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Earth Observations for Soil Resource Assessment

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AGNPS - Agricultural Non-Point Source Pollution
AHP - Analytical Hierarchical Process
ANN - Artificial Neural Networks
APEX - The Agricultural Policy / Environmental eXtender
AWiFS - Advanced Wide Field Sensor
BD – Bulk Density
CART - Classification and regression trees
CEC – Cation Exchange Capacity
CTI - Compound Topographic Index
DEM – Digital elevation Model
DSM – Digital Soil Mapping
DTA – Digital Terrain Analysis
DTM – Digital Terrain Model
EC – Electrical Conductivity
EMI - Electromagnetic Induction
EMR – Electromagnetic Radiation
EVI - Enhanced Vegetation Index
FC – Field Capacity
FCC – False Color composite
GEE – Google Earth Engine
GHG – Green House Gas
GIS - Geographic information systems
GPR - Ground-penetrating radar
HRS - Hyperspectral remote sensing
HRUs - Hydrological Response Units
ICAR - Indian Council of Agricultural Research
Landsat TM – Landsat Thematic Mapper
LCC - Land Capability Class
LDN - Land Degradation Neutrality
LIBS - Laser Induced Breakdown Spectroscopy
LiDAR - Light Detection and Ranging
LISS III - Linear Imaging Self Scanning (LISS-3)
LISS IV - Linear Imaging Self Scanning (LISS-4)
LST - Land Surface Temperature
LUT - Land Utilization Types
MDS- Minimum Dataset
MIR - Mid Infrared
ML - Machine learning
MLR - Multiple linear regression
MPTs - Multipurpose trees
MUSLE – Modified Universal Soil Loss Equation
NDSI - Normalized Differential Salinity Index
NDVI – Normalized Difference Vegetation Index
NPP - Net Primary Productivity
PAN - Panchromatic sensor
PCA - Principal Component Analysis
PD – Particle Density
PLSR - Partial least squares regression
PWP – Permanent Wilting Point
pXRF - portable X ray fluorescence
RDA - Redundancy Analysis
RF - Random forest
RMPs - Resource Management Practices
RPI - Runoff Potential Index
RS – Remote Sensing
RUSLE - Revised Universal Soil Loss Equation
SAR - Synthetic Aperture Radar
SAVI – Soil Adjusted Vegetation Index
SBI - Soil Brightness Index
SDGs - Sustainable Development Goals
SFF - Spectral feature fitting
SOC – Soil Organic Carbon
SOM – Soil Organic Matter
SPI - Stream Power Index
SSQI - Simple soil quality index
STCs - Staggered contour trenches
STI - Sediment Transport Index
SVM - Support Vector Machine
SWAT - Soil and Water Assessment Tool
SWIR – Shortwave Infrared
SYI - Sediment Yield Index
TCT - Tasseled Cap Transformation
TDR - Time Domain Reflectometry
U.S – United States
UAV - Unmanned Aerial Vehicle
UNCCD - United Nations Convention to Combat Desertification
USDA : United States Department of Agriculture
USLE - Universal Soil Loss Equation
VIs – Vegetation Indices
VNIR – Visible Near-Infrared
WEPP - Water Erosion Prediction Project
WSQI - Weighted soil quality index

1.0 Soils and their characteristics

The word 'soil' derives its origin from the *latin* word *'solum'* meaning floor or ground. We consider soil as three three-dimensional natural dynamic body developed through the combined influence of climate and vegetation on parent material, conditioned by relief over a period of time. A combination of physical, chemical and biotic forces acts on organic and weathered rock fragments to produce soils with a porous fabric that contain water and air (pedosphere). It serves as a natural medium for the growth of land plants.

1.1 Soil profile

A vertical section of soil through all its horizons, extending to the parent material is called a soil profile. A pedon description primarily involves examining the soil profile to describe the morphological characteristics of each horizon and collecting soil samples from each horizon for further analysis of physico-chemical properties of soils. A pedon is smallest volume of soil (3-dimensional natural body) used to characterize arrangement of soil horizons and physico-chemical characteristics of the soils. It is similar to soil profile and includes O, A, B, and C horizons where O, A, and B horizons collectively called as solum. Agricultural soils do not have O horizon as it is mainly found in forest soils.

Soil horizon: A soil layer or soil material which is roughly parallel to the land surface and has physical, chemical, and biological characteristics that differ from the layers above and below it. The standard/master horizons generally observed are O, A, E, B and C horizons depending on their relative positions as well as composition (Fig 1.1).

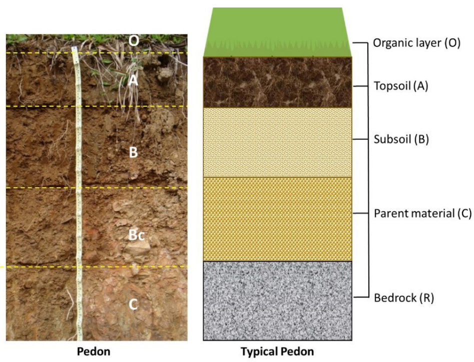


Fig 1.1: A Typical Soil Profile / Pedon

Soil Composition

Soils consist of four main components: mineral matter (40-60%), soil water (20-50%), soil air (0-40%), and a small percentage of organic material (0-5%). Mineral and organic matter components constitute the solid phase, whereas the pore spaces are occupied by water as well as air. In most of the soils, organic matter levels are quite low. i.e. less than 1%, whereas some wetland soils may exhibit very high organic matter contents, exceeding even 50% of the solid portion.

Mineral matter forming the inorganic constituents of soil mainly consists of very fine broken rock fragments and minerals. Primary minerals like quartz, feldspars, biotite and muscovite are mainly present in coarser soil fractions whereas, very finer clay size fractions in soil are dominated by secondary minerals viz, silicate clays and hydrous oxides of iron and aluminium.

Clay minerals are the active mineral component of soils, characterized by their colloidal and crystalline nature. Silicon (Si) tetrahedra and Aluminium (Al) octahedra, where planes of O_2 atoms are held together by Si and Al atoms, by ionic bonding, forms the basic unit of clay minerals. Based on the number of tetrahedral and octahedral units forming the basic unit and the different ways in which the numerous basic units are stacked together, clay minerals are categorised mainly into 1:1 as well as 2:1 clay minerals. Kaolinite, a predominant clay mineral found in red soils is an example of 1:1 clay type whereas Vermiculite found mainly in alluvial soils as well as Montmorillonite found in black soils are examples of 2:1 clay type.

Organic matter consists of highly complex substances such as carbohydrates (sugar, starch, hemicellulose, cellulose, etc.), lignin, proteins, fats (oils), waxes, tannins, resins, organo-mineral compounds, and more. It serves as a storehouse of plant nutrients, provides a medium for microbial growth and activities, influences cation exchange capacity, and enhances the physical condition of the soil.

1.2 Soil Properties

1.2.1 Physical Properties

Soil Texture: Soil texture refers to the relative proportions of sand, silt, and clay-sized particles in the mineral fraction of soil. It is determined primarily using the International Pipette method or the Bouyoucos Hydrometer method, both of which rely on the principle of sedimentation. Based on the proportions of sand, silt, and clay, soils are classified into one of 12 textural classes using a USDA textural triangle (Fig 1.2).

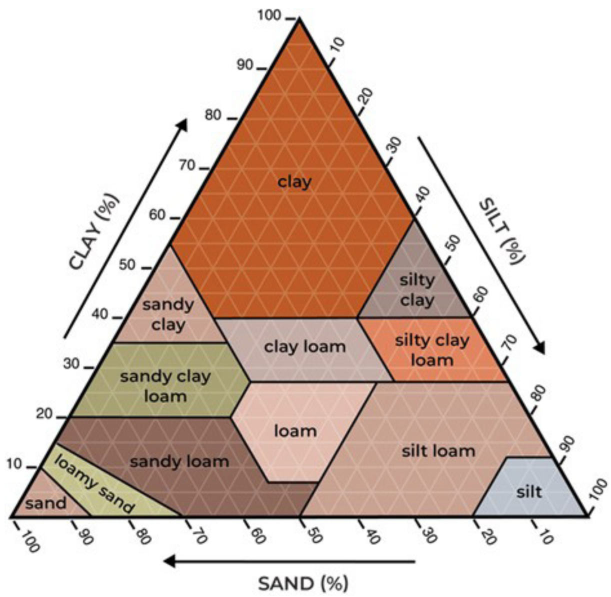


Fig 1.2: Soil textural triangle

Soil structure: Soil structure refers to the arrangement (grouping) of primary soil particles into aggregates (or peds). It is characterized by the type (shape), class (size), and grade (cohesive strength) of the aggregates. Different soil structures, such as platy, prismatic, blocky, and spheroidal, depend on the shape of the aggregates. Soil structure is crucial as it affects soil aeration, water and nutrient holding capacity, germination, root growth and development, water retention and movement, as well as soil thermal properties.

Soil Density: It is measured and expressed in the form of soil bulk density (BD) as well as particle density (PD). Bulk density is the dry mass of soil per unit volume of soil, whereas particle density is the dry mass of soil per unit volume of soil solids only. Bulk density accounts for both the solids and the pore space, whereas particle density considers only the mineral solids. Typical PDs for soils range from 2.60 to 2.75 g/cm³ for mineral particles, with an average value of 2.65 g/cm³ generally used. BD values range between 1.40 – 1.75 g/cm³ in coarse textured soils and 1.10 - 1.40 g/cm³ in fine textured soils, whereas an average value of 1.33 g/cm3 is widely used. PD and BD values help in the estimation of soil porosity.

Porosity: It refers to the fraction of the total soil volume occupied by pore spaces. It determines the aeration status, permeability, water availability as well as water movement through the soil. Coarse-textured soils (sandy) have larger individual pores but less total pore space, while fine-textured soils (clayey) have smaller individual pores but more total pore space.

Soil Water: Soil acts as store house of water (due to pore spaces) and ensures the controlled release and availability. The movement of water into soil is termed infiltration, while the downward movement within the soil is referred to as *percolation or permeability*. Infiltration and permeability describe the manner by which water moves into and through soil. Water held in a soil is described by the term water content, which can be quantified on both a gravimetric (g water/g soil) and volumetric (cm³ water/ cm³ soil) basis. The volumetric measure of water content is the most commonly used.

Field capacity: soil water content after the soil has been saturated and allowed to drain freely for about 24 to 48 hours. The water is held at a suction pressure of approximately 1/3 bar atm.

Permanent Wilting Point: Soil water content when plants have extracted all the available water. At the permanent wilting point, a plant wilts and does not recover. The water is held at a suction pressure of 15 bar atm.

Hygroscopic Water: Soil water content that is tightly bound to soil particles and aggregates, which the plants cannot extract. The water is held at a suction pressure of 31 bar atm.

Water holding capacity: The amount (mass or volume) of water held in the soil against gravity, or the total amount of water in the soil at field capacity. *Plant available water or available water capacity* is that portion of the water holding capacity that can be absorbed by the plant, and is the amount of water held between field capacity (FC) and wilting point (PWP).

Soil colour: It is an indicator of various physical and chemical characteristics. Organic matter as well as mineral content are the major soil coloring agents. Organic matter is known to impart dark color to soil layers, whereas iron (Fe) and manganese (Mn) are known to impart wide range of colors to soil depending on their state of oxidation. Soil color is primarily assessed using the Munsell Soil Color Chart, which categorizes soil color based on Hue, Value, and Chroma.

1.2.2 Chemical Properties

Soil pH: It is the negative log of the H+ activity in the soil solution. The value ranges from 0 to 14 and helps in categorizing soils into acidic, neutral as well as basic (alkaline) soils. It is commonly measured in saturation paste with water, or mixture with water (1:2 or 1:2.5) or 0.01M $CaCl_2$ (1:2 or 1:2.5) using H+ ion sensitive electrodes. pH plays a vital role in determining the availability of nutrients as well as toxic elements in the soils.

Electrical conductivity (EC): It measures is a measure of the total amount of soluble salts. EC has been used principally as a measure of soil salinity and is expressed in deciSiemens per meter (dS/m).

Cation Exchange Capacity: It represents the total capacity of a soil to retain exchangeable cations and is measure of the overall negative charge in the soil, that adsorbs cations of essential plant nutrients. The negative charges in the soil could be mainly attributed to the clay and organic matter present. CEC value depends on texture, organic matter and pH. It is an inherent soil characteristic.

