3.6	54.7	9.0	0.2	0.3	64.1	68.7	0.2	93.3
Cr	23–45	Weathered basalt											
Vizora series (Clayey-skeletal, smectitic, hyperthermic Lithic Ustorthents) on Subdued plateau													
Ap	0–12	7.2	0.2	0.8	0.7	30.6	12.7	0.2	0.6	44.0	48.7	0.4	90.4
Cr	12–35	Weathered basalt											
Borgaon Manju-1 series (Clayey-skeletal, smectitic, hyperthermic Lithic Ustorthents) on Upper footslopes													
A	0–15	6.9	0.3	0.6	0.9	25.2	14.4	0.1	0.3	40.0	43.5	0.3	92.1
Cr	15–32	Weathered basalt											
Sivani series (Clayey, smectitic, hyperthermic (Cal) TypicHaplustepts) on Lower footslopes													
A	0–11	7.2	0.2	0.7	2.8	31.8	17.2	0.2	0.3	49.4	59.1	0.3	83.6
Bw	11–32	7.3	0.2	0.6	2.0	34.5	17.9	0.2	0.2	52.8	58.3	0.4	90.6
Cr	32–50	Weathered basalt											
Borgaon Manju-2 series (Clayey, smectitic, hyperthermic Lithic Ustorthents) on Lower footslopes													
Ap	0–12	7.3	0.3	0.6	0.1	34.9	13.7	0.2	0.5	49.3	49.6	0.5	99.5
Cr	12–34	Weathered basalt											
Bonderkhed series (Very-fine, smectitic, hyperthermic (Cal) TypicHaplusterts) on Upper interfluvial slopes													
Ap	0–19	8.1	0.2	0.7	12.5	46.4	8.5	0.2	0.7	55.7	51.3	0.3	108.6
Bw	19–55	8.4	0.2	0.5	11.9	45.8	10.3	0.5	0.5	57.1	51.3	1.0	111.3
Bss1	55–88	8.6	0.4	0.5	11.4	45.4	11.2	3.3	0.5	60.3	51.3	6.4	117.6
Bss2	88–121	8.7	0.5	0.5	10.7	41.5	11.3	5.9	0.3	59.0	48.7	12.2	121.1
Bss3	121–150	8.6	0.9	0.3	12.0	40.5	13.3	8.4	0.5	62.6	54.8	15.2	114.2
Washimba series (Very-fine, smectitic, hyperthermic (Cal) TypicHaplustepts) on Upper interfluvial slopes													
Ap	0–17	8.0	0.2	0.8	2.1	37.4	8.9	0.3	0.9	47.5	51.3	0.6	92.5
Bw	17–50	7.9	0.2	0.6	3.0	37.9	8.8	0.5	0.7	47.8	49.6	1.0	96.5
Cr	50–80	Weathered basalt											
Dhotardi series (Fine, smectitic, hyperthermic (Cal) TypicHaplusterts) on Middle interfluvial slopes													
Ap	0–19	8.3	0.2	0.4	14.9	43.6	7.3	0.2	0.6	51.6	43.5	0.3	118.8
Bw	19–53	8.4	0.2	0.6	15.4	44.2	8.8	0.7	0.4	54.1	49.6	1.5	109.2
Bss1	53–82	8.8	0.2	0.6	10.9	42.2	9.5	1.7	0.4	53.8	55.6	3.1	96.7
Bss2	82–118	8.9	0.3	0.6	14.9	40.9	10.3	3.4	0.4	55.0	58.3	5.8	94.4
Bss3	118–150	9.0	0.4	0.6	11.3	40.7	12.9	5.9	0.5	60.0	59.1	10.0	101.4
Warudi series (Very-fine, smectitic, hyperthermic (Cal) TypicHaplusterts) on Lower interfluvial slopes													
Ap	0–17	8.1	0.1	0.8	10.3	50.5	9.9	0.1	1.0	61.5	51.3	0.2	119.9
Bw	17–47	8.2	0.1	0.6	11.3	46.5	11.8	0.2	0.5	59.0	50.4	0.5	117.0
Bss1	47–81	8.3	0.2	0.6	11.3	47.2	13.7	0.3	0.5	61.7	51.3	0.5	120.2
Bss2	81–116	8.5	0.2	0.5	11.2	45.8	15.6	0.5	0.4	62.3	50.4	0.9	123.5
Bss3	116–150	8.6	0.2	0.5	12.9	40.3	17.0	0.9	0.5	58.7	50.4	1.7	116.4
ApotiKhurud series (Very-fine, smectitic, hyperthermic (Cal) TypicHaplusterts) in Entrenched valley floor													
Ap	0–19	8.4	0.2	0.6	12.5	47.0	10.6	0.4	1.0	58.9	60.0	0.6	98.2
Bw	19–40	8.7	0.2	0.7	10.8	45.8	11.9	0.6	0.7	59.0	55.6	1.1	106.1

Table 3 (continued)