Available Nutrients: soil is the store house of various nutrients which are essential for plant growth and development. Currently there are 17 nutrients considered essential for plants.

1.2.3 Biological Properties

Soil respiration: It measures the carbon dioxide released from soil due to microbial decomposition of organic matter and plant litter. This serves as an indicator of soil biological activity or soil life.

Soil enzymes: Enzymes accelerate the rate at which plant residues decompose and release nutrients available to plants, thereby playing a critical role in nutrient cycles. The primary sources of soil enzymes include living and dead microbes, plant roots and residues, and soil animals. Enzymes also function as important indicators for assessing microbial activity. Dehydrogenase, beta glucosidase, urease, phosphatase, sulfatase etc are some of the most prominent soil enzymes.

Soil microorganisms: Bacteria, actinomycetes and fungi are the common soil microbes observed in global soils. Apart from these algae, protozoa, virus as well as nematodes are observed. These processes are essential for maintaining crop fertility, nutrient cycling, residue decomposition, environmental purification from pollutants, regulation of carbon storage, and production/consumption of many important greenhouse gases.

2.0 Soil Classification

Soil Taxonomy, the classification system originated in the US and used worldwide, primarily categorizes soils based on their properties and the arrangement of horizons within the soil profile". (Soil Survey Staff, 1999).

Soil Taxonomy is utilized to classify soils into categories based on their morphology (appearance and form). It defines soils as natural bodies and includes two other important features: (i) easily verifiable soil properties, and (ii) systems based on soil genesis. Another significant aspect of Soil Taxonomy is its unique nomenclature, which provides clear descriptions of the major characteristics of the soils being classified

2.1 Soil Taxonomy - *New Comprehensive Classification System*

Soil Taxonomy is based on the properties of soils as they are found today. While one of its goals is to categorize soils with similar origins, the criteria used to group soils primarily rely on soil properties. However, soil genesis is not disregarded in this process. Because soil properties are often closely linked to soil genesis, it is challenging to emphasize soil properties without indirectly highlighting soil genesis as well.

The chemical, physical, and biological properties serve as the criteria for Soil Taxonomy. Examples include soil moisture, temperature, color, texture, and structure. Other important criteria for soil classification include chemical and mineral properties such as organic matter content, clay, iron and aluminum oxides, silicate clays, salinity, pH, percentage of base saturation, and soil depth.

Diagnostic Horizons

Diagnostic soil horizons can be found in the surface or subsurface layers of soil. Surface horizons that are diagnostic are called epipedons (from the Greek words 'epi', meaning over, and 'pedon', meaning soil), whereas subsurface diagnostic horizons are called as endopedons (Table 2.1). Epipedons include the upper part of the soil that is darkened by organic matter, the upper eluvial horizons, or both. It may also include part of the B horizon if it is significantly darkened by organic matter. There are seven recognized epipedons.

Categories of the Soil Taxonomy

There are six categories in the U.S. System of Soil Taxonomy are, in decreasing rank, order, sub-order, great group, sub-group, family, and series. These categories are briefly defined and explained below:

Order

The ***order*** category primarily reflects soil-forming processes, determined by the presence or absence of major diagnostic horizons. Soils within the same order are presumed to share similar genesis, as indicated by their properties and the general processes involved in their formation. There are twelve soil orders in Soil Taxonomy (Table 2.2).

Table 2.1: Major features of diagnostic suface and sub-surface horizons

Diagnostic horizons	Major features
Surface Horizons = Epipedons	
Mollic	Thick, dark colored, high base saturation, strong structure
Umbric	Same as Mollic except low base saturation
Ochric	Light colored, low organic content, may be hard and massive when dry
Histic	Very high in organic content, wet during some part of year
Anthropic	Man-modified Mollic-like horizon, high in available P
Plaggen	Man-made sod-like horizon created by years of manuring
Melanic	Thick black horizon rich in organic matter usually associated with aluminum-humus complex
Subsurface Horizons	
Argillic	Silicate clay accumulation
Natric	Argillic, high in sodium, columnar or prismatic structure
Spodic	Organic matter, Fe and Al oxides accumulation
Cambic	Changed or altered by physical movement or by chemical reactions
Agric	Organic and clay accumulation just below plow layer resulting from cultivation
Oxic`	Highly weathered, primarily mixture of Fe, Al oxides and nonsticky-type silicate clays
Duripan	Hard pan, strongly cemented by silica
Fragipan	Brittle pan, usually loamy textured, weakly cemented
Albic	Light colored, clay and Fe and Al oxides mostly removed
Calcic	Accumulation of $CaCO_3$ or $CaCO_3.MgCO_3$
Gypsic	Accumulation of gypsum
Salic	Accumulation of salts
Kandic	Accumulation of low activity clays
Petrocalcic	Cemented calcic horizon
Petrogypsic	Cemented cypsic horizon
Placic	Thin pan cemented with iron alone or with manganese or organic matter
Sombric	Organic matter accumulation
Sulfuric	Highly acid with Jarosite mottles

Table 2.2: Soil Orders and their major characteristics

Soil Order	Description
Entisols	Little profile development, ochric epipedon common
Inceptisols	Embryonic soils with few diagnostic features, ochric or umbric epipedon; cambic horizon
Mollisols	Mollic epipedon, high base saturation, dark soils, some with argillic or natric horizons
Alfisols	Argillic or natric horizon; high to medium base saturation
Ultisols	Argillic horizon, low base saturation
Oxisols	Oxic horizon, no argillic horizon, highly weathered
Vertisols	High in swelling clays; deep cracks when soil dry
Aridisols	Dry soil, ochric epipedon, sometimes argillic or natric horizon
Spodosols	Spodic horizon commonly with Fe, Al, and humus accumulation
Histosols	Peat or bog; >30% organic matter
Andisols	From volcanic ejecta, dominated by allophane or Al-humic complexes
Gelisols	Permafrost within 100 cm

Sub-order: *Suborders* are subdivisions of orders that emphasize properties indicating genetic similarity. Therefore, factors such as wetness, climate, and vegetation, which influence the nature of soil formation processes, also play a role in determining the suborder classification of a soil.

Great Group: Diagnostic horizons are the main criteria for distinguishing between great groups within a suborder. Soils classified within the same great group share identical types and arrangement of these horizons.

Subgroup: Subgroups are subdivisions within the great groups. The central concept of a great group constitutes one subgroup (Typic). Other subgroups may exhibit characteristics that are intermediate between those of the central concept and soils from other orders, suborders, or great groups.

Family: The Family category includes soils with subgroups that share similar physical and chemical properties affecting their response to management, particularly the penetration of plant roots (e.g., soil-water-air relationships). Differences in texture, mineralogy, temperature, and soil depth are the main criteria for differentiating families.

Series: The series category is the most detailed unit of the classification system, and it is a subdivision of the family. The distinguishing characteristics of a series are primarily based on the type and arrangement of horizons. Conceptually, it comprises a single polypedon; however, in the field, aggregates of polypedons and associated inclusions are included in the soil series mapping units.

2.2 Soils of India

The most predominant soil types in India along with their geographical distribution and broad taxonomical details are given below in Table 2.3.

Table 2.3: Different Soil Types in India

Sl. No.	Soil types	Distribution in states	Soil orders USDA Soil Taxonomy
1.	Alluvial	Jammu and Kashmir, Himachal Pradesh, Punjab, Haryana, Delhi, Uttar Pradesh, Gujarat, Goa, Madhya Pradesh, Maharashtra, Andhra Pradesh, Karnataka, Tamilnadu, Kerala, Puducherry, Bihar, Odisha, West Bengal, Arunachal Pradesh, Assam, Nagaland, Manipur, Mizoram, Tripura, Meghalaya, Andaman & Nicobar	Inceptisols, Entisols, Alfisols and Aridisols
2.	Coastal alluvial	Andhra Pradesh, Karnataka, Tamilnadu, Kerala, West Bengal, Gujarat, Odisha, Puducherry, Lakshadweep, Andaman & Nicobar	Aridisols, Inceptisols, Entisols
3.	Red	Andhra Pradesh, Karnataka, Kerala, Tamilnadu, Puducherry, Rajasthan, Madhya Pradesh, Maharashtra, Gujarat, Goa, Arunachal Pradesh, Assam, Manipur, Meghalaya, Nagaland, Mizoram, Tripura, Delhi, Uttar Pradesh, Himachal Pradesh, Andaman & Nicobar	Alfisols, Ultisols, Entisols, Inceptisols, Mollisols, Aridisols
4.	Laterites	Andhra Pradesh, Karnataka, Kerala, Tamilnadu, Puducherry, Maharashtra,, Odisha, West Bengal	Alfisols, Ultisols, Inceptisols
5.	Black	Madhya Pradesh, Maharashtra, Rajasthan, Puducherry, Tamilnadu, Uttar Pradesh, Bihar, Odisha, Andhra Pradesh, Gujarat	Vertisols, Mollisols, Inceptisols, Entisols and Aridisols
6.	Desert	Rajasthan, Gujarat, Haryana, Punjab	Aridisols, Inceptisols, Entisols
7.	Terai	Uttar Pradesh, Sikkim	Mollisols, Entisols
8.	Hills	Uttarakhand, Manipur, Odisha, West Bengal, Tripura, Nagaland	Inceptisols, Entisols Mollisols

Alluvial Soils: Alluvial soils are among the most fertile lands and form a crucial group of soils for agricultural production. These soils are found in the Indo-Gangetic Plain, spanning from Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal, and Assam in the east, and also in the northern parts of Gujarat. They cover an area of about 75 million hectares and are also present in coastal and deltaic regions. Floodplain soils are typically classified as alluvial.

Black (Cotton) Soils: These soils are deeply dark colored and become extremely hard when dry, and sticky and plastic when wet. They are often challenging to cultivate and manage due to their high clay content and exhibit characteristics like shrink-swell properties. In dry regions, they often develop distinctive cracks that are 1 cm or wider and extend to a depth of at least 50 cm. Black soils are predominantly found in the central, western, and southern states of India

Desert (Arid) Soils: These soils are found in arid regions. Due to low rainfall, desert soils typically accumulate salts at or near the surface, forming horizons such as salic, sodic, gypsic, petrogypsic, calcic, or petrocalcic. They are located between the Indus River and the Aravalli Ranges in Northwestern India (Rajasthan, Gujarat, Haryana, and Punjab).

Red Soils: These soils are moderately to highly weathered, rich in secondary forms of iron and/or aluminium oxides (sesquioxides), low in humus content, and typically have a clay-enriched B-horizon. In India, the most common red soils develop under hot, semi-arid to (sub) humid climatic conditions in subtropical regions, covering approximately 13% of the land area. Red soils typically form on acidic igneous rock and occupy higher topographic positions, while black soils form on basaltic (basic) rock or alluvium derived from basalt, and occupy relatively lower topographic positions.

Laterites and Lateritic Soils: It consists of highly weathered material enriched in secondary forms of iron and/or aluminium, lacking in bases and primary minerals. It tends to be hard or hardens upon exposure to alternating wetting and drying conditions. This includes Plinthite.".

Salt-affected soils: These soils have significant amounts of soluble salts and/or sodium on their exchange complex. They are found in regions where potential evapotranspiration greatly exceeds precipitation, typically in arid and semi-arid areas. These salt-affected soils (SASs) encompass saline, sodic, and saline-sodic soils.

Forest and Hill Soils: These soils develop under forest cover, regardless of the forest species or profile development. They occur under various forest types, including tropical, deciduous, coniferous, and tropical evergreen forests.

Podzolic Soils: Soils formed under coniferous vegetation, with acid humus and low base status, exhibit some distinctive features associated with podzols. They are characterized by base leaching and the translocation of sesquioxides, leading to the development of a bleached A-horizon.

Peaty and Marshy Soils: The terms 'peaty' and 'marshy' refer to soils that have formed in low-lying coastal marshlands or in depressions left by dried lakes in alluvial and coastal plain areas, previously occupied by mangrove swamps. These soils are found in Goa, Kerala, Odisha, the Sunderbans in West Bengal, southeastern Tamil Nadu, and the northeastern states.

3.0 Remote Sensing of Soils

Remote sensing (RS) technology making use of emitted or reflected electromagnetic radiation (EMR) for obtaining information regarding a specific object, area or phenomenon from a distance, plays a vital role in the assessment and management of soil resources. Based on the source of EMRs, remote sensing is categorized broadly into active as well as passive remote sensing, where active RS instruments carry their own light or emission sources and passive ones rely on solar radiation. The radiations involved in remote sensing process also differ in their wavelengths and thus their energy content as well as nature of interaction with features on the earth surface. Based on the wavelength, EMRs has been grouped into visible (0.4-0.7 µm), near infrared (0.7-1.4µm), shortwave IR (1.4µm-3µm), thermal IR (3µm to 14µm) as well as microwave (1mm-30cm). Depending on the characteristics of the radiation as well as surface features, the incident radiation may get reflected, absorbed, transmitted as well as scattered, giving rise to specific features on the spectra which helps in identification as well as characterization of various components.

3.1 Soil Reflectance

Soil reflectance is a composite property influenced by the inherent spectral characteristics of the heterogeneous mix of minerals, organic matter, and fluids that make up mineral soils. Spectral reflectance measurements indicate that various soil properties such as soil moisture, organic matter content, particle size distribution, iron content, and surface conditions affect soil reflectance.

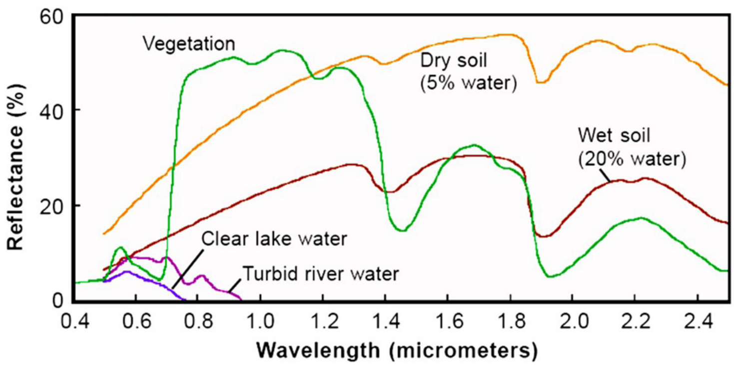


Figure 3.1: VNIR Spectral reflectance of common features on the earth surface

Figure 3.1 illustrates one of the most consistent characteristics of dry soil: reflectance increases with increasing wavelength, particularly in the visible, near-infrared, and mid-infrared regions of the spectrum.

3.1.1 Soil texture and Moisture Content

Soils with finer particles exhibit higher spectral reflectance due to near-specular reflection from the surface, compared to coarser particles. Generally, clayey soils appear darker to the eye than sandy soils, due to differences in mineralogy and the tendency of clay particles to aggregate and form clods, resulting in a rough surface as well as hold moisture.

An increase in moisture content leads to greater radiation absorption, thereby reducing overall soil reflectance. Higher moisture content in both sandy and clayey soils decreases reflectance across the visible and NIR regions, particularly in the water absorption bands at 1.4, 1.9, and 2.7 µm, and the hydroxyl absorption bands at 1.4 and 2.2 µm.

3.1.2 Soil Organic Matter

Increase in soil organic matter results in decreased reflectance. Organic matter exhibits spectral activity across the entire VNIR-SWIR region, particularly in the visible range. When organic matter content exceeds 2%, it can mask other absorption features in the soil spectra. If the content falls below 2%, its effect on soil reflectance is minimal. The wavelength range from 0.90 to 1.22 µm is well-suited for soil organic matter mapping.

3.1.3 Iron oxide

Iron (Fe) is a common principal component of many soil minerals. Numerous absorption features in soil reflectance spectra are attributed to the presence of Fe in various forms. Fe oxides increase reflectance in the red portion of the spectrum (600-700 nm). Other absorption bands often appear near 700 and 870 nm, causing strong absorption bands around 1.0 µm. In the mid-infrared (MIR) region, iron absorption can be intense enough to obscure the water absorption band at 1.4 µm.

3.1.4 Mineral composition

Soil minerals primarily affect the shortwave spectra more than the visible and near-infrared regions. Quartz exhibits high reflectance throughout the shortwave region, and its spectra lack absorption features unless impurities are present. Other primary minerals are less reflective and have spectra with absorption features caused by the vibrations of hydroxyl ions. For example, muscovite shows absorption bands at 1.4 µm and between 2.2 and 2.6 µm.

Hydroxyl bands around 1.4 and 2.2 µm are characteristic of layer silicates. The 2.2 µm hydroxyl band is typically difficult to identify in most soil spectra but becomes more pronounced in soils with clay content exceeding 20%.

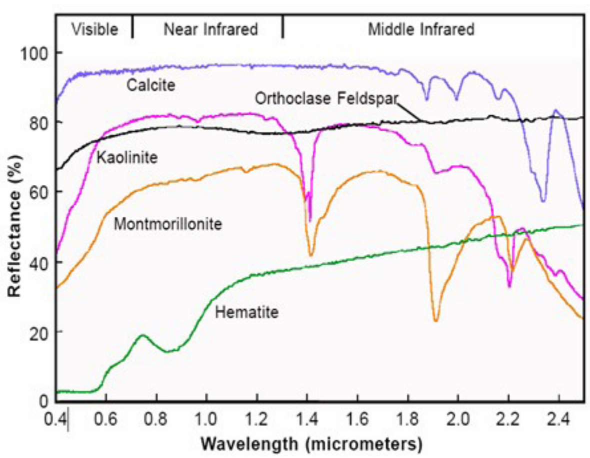


Fig 3.2. Spectral reflectance off various clay mineral present in the soils

Chapter 3

The spectra of other secondary minerals also exhibit distinctive features. Calcite spectra display absorption bands between 1.8 and 2.5µm due to the presence of carbonates. Gypsum spectra show absorption bands at 1.8 and 2.3µm, resulting from overtones and combinations of water molecule vibrational frequencies. Soils characterized by gypsic mineralogy demonstrate the highest spectral reflectance across all observed wavelengths. Soils dominated by montmorillonitic clay minerals show the lowest average spectral reflectance between 0.52 and 1.0µm. Soils with dominant Kaolinite clay minerals typically exhibit a broad absorption band near 0.9 µm, attributed to the common presence of free iron oxides.

3.1.5 Soil Salinity

Soil Reflectance tends to rise with increasing salt concentration on the surface. Salt-affected soils display higher reflectance in the Vis-NIR spectra in comparison to non-saline soils, making them appear as bright white patches in multispectral false color composites (FCC).

3.1.6 Surface roughness

Finer textured soils, such as clayey soils, generally exhibit higher reflectance compared to coarse textured soils, like sandy soils, assuming they are free of moisture, organic matter, and iron oxides. Dry, fine-textured clayey soils reflect more in the Vis-NIR regions than sandy or silty soils. However, the presence of soil moisture, organic matter, and other minerals can diminish the reflectance of fine clay. Consequently, fine-grained clayey soils with high moisture and organic matter have lower reflectance than coarser dry sands.

It can be concluded that soil spectra contain unique and significant information about various soil properties. Given the complexity of soil systems, interpreting soil spectra requires careful consideration. Advancing remote sensing for soil studies will benefit greatly from a deeper understanding of how light scatters off soil surfaces.

3.2 Microwave Remote Sensing of Soils

Microwave remote sensing of soils has emerged as a powerful tool in understanding soil properties and dynamics across various spatial and temporal scales. Unlike visible or infrared wavelengths, microwaves penetrate through clouds and canopies, providing valuable information regardless of weather conditions or vegetation cover. Due to their large wavelength, microwaves have the ability to penetrate soil surface, thus enabling us to measure and characterize soil in the subsurface layers.

Microwave RS is most widely used for estimation of soil moisture content, surface roughness as well as textural composition. Microwave radiation interact differently with various soil components, resulting in backscatter signals caused by varying degrees of signal attenuation. Microwave radiation interacts differently with wet and dry soils owing to the wide variations in dielectric constant, allowing for the estimation of soil moisture content at varying scales based on backscatter signals. This information is crucial for agricultural management, hydrological modeling, and drought monitoring.

Moreover, microwave remote sensing can provide insights into soil roughness and texture. The surface roughness of soil affects the scattering of microwave radiation (rough surfaces scatter more), allowing researchers to infer soil texture and composition. This information aids in soil classification and mapping, facilitating land management decisions and soil conservation efforts. Microwave remote sensing also enables the monitoring of soil freeze-thaw cycles in cold regions. As soil freezes, its dielectric properties change, influencing microwave backscatter. By observing these changes, researchers can track freeze-thaw dynamics, which are essential for understanding ecosystem processes and climate change impacts.

3.3 Thermal Remote Sensing of Soils

Thermal remote sensing of soils harnesses the Earth's natural thermal emissions (radiations in thermal wavelength region) to gather valuable information about soil properties and processes. The surface temperature of various features could be estimated by measuring the emitted thermal radiations, thus help in retrieval of properties. This technique relies on the principle that different soil properties, such as moisture content and texture, influence the soil's thermal behavior, allowing researchers to infer these properties remotely.

Soil moisture influences thermal inertia, affecting temperature variations, which serves as the foundation for estimating soil moisture. By processing thermal radiation from the soil, land surface temperature (LST) can be determined, allowing for the inference of soil moisture variations. This information is crucial for irrigation management and drought monitoring.

Accurate soil temperature data is essential for understanding soil processes, crop growth, and microbial activity. Thermal sensors provide spatial and temporal soil temperature patterns that can be used in agricultural planning and climate studies. Similarly, LST data helps in understanding the heat exchange between the land surface and the atmosphere. This is vital for weather forecasting, climate models, and studying urban heat islands.

Thermal RS has also been used for identifying and mapping soil degradation especially with respect to salinity and heavy metal contaminations, due to their influences on soil thermal properties. High salinity areas often show distinct thermal signatures due to differences in heat capacity and thermal conductivity. A list of commonly used satellites for remote sensing of soils is indicated below in Table 3.1.

Table 3.1: List of commonly used satellites

Satellite	Country	Wavelength Range
Optical region		
Resourcesat Series	India	Visible, NIR
Cartosat series	India	Visible, VNIR & SWIR
Landsat series	USA	Vis, NIR, SWIR, Thermal IR

Sentinel – 2A & 2B	European Union (EU)	VNIR, SWIR
Worldview-3	USA	VNIR, SWIR
MODIS	USA	VNIR, SWIR
SPOT -7	France	VNIR
Rapid Eye	Germany	VNIR
Microwave Region		
RISAT series	India	C band SAR
ALOS-2	Japan	L band SAR
RADARSAT series	Canada	C band SAR
TerraSAR-X	Germany	X band SAR
Sentinel-1A & 1B	EU	C band SAR
TanDEM-X	Germany	X band SAR
KOMPSAT-5	South Korea	C band SAR

4.0 Soil Resource Mapping

Soil forming factors

Soils are formed by two consecutive stages (i) weathering of rock into regolith and then (ii). by soil forming processes governed by soil forming factors over the regolith as parent material. Soil profiles are shaped by the interaction of five factors: parent material, climate, topography, organisms, and time. Soil scientists refer to these as ***soil-forming factors***. The soil formation is described by Jenny (1941) as

$$S = f(cl, o, r, p, t,) \ldots\ldots\ldots\ldots\ldots \text{ Eq 4.1}$$

where, cl-Climate, o- Organism, r- Relief, p-Parent material, t-Time

Kinds of soil that develop are largely determined by these five major factors:

I. Climate (particularly, precipitation and temperature)
II. Living organism (spatially native vegetation, microbes, soil animals and human being)
III. Nature of parent material
IV. Topography of the site
V. Time for which parent materials are subjected to soil formation.

Geological processes have brought a variety of parent materials to the Earth's surface, forming the basis for soil development. The nature of these parent materials significantly affects soil characteristics, influencing their physio-chemical properties. Topography, which refers to the land surface configuration including elevation and slope differences, also plays a crucial role. Rolling to hilly terrains promote natural erosion of the surface layer, reducing the likelihood of deep soil formation. There is a definite interaction among topography, vegetation, and soil formation. Additionally, the duration for which materials have been subjected to weathering impacts soil development.

4.1.1 Climate (Cl)

Climate (Cl) is the most influential factor in soil formation, as it dictates the nature of weathering and affects the natural vegetation and soil organisms, which are crucial for profile differentiation. The two most important aspects of climate that directly impact soil formation are precipitation (total amount, intensity, and distribution) and temperature (soil temperature). These elements are the primary forces driving soil-forming processes during soil development.