Horizon	Depth (cm)	pH (1:2.5)	EC (1:2.5) (dSm ⁻¹)	OC	CaCO ₃ (%)	Exchangeable cations				Sum of cations	CEC	ESP (%)	BS (%)
						Ca ⁺⁺ cmol(p ⁺)kg ⁻¹	Mg ⁺⁺	Na ⁺	K ⁺				
Bss1	40–74	8.8	0.3	0.5	10.0	44.1	13.2	2.6	0.6	60.5	55.6	4.7	108.6
Bss2	74–104	8.9	0.3	0.6	8.5	41.3	14.3	3.9	0.6	60.1	59.1	6.6	101.7
Bss3	104–150	9.1	0.4	0.5	9.9	38.6	17.8	6.3	0.7	63.4	58.3	10.9	108.8
Kumbhari-1series (Very-fine, smectitic, hyperthermic (Cal) TypicHaplusterts) in Narrow valleys													
Ap	0–18	8.1	0.2	0.8	11.6	47.7	12.1	0.2	0.3	60.3	61.7	0.3	97.8
Bw1	18–43	8.2	0.2	0.5	11.3	46.2	14.8	0.4	0.2	61.5	63.5	0.7	96.9
Bss1	43–77	8.4	0.2	0.4	12.3	41.1	18.6	1.2	0.2	61.0	61.8	1.9	98.8
Bss2	77–107	8.5	0.3	0.4	21.3	38.1	20.9	2.8	0.2	61.9	63.5	4.3	97.5
Bw2	107–142	8.6	0.3	0.2	21.9	37.3	16.5	2.6	0.2	56.6	60.9	4.3	92.9
Crk	142+	Soft powdery lime layer											
Kumbhari-2 series (Fine, smectitic, hyperthermic (Cal) Vertic Haplustepts) in Narrow valleys													
Ap	0–15	7.9	0.2	1.5	10.0	49.3	12.3	0.1	0.7	62.3	63.5	0.2	98.2
Bw1	15–35	8.1	0.2	0.8	19.6	47.0	13.4	0.2	0.3	60.8	61.8	0.3	98.5
Bw2	35–55	8.2	0.2	0.7	20.2	45.0	12.7	0.2	0.3	58.2	60.0	0.4	97.0
Bw3	55–82	8.2	0.2	0.6	20.9	43.5	13.5	0.3	0.2	57.5	60.0	0.5	95.8
Crk	82–140	Weathered basalt with CaCO ₃ layer											
Shamabad series (Clayey, smectitic, hyperthermic Calcic Haplustepts) in Main valley													
Ap	0–21	8.4	0.1	0.7	23.0	30.9	6.6	0.2	0.7	38.5	34.8	0.6	110.6
Bw1	21–68	8.5	0.2	0.5	23.8	29.1	7.1	0.3	0.6	37.1	26.9	1.0	137.5
Bw2	68–115	8.5	0.4	0.4	13.8	36.6	13.9	1.1	0.7	52.3	46.9	2.4	111.3
Bw3	115–150	8.7	0.2	0.3	16.8	34.3	14.7	0.7	0.5	50.2	47.8	1.5	104.9
SangludBuzurug series (Very-fine, smectitic, hyperthermic Sodic Calcicusterts) in Main valley													
Ap	0–17	8.2	0.2	0.7	18.6	39.9	10.0	0.7	1.1	51.6	46.1	1.4	111.9
Bw	17–53	8.8	0.6	0.5	15.4	38.0	13.3	3.7	0.7	55.7	45.2	8.2	123.2
Bss1	53–89	8.9	0.6	0.5	16.1	34.0	15.3	7.4	0.6	57.4	46.9	15.8	122.3
Bss2	89–118	9.0	0.6	0.3	16.0	30.6	16.4	2.0	0.6	49.7	46.1	4.4	107.8
Bss3	118–150	8.8	1.3	0.2	18.1	27.4	18.1	9.3	0.6	55.4	40.0	23.4	138.6

cotton/mung bean-fallow system. These soils occupy about 3356.9 ha (18.2 %) of TGA of the watershed.

Soils of Lower Interfluvial Slopes

Warudi soils are associated with level to nearly level (0–1 %) slope. They are deep (>150 cm), moderately well drained, very dark grayish brown (10 YR 3/2) in color with clayey surface and are moderately alkaline in reaction. These soils have very slight (<3 %) surface stoniness and are moderately eroded. The AWC ranges from 12.7 % to 15.9 % and organic carbon content in surface soil is 0.8 %. They are mainly under cotton-fallow, cotton/pigeonpea-fallow, cotton/mung bean-

fallow and cotton/mung bean/pigeonpea-fallow systems. These soils occupy about 1824.7 ha (9.9 %) of TGA of the watershed.

Soils of Entrenched Valley Floor

Apoti Khurud soils formed on very gently sloping (1–3 % slope) entrenched valley floor underlain by basaltic alluvium. These soils are very deep (>150 cm), moderately well drained, very dark grayish brown (10 YR 3/2) in color with clayey surface and are moderately alkaline in reaction. These soils have very slight (<3 %) surface stoniness and are moderately eroded. The AWC ranges from 14.8 % to 21.3 % in

the profile and organic carbon content in surface soil is 0.6 %. They are mainly under cultivation of cotton/pigeonpea-fallow and mung bean-wheat/bengal gram/linseed/safflower system. Soils of Kumbhari-2 were associated as sub dominant soils in this unit. These soils occupy about 1731.9 ha (9.4 %) of TGA of the watershed.