4.1.2 Parent material (P)

Landforms serve as the foundation for identifying and mapping parent material types in the study area. Geomorphology, the study of landforms, examines their composition and the processes that create and shape them. The synoptic and temporal capabilities of satellites are effectively utilized to map various landform types. These landform types can be broadly categorized as:

I. Landform of structural origin: Landforms of structural origin are related to the structural aspects of the area. Most landforms in this category have their genesis linked to the underlying geological structures. The structure plays a significant role in reducing the resistance of rock, leading to various geomorphic forms.

These landforms mainly include Dissected Structural Hills and Valleys, which result from tectonic processes and are heavily dissected by drainage lines.

II. ***Landforms of denudational origin:*** These landforms originate where denudation processes prevail over others. Denudation involves the removal of materials through erosion and weathering, resulting in various distinct shapes and forms of land. Important denudational landforms are categorized as:

» *Bajada:* A wide, uninterrupted alluvial slope or gently inclined detrital surface that extends along and descends from the base of a mountain range in semi-arid or desert regions.

» *Butte:* A prominent, typically solitary hill or small mountain with a generally flat top and relatively steep slopes.

» *Pediment:* A broad, flat, or gently sloping erosion surface or plain with a rock floor and low relief, typically formed by subaerial agents (including running water) in an arid or semi-arid region. This feature develops at the base of an abrupt and receding mountain front or plateau escarpment and is underlain by bedrock.

» *Plateau:* Generally, a plateau is any relatively flat area of significant extent and elevation, typically rising more than 150-300 meters above the surrounding terrain.

III. ***Landforms of fluvial origin:*** In earth science, the term "fluvial" refers to processes and landforms created by running water. Like other surface processes, running water can erode material from the landscape or deposit layers of sediment. They are mainly alluvial plain, alluvial fan, terrace, flood plain, levee / natural levee, braided bar, palaeochannel: oxbow lake, meander scar, point bar, etc.

IV. ***Eolian landforms:*** Wind is a significant geological agent that plays a dominant role in the formation of Aeolian landforms. These areas typically lack vegetation, making wind erosion and deposition the primary processes shaping Aeolian landforms. Examples are aeolian plains, dune complex, barchan, loess, longitudinal dune, parabolic dune etc.

V. ***Topography (r)***: Topographic relief, including the slope and aspect of the land, significantly influences soil distribution across a landscape. Slope determines the amount of precipitation that infiltrates into the soil versus the amount that runs off the surface. Aspect, or the direction a slope faces, affects soil temperature. Variations in moisture and temperature regimes create microclimates, leading to differences in vegetation depending on the aspect.

Slope classes: It can be subdivided as follows:

» Nearly level (0-1 %)-Level, nearly level

» Gently sloping (1-3%)-Very gently sloping, gently sloping

» Undulating (3-8%)-Gently undulating, undulating

» Strongly sloping (8-15%)-Sloping, strongly sloping, moderately sloping

» Moderately steep (15-30%)-Rolling, strongly rolling

» Steep sloping (30-50%)

» Very Steep Sloping (>50%)

4.1.4 Time (t)

Time is a crucial factor in soil formation, as soils develop over extended periods. Soil formation is a dynamic process, gradually approaching a steady state, although this equilibrium is rarely achieved.

4.1.5 Land Use / Land cover (O)

Organism refers to macro and micro-organism both. Land use / land cover types are considered as macro organism and it largely contribute in developing various types of soil i.e. horizonation, nutrients availability etc. Animals and microorganisms create pores and crevices in the soil, significantly influencing soil formation and structure. Furthermore, decomposing leaves and other plant materials contribute to soil organic matter and nutrients.

4.2 Soil Resource Mapping

Soil mapping is crucial for the effective implementation of sustainable land use management. It involves delineating natural soil bodies, classifying and grouping these soils into map units, and capturing soil property information to interpret and depict soil spatial distribution on a map.

Soil Mapping Unit: Soil map units outline an area with a clearly defined, closed border drawn by a soil scientist, typically representing a single soil type. A mapping unit is almost equivalent to a soil phase and is usually named according to the soil series classification of the dominant soil.

Catena concept

A catena is a sequence of soils of similar age, derived from comparable parent material, and occurring under similar climatic conditions, but exhibiting different characteristics due to variations in relief (slope) and drainage. Catenary soil-landscape relationships have proven to be one of the most powerful tools in soil-landscape modelling.

The position within the landscape influences water movement, drainage, microclimate, and consequently, the physical, chemical, and biological properties of soil. Therefore, even if soils share the same age, climate, and parent material, their properties can vary depending on their location along the catena.

Pedon and polypedon

Pedon: It is the smallest unit of soil that is large enough to represent the nature and arrangement of horizons and the variability in other properties. A pedon lacks boundaries with neighboring pedons (Soil Survey Staff, 1999) and serves as a fundamental unit for observation, sampling, and classification.

A pedon extends from the soil surface to its lower limit. Its surface typically forms a polygonal shape, ranging in area from 1 to 10 square meters. A depth of 2 meters provides a comprehensive sample of the major soil horizons, even in thicker soils. The pedon is the individual unit classified within Soil Taxonomy.

Polypedon: A pedon, on its own, is too small to serve as the unit for soil mapping. The concept of a polypedon is, practically speaking, roughly equivalent to the component used in soil mapping, with one technical distinction.

The polypedon serves as the fundamental unit for interpretation and soil management in mapping. While the pedon is described as the taxonomic unit, the polypedon is the unit used in soil mapping. Multiple contiguous pedons that share the same classification and occur together in landscapes define soil series. Conceptually, these contiguous pedons are referred to as polypedons.

Taxonomic classes are conceptual categories in soil science. Each taxonomic class is defined by specific set of soil characteristics with well-defined limits. These classes serve as a framework for systematically comparing and classifying soils.

Some commonly used term in mapping and classification of soils are:

Solum: The solum (plural, sola) of a soil comprises a sequence of horizons that have developed over the same period of soil formation (pedogenesis). It excludes any buried soil or layer unless it has acquired properties from currently active soil-forming processes. The solum extends from the soil horizons above to the parent material, C, or R horizon. It typically includes the O, A, E, and B horizons along with their transitional layers.

Organic soil: Layers that are not continuously saturated with water for more than a few days are considered organic if they contain 20 percent or more organic carbon.

Muck soil: A soil containing 20-50 % organic matter.

Lithic contact: A boundary between soil and continuous coherent, underlying material that has a hardness of >3 on the Moh scale. Soils called Lithic soils if the rock encountered within 50 cm. depth of soil.

Paralithic contact: A boundary between soil and underlying coherent material, with a hardness of <3 on the Moh scale. The roots may penetrate at irregular and infrequent intervals of >10 cm.

Skeletal soil: It refers to soils having 35 percent or more (by volume) of rock fragments, cobbles, gravel, and laterite concretions or ironstones with diameters larger than 2 mm, typically found within shallow depths (less than 50 cm).

Fragmental soil: Soil material that consists of 90 percent or more rock fragments. Less than 10 percent of the soil consists of particles 2 mm or smaller.

Regolith: It is the material above the rock as the unconsolidated weathered rock material i.e. parent material. Regolith further alters by soil forming factors to form soil.

4.3 Kinds of Soil Survey

Standard soil surveys are normally carried out in different mapping levels e.g. *Reconnaissance; Semi-detailed and Detailed,* depending on the requirement of the user area (Table 4.1).

Table 4.1: Kinds of soil survey commonly undertaken

Sl. No.	Soil survey Scale	Satellite / Sensor used	Soil Classification	Useful for
1.	1:250,000 (Reconnaissance scale)	IRS - LISS -1, 2 IRS-AWiFS Landsat-TM Sentinel -1, ASTER	**Sub-groups** / Family Associations	Soil Inventory at regional scale / State Level
2.	1:50,000 (Semi-detailed)	IRS – LISS -II, III Landsat-TM Sentinel -1, ASTER	**Soil Family** / soil series associations	District Level
3.	1:25,000 (Detailed)	IRS-LISS IV IRS- LISS III+PAN	**Soil series** and their association	Block / Tehsil level
4.	1:10,000 or larger (Very detailed)	IRS – LISS IV + PAN (Cartosat) IKONOS QUICKBIRD	**Soil Types** & Phases	Village level / Panchayat

4.3.1 Conventional soil survey

It is based on the soil-landscape / soil-physiographic analysis which follows the concept of soil forming factors. Soil surveyors identify various soil-forming environments by visually interpreting geological maps (parent material), topographical features like slope and aspect, and predominant land use and land cover (organisms) using satellite remote sensing data, topographic maps, and other supplementary maps and data. The spatial boundaries of soil-formative environments are utilized to delineate soil-landscape units referred to as physiographic units. These units are typically first identified on satellite imagery, then verified through field observations and integrated into a base map. Soil profiles within these physiographic units are then examined to characterize and classify the soils, ultimately creating a physiographic-soil map.

Soil forming factors affect the soil pedogenic processes that determine soil development and its soil properties. Soil development variations are further explained by catena concept that attributes soil variation. It follows conventional soil-landscape model (CSM) based on the Clorpt model i.e. $S = f(cl, o, r, p, t)$ which define the state of a soil system governed by soil forming factors (Jenny, 1941).

Remote Sensing Data

Satellite data offer comprehensive coverage of large areas, allowing surveyors to analyze different landforms, geomorphic processes, and their correlation with natural vegetation. Satellite imageries (Standard False Color Composites-FCCs) are commonly used to interpret soil-forming factors governing variability of soils represented by soil-landscape units. RS data in mapping boundaries based on image characteristics to identify parent materials, vegetation types, drainage conditions, and other factors affecting surface reflectance.

A physiographic unit or soil-landscape unit is the area which has similar soil forming factors. It is assumed that similar soil forming factors will result similar pedogenic processes and will result similar soils.

The soil survey methodology comprises 3- tier approach described as below:

a. ***Pre-field interpretation:*** Satellite imageries in False Colour Composite (FCCs) of study at appropriate scale are procured. The imageries are visually interpreted for geomorphology / geology/ lithological (parent material) units which are initially delineated based on available ancillary geological maps. It is followed by delineation of broad physiographic units based on relief information available in topographical maps or Digital Elevation model (DEM) and broad land use / land cover types (Fig 4.1).

b. ***Field Survey:*** Field work is carried out to study physiography and their associated soils. Sample strips (generally three nos.) covering all the units, were selected on the interpreted map, for ground verification. These sample strips studied in the field for verification of interpretation and soil profile observation.

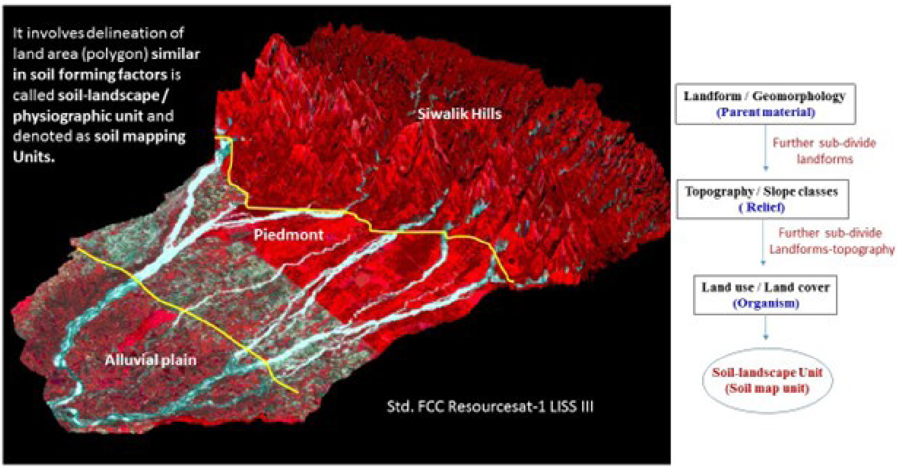


Fig 4.1 : Overall methodology of RS data based delineation of soil –landscape units

c. ***Post-field interpretation:*** After field work, ground truth observation and soil information are compiled. Modification in the physiographic units, delineated earlier, are made. Physiographic units are subsequently translated into soil-landscape units by incorporating information on soils. soil-landscape units are subsequently transferred onto base map of the same scale generated from topographical maps. Area under each soil-landscape unit estimated and its soil characteristics are described accuracy assured.

4.3.2 Digital vs. Conventional Soil Mapping

Traditionally, soil mapping has employed a discrete model to depict individual soil types and groups of soil types across the landscape as map units. In discrete models, thematic data are represented by values corresponding to predefined classes, assuming that soils within the map unit are similar (Fig 4.2).

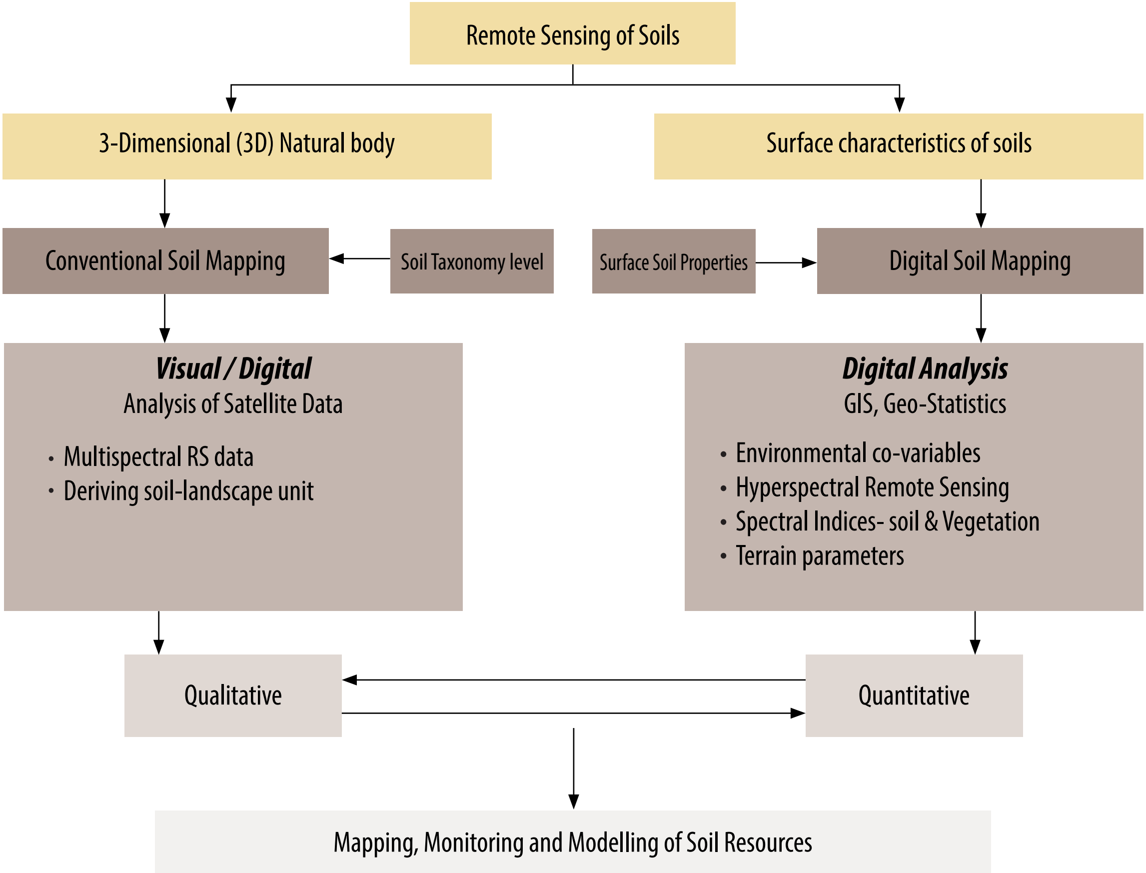


Fig 4.2: Schematic diagram showing applications of RS data in conventional vs Digital soil mapping

However, the key difference between digital soil mapping and conventional soil mapping lies in the approach: digital soil mapping utilizes quantitative inference models to predict soil classes or properties within a geographic database (raster). These models leverage data mining, statistical analysis, and machine learning to organize extensive geospatial data into coherent clusters, identifying spatial patterns effectively. Statistical techniques like multiple regressions, artificial neural networks, or classification and regression trees (CARTs) are frequently employed to establish relationships for predicting soil attributes or classes. These methods are utilized to estimate soil attributes at locations where no samples have been taken. Geospatial models predict soil attribute values at unsampled locations based on spatially distributed observations of soil attributes across the mapping area (Fig 4.2). A more detailed exploration of digital soil mapping will be presented in a separate chapter.

5.0 Terrain Analysis for Soil Mapping

Terrain or topography refers to the shape and/ or configuration of the land surface. Terrain analysis involves investigating and studying the features and properties of the Earth's surface, with a focus on its topography, landforms, and associated features. It mainly involves the collection, interpretation, and visualization of spatial data related to the landscape.

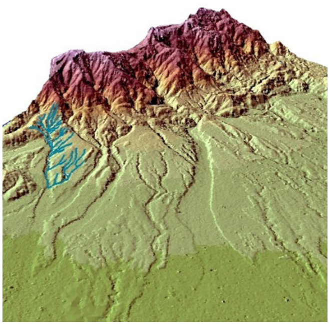
5.1 Digital Elevation Model (DEM)

DEM (Digital Elevation Model) is a broad term referring to any digital representation of a topographic surface that conveys elevation or height information at regular intervals. It digitally portrays the continuous variation of terrain relief across a geographic area.

DSM (Digital Surface Model) represents the top surface of the Earth, including all objects on the terrain, such as buildings, vegetation, and other human-made and natural features. It includes both the bare ground elevation and the elevation of any objects or features present on the Earth's surface.

Whereas, a DTM represents the bare Earth's surface without any human-made or natural objects. It provides elevation values for the ground itself, excluding features like buildings, vegetation, and bridges. The elevation values in a DTM are typically obtained from ground surveys or LiDAR data. The generic term "DEM" will be used further in the chapter, for general understanding and discussion.

3D- View of the Terrain



Terrain Variables
Primary: Slope, Aspect, curvature, flow direction, flow accumulation etc
Secondary: Terrain wetness Index, Stream Power Index, Sediment Transport Index, solar insolation, topographic position index etc.

Fig 5.1: DEM showing 3-D view of a terrain and the list of commonly used terrain variables

5.1.1 DEM data sources

DEMs are generated using different techniques, depending on the data source and the required level of detail. These techniques include ground surveys (using GPS), photogrammetry (using stereoscopic imageries), radar interferometry (using Synthetic Aperture Radar - SAR data), airborne laser scanning (using LiDAR - Light Detection and Ranging), Unmanned Aerial Vehicle (UAV) data capture, interpolation techniques (using elevation information in the form of point clouds or contour lines, existing cartographic surveys / toposheets) as well as data fusion (using data form multiple sources). A list of few freely available DEMs are given in Table 5.1.

5.2 Terrain Analysis

Terrain analysis is a general term for set of techniques used for derivation of terrain parameters from DEM and their application. Digital terrain modelling/analysis (DTM/DTA) encompasses general tasks including DTM/DEM generation, manipulation, interpretation, visualization and application for various purposes. DEM enables the user to derive any other terrain attribute (eg: slope) quantitatively using a digital elevation data, within a very short time. It allows for a more realistic visualization of topography, such as generating 3D models, and facilitates the digital storage, updating, and manipulation of topographic data. DEMs also enable the derivation of indices that serve as indicators for environmental processes. Such DEM derived parameters are widely being used in various fields such as soil erosion modelling, hydrological modelling, watershed management, ecosystem services analysis, digital soil mapping etc.

5.2.1 Terrain parameters

Various terrain parameters can be categorized broadly into three groups, namely:

» Morphometric parameters

» Hydrological parameters

» Climatic terrain parameters

Morphometric parameters are those which describe the shape and form (morphology) of the earth's surface. These parameters are important for characterizing landforms, analyzing the topography, and understanding the geomorphology of a region. It comprises of elevation change gradients (eg: elevation, Slope, terrain roughness etc), orientation change gradients (aspect, steepest downhill slope, view shed etc) as well as curvature gradients (Horizontal/tangent curvature, vertical/profile curvature, mean curvature etc).

Hydrological parameters are specific terrain characteristics that play a crucial role in hydrological modeling, watershed analysis, and understanding how water moves through a landscape. These parameters are based on flow accumulation, describing the potential movement of materials and aiding in quantifying and modeling factors like flow intensity, accumulation potential, and soil erosion potential. The most widely used hydrological parameters are Compound Topographic Index (CTI), Stream Power Index (SPI), Sediment Transport Index (STI) etc.

Climatic terrain parameters are climatic variables adjusted for relief factors. Computation of these parameters are much more complex than morphometric and hydrological parameters. Also a large number of input parameters are required for their computation making their accurate generation and adoption slightly difficult. Some of the examples are Direct/diffuse solar insolation, slope insolation etc.

The various categories of terrain parameters are widely used in various applications related to watershed delineation/ characterization, soil erosion risk modeling and mapping, soil-landscape modeling and mapping, geostatistical interpolation based soil property mapping as well as digital soil mapping approaches. Apart from these categories, DEM has also been used for generation of various generic terrain parameters which are used for delineation of landforms.

6.0 Digital Soil mapping

Digital soil mapping (DSM) is the computer-assisted production of digital maps of soil type and soil properties using various quantitative mathematical and statistical models that combine soil information with data contained in correlated environmental variables and remote sensing images.

DSM approaches involve the use of digital technologies, geospatial data, and statistical methods to create detailed and accurate maps of soil properties and classes across different landscapes. It also referred as predictive soil mapping, involves collection of various forms of data, such as elevation, climate, vegetation, and existing soil observations, and uses advanced techniques to predict and interpolate soil information in areas where direct measurements might be lacking.

DSM can be described as an advanced method for mapping either a. fundamental soil properties or soil classes, b. secondary soil properties, or c. soil functions and/or threats. The general principle underlying DSM activities is widely referred as 'scorpan' principle, which is a modification of the state factor equation for soil genesis ('clorpt').

$$S = f\,(S, C, O, R, P, A, N) + e \quad \ldots\ldots\ldots\ldots\ldots \text{Eq. 6.1}$$

Where, S : soil class or other properties or prior knowledge of the soil at a point

f : (numerical model) Decision trees, Random forests, neural networks etc.

C: climate, climatic properties of the environment at a point; climate model outputs

O : organisms, vegetation or fauna or human activity

R : topography, landscape attributes, relief

P : parent material, lithology

A : age, the time factor

N : space, relative spatial position

e: auto correlated random spatial variation (spatially dependent residuals)

The equation simply states that "the soil type or attribute at an unvisited site (S) can be predicted from a numerical function or model (f) given the factors just described plus the locally varying, spatial dependent residuals (ε)".

The Scorpan model is utilized to quantitatively predict soil classes or continuous soil attributes based on empirical observations, without focusing on identifying the factors contributing to soil formation or development. These various scorpan factors form the basis of DSM and are referred as environmental covariates.

6.1 Environmental covariates for DSM

Environmental covariates representing various 'Scorpan' factors are generated or obtained digitally from sources such as remote sensing images, digital elevation models, existing soil maps, etc., at different spatial and temporal resolutions. These covariates are further integrated into the DSM framework.

Prior soil information mainly arises from two sources namely, legacy soil information as well as soil sensing approaches. Legacy soil information comes from or comprises of data regarding soil samples, soil profiles, existing soil maps, or information derived from expert knowledge etc. Additionally, soil information could also be generated using various soil sensing techniques employing remote sensing as well as proximal sensing approaches involving the use of hyperspectral RS data, sensors such as chromameters, pXRF (portable X ray fluorescence), LIBS (Laser Induced Breakdown Spectroscopy) etc.

Climate, an active soil forming factor owing to its influence on the nature and rate of biophysical and geochemical process/activities, play a crucial role in governing the geographical distribution as well as variability of soil types as well as properties. Typical climatic variables routinely observed and mapped across countries include minimum and maximum temperatures, mean temperature, cumulative mean temperature, precipitation, potential evapotranspiration, climatic water balance, global radiation, and snow depth. Such climate data may exist as point data or raster format, which needs to be processed accordingly.

6.1.1 Remote Sensing data derived information

They are mainly in the form of vegetation images, land use / land cover maps, spectral bands / indices, emissivity/ land surface temperature etc are widely used in DSM activities across the globe, owing to their ability in representing vegetation influences on soil properties.