Soils of Narrow Valleys

Kumbhari-1 and Kumbhari-2 soils were identified in this unit and are formed on very gently sloping (1–3 % slope) narrow valleys underlain by weathered basalt. Soils of Kumbhari-1 are deep (142 cm), moderately well drained, very dark brown (10 YR 2/2) in color with clayey surface and are slightly alkaline in reaction. These soils have very slight (<3 %) surface stoniness and are moderately eroded. The AWC ranges from 8.2 % to 12.6 % in the profile and organic carbon content in surface soil is 0.8 %. Soils of Kumbhari-2 are moderately deep (82 cm), moderately well drained, very dark grayish brown (10 YR 3/2) in color with clayey surface and are moderately alkaline in reaction. These soils have slight (3–15 %) surface stoniness and are moderately eroded. The AWC ranges from 12.6 % to 13.7 % in profile and organic carbon content is 0.2 % in the surface soil. They are mainly under cultivation of cotton-fallow, cotton/pigeonpea-fallow and cotton/sorghum-fallow systems. These soils occupy about 1678.7 ha (9.1 %) of TGA of the watershed.

Soils of Main Valley

Shamabad and Sanglud Buzurug soils were identified in this unit. They are formed on level to nearly level (0–1 % slope) main valley underlain by basaltic alluvium. Soils of Shamabad are very deep (>150 cm), well drained, very dark grayish brown (10 YR 3/2) in color with clayey surface and moderately alkaline in reaction. These soils have very slight (<3 %) surface stoniness and are moderately eroded. The AWC ranges from 9.6 % to 14.6 % in the profile and organic carbon content is 0.7 % in surface soil. Soils of Sanglud Buzurug are very deep (>150 cm), well drained, very dark grayish brown (10 YR 3/2) in color with clayey surface soils and are moderately alkaline in reaction. These soils have very slight (<3 %) surface stoniness and are moderately eroded. The AWC ranges from 14.0 % to 22.4 % in profile and organic carbon content

is 0.7 % in surface soil. Cotton/pigeonpea-fallow and cotton/mung bean-fallow are the dominant land use systems. These soils occupy about 724.1 ha (3.9 %) of TGA of the watershed.

Landform-Soil Relationship

The landform units were compared with pedological descriptions of soil profiles and a relationship between the landform and the soils were established. The landform-soil relationship indicates that soils developed on the landforms of upper reaches are very shallow to shallow, whereas, the soils developed on the landforms of lower reaches are deep to very deep. The inter-relationship between landform and soils is utilized while deriving information on soils from satellite data (Kudrat et al. 1992). Soils formed on gently sloping landform have moderate (15–40 %) surface stoniness and are severely eroded. However, the soils formed on level to nearly level (0–1 % slope) slope in the main valley have very slight (<3 %) surface stoniness and are moderately eroded. In general, AWC is low in upper reaches and high in the lower reaches. Baring few, across the landscape the increasing trend of bulk density has been observed down the profiles. The soil reaction (pH) shows that soils are neutral in the upper reaches, whereas, the soils are moderately alkaline in lower reaches. Soils in the watershed are grouped into Lithic Ustorthents, Vertic Haplustepts, Calcic Haplustepts, Typic Haplustepts, Typic Haplusterts and Sodic Calcicusterts (Soil Survey Staff 2010). The landform processes, soil physical and chemical properties in a toposequence indicate a clear landform-soil relationship in the watershed area. The observed soil properties are akin to the landform characteristics, which explain the utility of high resolution satellite data in delineation of distinct landform units and forms the basis to understand the landscape origin, geomorphic evolution and land surface processes, physical and chemical characteristics of soils.

Conclusions

The study reveals that terrain characterization through analysis of SRTM data for broad landform units and high resolution IRS-P6 LISS-IV satellite data in GIS environment with necessary field verifications will be

of immense help in deriving reliable information on distinct landform units in a toposequence. The analysis shows nine distinct landform units in the study area and the soils on these landform units were characterized and classified. Fourteen soils series have been identified in the watershed and soil map has been generated with nine soil series associations and described. The soils in the watershed were grouped into Lithic Ustorthents, Vertic Haplustepts, Calcic Haplustepts, Typic Haplustepts, Typic Haplusterts and Sodic Calcicusterts. The analysis of landform-soil relationship indicates that topographic position governs soil depth, surface drainage, AWC and chemical properties like OC, pH as well as their differential distribution within the soil profile. The characterization of landforms and soils in the watershed is of immense help in natural resource planning and management towards sustainable land use planning. The study demonstrates that the utility of high-resolution IRS-P6 LISS-IV data and GIS technologies supplemented with sufficient ground truth is found to be the most efficient and effective way in terrain characterization and soil resource inventory in a toposequence and establish soil–landform relationship to characterize the landform and soil properties.

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