Land use and/or land cover data is undoubtedly one of the most crucial datasets representing the impact of vegetation. Apart from LULC maps/products, spectral indices such as NDVI, EVI, SAVI etc. form the most widely used environmental covariates for DSM activities. Google Earth Engine (GEE) platform helps in the processing of time series satellite data as well as generation / utilization of long-term average vegetation indices for various applications using moderate to high-resolution RS datasets.

Topographical variables representing 'relief' are the most widely used covariates in DSM activities globally. Terrain attributes can be broadly categorized into two groups: (1) primary attributes, which are directly calculated from a Digital Elevation Model (DEM); and (2) compound attributes, derived from combinations of primary attributes. Slope gradient, aspect, wetness index, slope length, curvature, ruggedness index, landform etc are some of the examples of terrain attributes. By utilizing various combinations of these terrain attributes, unique land features and geomorphic surfaces can be generated. This approach also offers insights into the processes of soil formation, development, material movement, and redistribution.

Parent material information, a vital component governing the innate variability of soil characteristics could be obtained from published geological, geomorphological, or rock type or parent material or litho-stratigraphic maps of the study area, depending on their scale and availability.

6.1.2 Proximal Sensing and Spectroscopy for DSM

» Proximal sensing utilizes sensors and instruments positioned near to or in direct contact with the soil surface. These sensors provide certain advantages such as non-destructive measurement, rapid data collection as well as real-time or near-real-time monitoring and data collection. Some of the most widely employed proximal sensors for soil related studies include electromagnetic induction (EMI), ground-penetrating radar (GPR), acoustic sensors, handheld portable x-ray fluorescence (pXRF), pH and Electrical Conductivity (EC) Sensors, Time Domain Reflectometry (TDR) Sensors, Gamma Ray Soil Density Sensors, Infrared Thermometers etc.

» Spectroscopy involves study of the interaction between electromagnetic radiation (EMR) and matter (soil samples) to obtain information about the composition and properties of soils. This technique provides insights into various aspects of soil, including its mineralogy, organic matter content, moisture levels, and even microbial activity.

» VNIR spectroscopy entails examining the reflectance or absorbance of light across the visible and near-infrared spectra (typically 350 to 2500 nm). This method is commonly employed to quickly assess soil properties such as organic matter content, mineral composition, and moisture content. It relies on the fact that different components of soil absorb and reflect light differently at various wavelengths.

Various RS derived environmental covariates as well proximal sensing derived soil information provide vital information for digital mapping of soil characteristics employing various predictive modelling based DSM techniques.

6.2 DSM techniques

The techniques most widely employed for DSM activities across the world mainly belongs to three major groups of mathematical or statistical models:

I. Regression models (linear regression, multiple linear regression, geographically weighted regression, non-linear regression etc.)

II. Geostatistical techniques (Kriging, cokriging, regression kriging etc based spatial interpolation)

III. Machine learning techniques (Decision trees, Random Forests, support vector machines, neutral networks, deep learning, image clustering techniques, ensemble modelling, cloud computing etc).

» ***Regression models:*** provides mathematical (quantitative) functions describing the relationship between various soil properties (dependent/response/target variable) and one or more environmental covariates (independent variables). When the soil property and environmental covariate(s) are linearly related, the resultant model will be a (multiple) linear regression model, which could be used for spatial prediction and mapping of the property in the area.

» ***Geostatistical techniques*****:** These techniques are based on mathematical functions as well as statistical theory, where the various models parameters (indicating spatial autocorrelation) are estimated based on probability theory. Geostatistical analysis mainly involves spatial modelling, through which spatial autocorrelation / spatial dependence is quantified in the form of variogram model and further used for the interpolation (kriging) of target variables at unsampled locations followed by estimation of prediction uncertainty.

» ***Machine learning (ML) techniques***, a subset of artificial intelligence, offer sophisticated algorithms that can learn patterns and relationships within large and complex datasets, using data mining techniques. ML techniques empowers computers to learn from data and improve their performance over time without being explicitly programmed. In the context of digital soil mapping, these algorithms enable the extraction of meaningful insights from various sources of spatial and non-spatial data, including remote sensing imagery, geophysical measurements, climate data, and terrain attributes. Such techniques offer a data-centric approach to soil mapping by leveraging vast datasets comprised of environmental variables, such as topography, climate, vegetation, and remote sensing data (Fig 6.1). ML techniques are widely and increasingly being used for soil mapping activities.

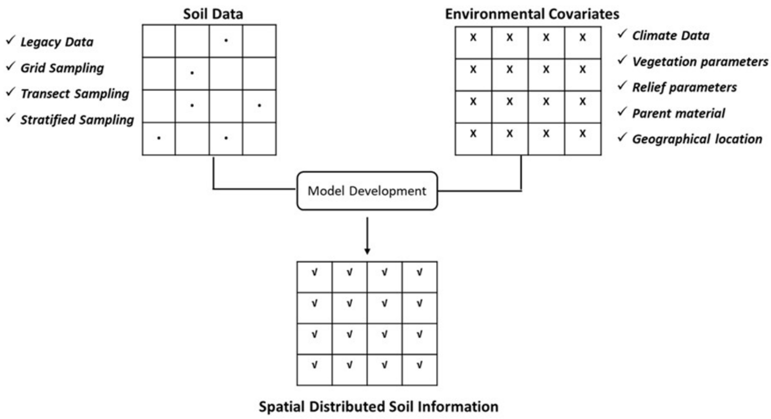


Fig 6.1: Conceptual diagram depicting digital soil mapping process

7.0 Soil Quality

Healthy soils are essential for providing clean air and water, abundant crops and forests, productive rangelands, diverse wildlife, and beautiful landscapes by performing several key functions, such as:

» Nutrient Cycling - stores, moderates the release of, and cycles nutrients and other elements.

» Water Relations - Regulates the drainage, flow, and storage of water and solutes, managing water distribution for groundwater recharge and use by plants and soil animals.

» Biodiversity and Habitat - supports the growth of diverse plants, animals, and soil microorganisms by providing a varied physical, chemical, and biological habitat.

» Filtering and Buffering - acts as a filter to protect the quality of water, air, and other resources by degrading toxic compounds or making excess nutrients unavailable.

» Physical Stability and Support - allows the passage of air and water, withstands erosive forces, provides a medium for plant roots, offers anchoring support for human structures, and protects archaeological treasures.

Soil quality is the ability of a soil to perform functions that are essential to people and the environment. It is defined as (Karlen et al.,1997) as "the capacity (or fitness) of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation".

With respect to agriculture, soil quality would be the soil's fitness to support crop growth without becoming degraded or otherwise harming the environment.

Soil quality encompasses two dimensions and can be viewed in two different ways:

» Inherent soil quality and

» Dynamic soil quality

Inherent soil quality is a soils natural ability to function and is use-invariant. These characteristics are generally stable and do not change easily, if at all, with management. Inherent soil properties primarily result from soil-forming factors (climate, topography, vegetation, parent material, and time) and are developed over thousands of years. Examples include soil texture, type of clay, cation exchange capacity (CEC), and drainage class. Inherent properties determine the maximum or ideal potential of a soil to perform specific functions, with some soils capable of functioning at higher potentials than others.

Dynamic soil quality depends on management practices. Soil properties are influenced by human management and natural disturbances over a human time scale, ranging from decades to centuries. Examples of dynamic soil quality include soil organic matter content, soil structure, soil depth, and water and nutrient holding capacity. Soils respond differently to management based on their inherent properties and the surrounding landscape. Therefore, dynamic indicators should be interpreted with consideration of the soil's inherent properties (Fig 7.1).

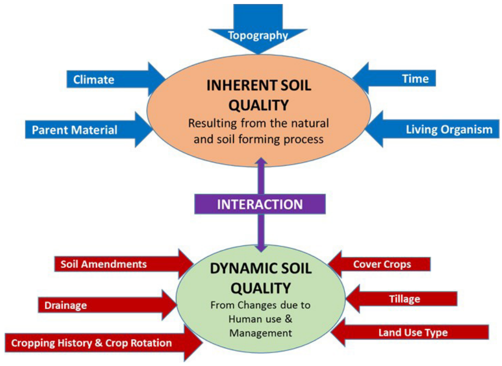


Fig 7.1: Flow diagram showing interaction of Inherent and Dynamic soil quality

7.1 Soil Quality Assessment

Soil quality assessment involves measuring changes in soil induced by management practices as we aim to optimize soil performance. Assessing soil quality means evaluating how well the soil currently performs its functions and how well these functions are preserved for future use. As soil quality is a complex characteristic of land which has a well understood influence on the capability of land for a specific use, it cannot be determined by measuring only crop yield, water quality, or any other single outcome.

Soil quality cannot be directly measured. It is a complex attribute of land that is assessed using indicators. Indicators are measurable properties of soil or plants that offer insights into how well the soil can function. These properties serve as proxies for soil function because directly measuring function can be challenging and observations may be subjective. An efficient indicator set refers to a collection of low-cost, easily measurable indicators that accurately predict the soil functions of interest.

7.2 Soil Quality Indicators

An indicator is a chemical, physical, or biological characteristic of soil that is responsive to disturbances and reflects the performance of ecosystem functions within the soil of interest. Indicators primarily encompass dynamic soil properties. Assessing soil quality involves identifying soil properties that respond to management practices, influence or correlate with environmental outcomes, and can be accurately measured within specific technical and economic limitations. Soil quality indicators can be qualitative (e.g., drainage class) or quantitative (e.g., infiltration rate).

Ideal soil quality indicators should possess the following characteristics:

» correlate well with ecosystem processes

» are easy to measure

» Integrate/encompass soil physical, chemical, and biological properties & processes

» be accessible to many users and applicable to field conditions

» be sensitive to variations in management & climate

Soil quality aims to incorporate all three types of indicators. The table below illustrates the connection between indicator type and soil function.

Among the indicators utilized, Organic Matter (OM), particularly soil carbon, transcends all three indicator categories and is widely acknowledged for its significant impact on soil quality.

Table 7.1: Relationship between indicator type and soil function

Indicator Category	Properties	Related soil function
Chemical	Soil pH, EC, NPK, micronutrients	Nutrient Cycling, Buffering capacity
Physical	Texture, Bulk density, structure, Infiltration rate, Hydraulic conductivity, surface crust	Physical Stability and Support, Water Relations , Habitat
Biological	Soil organic carbon (SOC), earthworm, respiration rate, microbial biomass	Biodiversity, Nutrient Cycling, Filtering

Major soil quality parameters criterion used in assessing soils into three major soil quality groups are as low, medium and high are given in the Table 7.2.

Table 7.2 General criteria for soil quality assessment

Indicator	Ranking		
	Low	Medium	High
Soil textural class	Coarse	Medium	Fine
Bulk density (g cm^{-3})	>1.70 or <1.20	1.50 - 1.70	1.20 - 1.50
Soil pH	>9.0 or <5.0	7.5 - 8.5 or 5.0 - 6.5	6.5 - 7.5
EC (milli mhos cm^{-2})	>4	2 - 4	<2
Soil Organic Carbon (%)	<0.5	0.5 - 0.75	>0.75
Available Nitrogen (N) (Kg ha^{-1})	<240	240 - 480	>480
Available Nitrogen (P) (Kg ha^{-1})	<11	11 - 22	>22
Available Nitrogen (K) (Kg ha^{-1})	<110	110 - 280	>280
Cation Exchange Capacity (meq. 00g^{-1})	<10	10 - 20	>20

7.3 Soil quality indicator selection

The collection of indicators used to assess a soil's quality is also known as a minimum data set (MDS). Two primary methods for selecting a MDS have been established: expert opinion and statistical data reduction.

- **Expert opinion** - requires specialized knowledge of the system. Utilizing a hierarchical framework for indicator selection may aid in making the selection more systematic. AHP (Analytical Hierarchical Process) is commonly employed for this purpose. The indicator set should be further tailored based on factors such as climate, soil type, plant community, and others.
- **Statistical data reduction techniques** - These can effectively choose indicators in diverse soil systems. They can help mitigate disciplinary biases that may arise from expert selection of indicators, but they do assume that the original dataset contains suitable indicators (thus requiring a minimum level of knowledge). Examples of statistical techniques include Principal Component Analysis (PCA), Redundancy Analysis (RDA), and Discriminant Analysis, among others.

7.4 Scoring of indicators

During scoring, indicators in MDS is converted into dimension less values to normalize all indicators ranging from 0 to 1. Non-linear as well as Linear scoring functions are widely used for scoring of indicators. The most widely used three main scoring curves are more is better, less-is-better, and mid-point optimum curves.

7.5 Computation of Soil Quality Index

Once scored, indicators can be combined in a variety of ways, such as additive, weighted or multiplicative indexes. Few differences could be found among index outcomes when calculated by differing methods. Simple soil quality index (SSQI), which is additive in nature and Weighted soil quality index (WSQI), which is weighted in nature are examples of most widely adopted quality indices in soil studies.

$$SSQI = \sum_{i=1}^{n} S_i \qquad\qquad WSQI = \sum_{i=1}^{n} W_i * Si$$

Where, n is the number of indicators included in the index (MDS); S_i is the linear or nonlinear score of the i^{th} indicator and W_i is the weight assigned to the i^{th} indicator.

7.6 Geospatial technology for Soil quality

Geospatial technology is vital for evaluating and monitoring soil quality and health. By integrating geographic information systems (GIS), remote sensing, and other geospatial tools, it becomes possible to create detailed maps and models of soil properties and conditions, for various purposes related to sustainable land management. Various RS based data sources are known for their ability to generate different environmental covariates corresponding to *'scorpan'* factors, thus playing vital roles in digital soil mapping activities aimed at spatial mapping of soil properties as well as soil quality. Similarly, the location specific observations and computed values of soil quality indicators as well as indices could be interpolate onto a spatial domain for easy visualization and policy purposes using various GIS analysis.

8.0 Soil Carbon

Carbon is present in all living organisms and serves as a fundamental building block for life on Earth. The Earth's atmosphere (dry air) is composed of 78.09% nitrogen, 20.95% oxygen, 0.04% carbon dioxide, and trace amounts of other gases by volume. The exchange of carbon is facilitated by natural processes such as photosynthesis (plants absorbing carbon dioxide), respiration (the release of energy and carbon dioxide), and dissolution and carbonate precipitation.

The major GHGs are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Since the industrial revolution, the concentrations of CO_2, CH_4, and N_2O in the atmosphere have increased by approximately 30%, 145%, and 15%, respectively, primarily due to human activities.

While oceans store most of the Earth's carbon, soils contain approximately 75% of the carbon pool on land, which is three times more than the amount stored in living plants and animals. Therefore, soils play a critical role in maintaining a balanced global carbon cycle.

8.1 Indian Soil Carbon status

Various authors have estimated the size of the soil organic carbon (SOC) pool in India to range between 21 and 27 Pg (Petagram). Additionally, SOC densities for different forest types and the SOC pool for forest ecosystems have been estimated at 4.13 Pg and 5.25 Pg, respectively, for the top 50 cm of soil depth. In most recent study, The SOC, SIC and total soil carbon pool size of India has been estimated at 22.72 ± 0.93 Pg,12.83 ± 1.35 Pg and 35.55 ± 1.87 Pg, respectively.

8.2 RS of Soil carbon

8.2.1 Soil carbon sequestration

» Carbon sequestration involves the long-term storage of carbon dioxide or other carbon forms in oceans, soils, vegetation (particularly forests), and geological formations. This process aims to mitigate or delay global warming by reducing the atmospheric accumulation of greenhouse gases emitted from human activities.

» Mitigating greenhouse gases, particularly carbon dioxide, can help control the increase of carbon in the atmosphere by sequestering carbon into soil. CO2 is a unique greenhouse gas that traps long-wave radiation reflected from the Earth's surface.

» Photosynthesizing vegetation absorbs carbon dioxide and stores it as biomass carbon in the terrestrial carbon pool. This carbon is stored in plant biomass (trunks, branches, leaves, and roots) and organic matter in the soil. Carbon dioxide enters the soil carbon pool through decomposition of dead biomass. The amount of terrestrial carbon sequestration depends on land use practices.

» Agricultural and degraded soils worldwide have a carbon sink capacity that amounts to 50 to 66% of the historical carbon loss estimated at 42 to 78 gigatons of carbon. Soil carbon sequestration is a strategy aimed at enhancing soil quality to achieve food security.

8.2.2 Soil Carbon stock

- The main way carbon is stored in soil is through soil organic matter (SOM), which is a complex mixture of carbon compounds including decomposed plant and animal tissues, microbes, and carbon bound to soil minerals. Carbon in soil can persist for millennia or be rapidly released back into the atmosphere.
- The SOC pool is the largest among terrestrial carbon pools. It is more than three times the size of the atmospheric pool (760 Gt) and approximately 4.5 times the size of the biotic pool (560 Gt).
- Worldwide, the soil carbon pool, also known as the pedologic pool, is estimated to be 2,500 Gt upto a depth of 2 meters. Within this total, the soil organic carbon pool accounts for 1,550 Gt, while the soil inorganic carbon and elemental pools make up the remaining 950 Gt.

Soil carbon stock estimated as:

$$Qi = Ci * Di * Ei * (1-Gi) \quad \ldots\ldots\ldots\ldots\ldots \text{ Eq 8.1}$$

Where, Soil organic carbon stock *Qi* (Mg m^{-2}) in a soil layer or sampling level *i* with a depth of *Ei* (m) depends on the carbon content *Ci* (g C g^{-1}), bulk density *Di* (Mg m^{-3}) and on the volume fraction of coarse elements *Gi*.

8.2.3 Soil Carbon Models

Modeling stands out as one of the most promising tools for estimating soil organic carbon (SOC) stocks. Various models, including RothC, CarboSOIL, DNDC, CENTURY, DAISY, among others, are utilized for this purpose. By linking simulation models with spatial datasets such as soils and land use enables the estimation of present and future regional stocks of soil organic carbon (SOC) and its sequestration. RothC and CENTURY are among the extensively utilized and validated models for soil organic matter (SOM) studies

- The CENTURY model is a comprehensive ecosystem model designed to simulate the cycling of carbon (C), nitrogen (N), phosphorus (P), and sulfur (S) within soil-plant systems. It requires highly detailed input data, which can be a challenge to acquire for all agricultural soils within a specific region or country
- RothC -26.3 was originally developed and calibrated to simulate the turnover of organic carbon (C) in arable topsoil using data from the Rothamsted Long Term Field Experiments. It has been tested extensively across various soils and climatic conditions in long-term experiments
- CarboSOIL was developed to predict the dynamics of soil carbon (C) in natural or cultivated systems under different scenarios of climate change or land use change. It operates as an empirical model based on regression techniques.

8.3 SOC and Climate Change

- Global warming is a "century-scale" problem. Soil carbon (C) sequestration serves as a vital connection addressing three global issues-climate change, desertification, and biodiversity-and acts as a natural link between three UN conventions. It is a natural, cost-effective, and environmentally friendly process. Once carbon is sequestered, it remains stored in the soil as long as practices like restorative land use, no-till farming, and other resource management practices (RMPs) are implemented

» Soil organic carbon (SOC) sequestration has the potential to mitigate fossil-fuel emissions by capturing 0.4 to 1.2 gigatons of carbon (Gt C) annually, which corresponds to 5 to 15% of global emissions. Depletion of the SOC pool significantly degrades soil quality, reduces biomass productivity, and negatively impacts water quality. This depletion may worsen with projected global warming.

» The potential of soil C sequestration as a win-win strategy is certain and realizable over a relatively short period of 20 to 50 years. The intimate connection between soil carbon sequestration, global food security, and climate change is critical and must not be overlooked or underestimated.

9.0 Land Degradation

Land resources already scarce are under tremendous pressure for improved production and meeting the various requirements/demands of ever-increasing world population. The various natural and anthropogenic influences result in reducing/diminishing the quality of different land components, ultimately resulting in different forms of land degradation. FAO (1979) defined Land Degradation as "*a process which lowers the current and/or the potential capability of soil to produce goods or services".*

Globally soil erosion, chemical deterioration and physical degradation are the important types of land degradation. Water erosion is the most important type of soil degradation (55%) followed by wind erosion (2 %), nutrient depletion (7%), salinization (4%) and compaction (3%). In India, 120.4 million hectares or 36.7 % of total arable and non-arable lands are degraded due to various degradation types namely: water erosion (82.6 Mha), wind erosion (12.4 Mha), chemical degradation due to salts (24.8 Mha) and physical degradation due to mining and waterlogging (1.07 Mha). A total of 96.72 Mha (80.19 Mha on arable land and 16.53 Mha under open forest) land is affected by water erosion accounting 80% of total degraded land of the country.

9.1 Drivers of Land degradation

Numerous natural as well as anthropogenic processes and factors are known to cause as well as influence land degradation processes at varying time scales and geographical extents. The causative factors are mainly classified as proximate causes, underlying causes as well as climatic factors.

9.1.1 Proximate causes

Proximate causes are those which are immediately responsible for causing different types of land degradation due to their direct impact on various terrestrial ecosystems. The proximal causes can be further categorized into biophysical proximate causes and unsustainable land management practices, based on whether the causative factors are natural or anthropogenic.

Topography, land cover change, soil types and climate identified as the major biophysical factors acting as proximate drivers of land degradation. The climatic parameter especially rainfall intensity, amount as well as duration also plays a crucial role in determining the water erosion rates from different regions. Low intensity and scanty rainfall, a characteristic feature of arid, semi-arid and dry sub-humid regions could lead to vegetation degradation as well as development of soil salinity.

Unsustainable land management and infrastructure development are the major proximate causes of anthropogenic nature, leading to land degradation. Unsustainable land management comprises mainly of various activities associated with intensive agriculture/crop production such as land clearing for increasing cultivable areas, overgrazing of rangelands, cultivation of steep slopes without proper soil/water conservation and management practices, as well as crop residue burning etc.

9.1.2 Underlying causes (policies, institutions, and other socio-economic factors)

Underlying causes influence various proximate drivers and thus indirectly results in various categories of degradation. They mainly include various policies, institutional interventions, as well as numerous socio-economic factors. Population density is as an important underlying driver of land degradation. Poverty is another important underlying cause whose exact causality is not clearly defined.

9.2 Land Degradation Processes / Type of Land Degradation

Land degradation can be broadly classified into physical, chemical, and biological types based on the nature of predominant processes and their resultant impacts.

- » Physical land degradation refers to various forms of soil erosion, alterations in the physical structure as well as properties of soil such as bulk density, porosity, infiltration capacity etc. ultimately leading to crusting, compaction as well as waterlogging.
- » Chemical degradation refers to the adverse changes in chemical properties/characteristics of soil due to various processes such as acidification, salinization, alkalinisation, laterization, podsolization, leaching etc. leading to nutrient imbalances as well as lowering of soil fertility levels.
- » Biological degradation mainly includes loss of soil organic matter due to mineralization, vegetal degradation especially rangeland degradation, deforestation, associated loss of biodiversity comprising loss of soil flora, fauna populations as well as various soil species.

9.3 Land Degradation and Climate Change

Climate change has been shown to impact soil erosion globally, with numerous studies indicating rainfall as the primary influencing factor. These studies employed empirical and process-based models to simulate long-term soil erosion and used downscaling methods to predict future climate scenarios for the study areas.

Erosion degrades land, diminishing the vegetation that can absorb climate-warming carbon dioxide. In a single year, soils can sequester enough greenhouse gases to account for approximately 5% of all human-induced GHG emissions. Improved land management can enhance the ability of vegetation to capture CO_2.

Soil erosion occurs in four three stages: sediment detachment, breakdown, transport/redistribution, and deposition. The total amount of carbon displaced globally by erosion is estimated to be between 4.0 and 6.0 Pg (petagrams) per year globally. With approximately 20% of this displaced carbon undergoing mineralization, erosion-induced emissions might range from 0.8 to 1.2 Pg of carbon per year. This highlights how soil erosion exacerbates climate change by increasing the concentration of carbon in the atmosphere.

10.0 Remote Sensing of Soil Erosion

Soil erosion involves the removal of topsoil by physical forces, occurring faster than the rate of soil formation. It is a two-phase process: detachment of individual soil particles from the soil mass and their transport by erosive agents like running water and wind. Soil erosion is classified into two categories: geological and accelerated erosion. Geological erosion is a natural phenomenon, whereas accelerated erosion occurs when the rate of soil erosion surpasses a certain threshold due to anthropogenic activities, such as poor agricultural practices. Soil erosion is a major cause of land degradation, alongside other processes like soil compaction, waterlogging, acidification, alkalinization, and salinization.

Soil erosion by water is the most severe type of erosion in the world and in India. Water erosion consists of three basic phases: detachment, transportation, and deposition. Rainfall is a major factor that causes the detachment and movement of soil particles. Soil erosion is categorized into various types based on the mechanism of occurrence, including splash, sheet, rill, and gully erosion (Fig 10.1).

Rills and Gullies

Sheet erosion

Sheet and rills

Fig 10.1: Field photographs showing different categories of water induced erosion types

10.1 Water Induced Erosion Types

Splash erosion primarily occurs due to the detachment of soil particles caused by the direct impact of raindrops on the soil surface or shallow water surfaces.

Sheet erosion refers to the even removal of detached or splashed soil particles by surface runoff, typically observed on gently sloping lands.

Rill erosion refers to the loss of soil particles carried by concentrated runoff in small channels known as rills, which are typically a few millimeters wide and deep.

Gully erosion is recognized as the most advanced and severe type of soil erosion, involving the removal of soil particles by concentrated runoff in more permanent channels known as gullies. These channels typically have larger dimensions in terms of width and depth, with steeper side slopes.

Ravines are characterized by a network of deep and narrow gullies that run parallel to each other and connect with the river system. The dissection of land can lead to the formation of ***ravinous landscapes*** through the interconnected and networked gullies.

Tunnel erosion, also known as pipe erosion, refers to sub-soil erosion caused by runoff flowing through channels, while the surface soil remains undisturbed. This phenomenon typically occurs in arid and semi-arid regions where soil permeability varies within the soil profile.

10.2 Field measurements of erosion

Erosion features are considered the most reliable methods for obtaining accurate soil loss data, while laboratory-based experiments allow for controlled analysis of factors and their impacts to identify erosion causes and understand processes. Point measurement methods include the use of erosion pins, paint collars, bottle caps, pedestals, tree mounds, tree roots, and profile meters.

Hydrological methods represent another widely utilized approach for erosion measurement, focusing on the measurement of stream flow or runoff in channels and sediment transport. Discharge in channels can be determined using various methods, including the volumetric method (direct measurement for small channels), velocity-area method (utilizing average flow velocity and channel cross-sectional area), and rating gauge stations (employing rating curves). These methods also involve the use of empirical formulas for velocity estimation, as well as various types of gauging weirs, measuring flumes, and water level recorders.

10.3 Remote Sensing of Soil Erosion

Due to soil erosion, top (surface) soils are washed out that removes fine soil particles (clay and silt) and organic carbon from the soil. Whereas sand particles and gravels are left into the soils that provide high reflectance in visible and infrared spectral regions. As these soil lost organic matter (OM) which impart dark colour to the soil as well as also hold soil moisture. Therefore, cumulative reflectance will be higher in these spectral wavelength region. These soils appear whitish tone with smooth texture on Std. FCC (Fig 10.2). Rills infested area denote moderate to severe soil erosion are relatively lighter in white tone. In high spatial resolution remote sensing data (<2m), rills area can be delineated whereas gully and ravines can be seen on 2-5 m spatial resolution data.

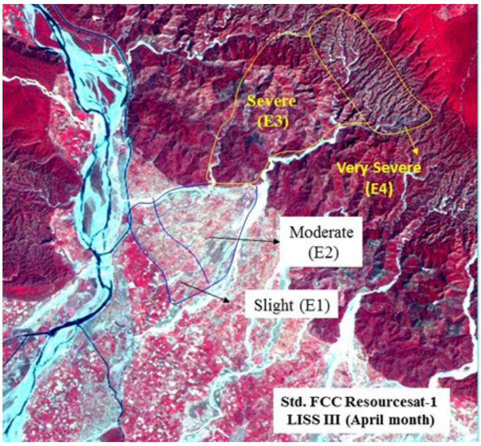


Fig 10.2. Std. FCC showing Erosion types; ***Sheet Erosion (E1); Sheet & Rill Erosion (E2); Gully Erosion (E3); Dense Gully Erosion (E4)***

Soil Erosion Modelling

Modeling soil erosion involves mathematically describing the processes of soil particle detachment, transport, and deposition on land surfaces. Physically based mathematical models can predict the locations and timing of erosion, enabling conservation planners to focus their efforts on reducing erosion effectively.

There are three main types of erosion models: empirical, semi-empirical, and physically based. Empirical models, such as the USLE, rely primarily on observations and are typically statistical in nature. Semi-empirical models bridge the gap between physically based and empirical models, using spatially aggregated forms of water and sediment continuity equations. Conceptual models predict sediment yields based on unit hydrographs. Lumped conceptual models utilize spatially averaged parameters and compute results across entire catchment areas. Process based physical model uses a steady state sediment continuity equation in predicting sediment loss and deposition over the land surface.

The Universal Soil Loss Equation (USLE) is one of the most extensively applied erosion models across various crop management systems. It is an empirical model derived from the analysis of over 10,000 plot-years of runoff and soil loss data collected from small plots across the eastern United States (Wischmeier and Smith, 1965, 1978). The USLE primarily operates at the field or plot scale. The USLE can be formulated as:

$$A = R\,KL\,S\,CP \quad \text{.................. Eq 10.1}$$

where A is the average annual soil loss (mass/area/year), R represents the erosivity index, K denotes the soil erodibility factor, L accounts for the effect of slope length, S considers the impact of slope gradient, C represents the crop and crop management factor, and P stands for the conservation practice factor.

Revised Universal Soil Loss Equation (RUSLE)

The RUSLE model maintains the fundamental structure of the USLE, but the algorithms for calculating individual erosion factors have been substantially revised (Renard et al., 1997). It has been widely employed for estimating soil erosion losses, evaluating erosion risks, and guiding the formulation of conservation plans aimed at erosion control across diverse land cover scenarios. The RUSLE model is defined as (A) below:

$$A = R * K * LS * C * P \ldots\ldots\ldots\ldots\ldots \text{Eq 10.2}$$

Where, A (t ha^{-1} y^{-1}) represents the annual average soil loss per year; R (mt ha^{-1} cm^{-1}) is the rainfall erosivity factor; K (t ha^{-1} R^{-1}) is the soil erodibility factor; LS (dimensionless) is the topographic factor; C (dimensionless) is the land cover factor; and P (dimensionless) represents the soil conservation or prevention practices factor.

The major modification in RUSLE model was computation of LS factor that is derived spatially using Digital Elevation Model (DEM) in GIS environment. Therefore, RUSLE model is GIS integrated and widely used in the world. It is being used for soil erosion risk assessment in the watershed at various scale.

Modified Universal Soil Loss Equation (MUSLE)

The rainfall erosivity factor in the USLE was replaced with a runoff rate factor. This factor is calculated based on the runoff volume and peak runoff rate of the catchment or watershed. It depends on watershed characteristics such as drainage area, stream slope, and watershed shape, which influence runoff rates and delivery ratios. Consequently, the USLE model was modified to replace the rainfall erosivity factor with the runoff factor and can be expressed as:

$$Sye = Xe\ K\ L\ S\ Ce\ Pe \ldots\ldots\ldots\ldots\ldots \text{Eq 10.3}$$

where, SYe is the event sediment yield (metric tons)

$$Xe = 11.8\ (Qe\ qp)^{0.56} \ldots\ldots\ldots\ldots\ldots \text{Eq 10.4}$$

where, represents the surface runoff amount (mm ha^{-1}) and qpqp is the peak runoff rate (m^3 s^{-1}) observed during the erosion event. The factors K, L, S, Ce, and Pe are defined similarly to those in the USLE/RUSLE. This version is referred to as the Modified Universal Soil Loss Equation (MUSLE).

Fig 10.3: Field photograph showing surface runoff and sediment loss

11.0 Remote Sensing of Salt-affected Soils

Salt-affected soils are characterized by a high content of soluble salts and/or elevated levels of sodium ions. These soils form as a result of salinization or alkalization processes occurring in arid, semi-arid, and dry sub-humid regions worldwide.

Currently, salt-affected soils in India are estimated to cover 6.74 million hectares (Mha), a figure that could rise to 16.2 Mha by 2050, if continued without remedial measures. These soils, consisting of saline and alkali (sodic) types, are estimated at 2.95 Mha and 3.77 Mha respectively, and are distributed across seven physiographic regions of the country.

Soils are classified as salt-affected when their electrical conductivity (EC) values exceed 4 dS/m at 25°C in a saturation paste extract. Based on the nature of the salts and resultant soil characteristics, soil salinity is broadly categorized into saline, alkali, and saline-alkali soils. Saline soils predominantly contain chlorides and sulfates of sodium, calcium, and magnesium. Alkali soils, on the other hand, are characterized by a predominance of sodium ions in the form of carbonates and bicarbonates. Saline-alkali soils contain varying amounts of both soluble and alkali salts, exhibiting characteristics of both saline and alkali soils.

Salt-affected soils	pH	EC	ESP
Saline	<8.5	>4.0 dSm^{-1}	<15 (%)
Saline-alkali	<8.5	>4.0 dSm^{-1}	<15 (%)
Alkali	>8.5	<4.0 dSm^{-1}	<15 (%)

ESP: Exchangeable Sodium Percentage, EC : Electrical Conductivity

11.1 Formation

Soil salinity is broadly classified into two types based on its origin: primary and secondary salinization. Primary, or natural, salinization occurs naturally in soils due to factors such as high inherent salt concentrations, impeded drainage or waterlogging, flooding in natural depressions, seawater intrusion, shallow groundwater levels, high evaporation rates, or a combination of these factors. These processes are typically associated with various geomorphological and hydrogeological conditions.

Secondary salinity refers to the increase in salt concentration primarily due to human activities such as irrigated agriculture, land development, and industrial activities, particularly in arid and semi-arid regions. In this process, salts already present in the soil are brought to the surface due to these human interventions. Excessive irrigation and soil leaching without proper drainage can also raise the groundwater table, causing more salts to accumulate in the upper soil layers and on the surface.

11.2 Spectral Characteristics of Salt-Affected soils

Salt-affected soils exhibit higher reflectance in the Vis-NIR spectrum compared to non-saline and cultivated soils, appearing as bright white tones in multispectral FCCs. As salt concentration increases, soil reflectance generally increases, making it easier to identify severely salt-affected soils compared to those with lower salinity levels. These soils develop white, smooth salty crusts, while an abundance of sodium sulfate results in puffy crusts. The chemical composition of salts (salt mineralogy), including sulfates, chlorides, carbonates, and others, dictates the presence or absence of absorption bands across the entire electromagnetic spectrum, spanning from visible and NIR to mid-IR and thermal regions.

These soils generally exhibit higher reflectance in the visible and near-infrared (VNIR) region. Specifically, six spectral ranges including visible (0.55-0.77 μm), NIR (0.9-1.3 μm), and mid-IR (1.94-2.15 μm, 2.15-2.3 μm, and 2.33-2.4 μm) bands have been identified as useful for characterizing different levels of soil salinity.

11.3 RS data analysis for mapping salt-affected soils

Methods for studying soil salinity can be broadly categorized into direct and indirect approaches. Direct approaches involve observing bare soil surfaces with efflorescence and salt crust, while indirect approaches involve studying the impacts on vegetation growth and moisture conditions in the area.

Choosing remote sensing data from the appropriate season is crucial for detecting and mapping salinity. It's advisable to avoid images captured during or immediately after the rainy/monsoon season because this period can lead to leaching and dilution of salinity. This can result in significant confusion between saline patches and non-saline areas.

The fallow period in summer (March - May) and crop maturity stages (March - April) are optimal times for mapping soil salinity using passive remote sensing data (optical and IR). During these periods, the peak vegetation growth aids in highlighting salinity because areas affected by salinity typically exhibit very low or minimal fractional vegetation cover.

When using active (microwave) remote sensing data, it is important to acquire data during periods of sufficient soil moisture. This helps in characterizing salinity through radar backscatter inversion techniques and estimating parameters such as dielectric constant and permittivity.

Most commonly adopted methods of using RS data for studying salt affected soils are:

I. Visual Interpretation of standard FCCs,
II. Digital Image Classification (supervised and unsupervised classifiers), and
III. Spectral Indices using multispectral bands

» ***Visual interpretation:*** Soils with salt encrustations on the surface appear smoother than normal soil and exhibit higher reflectance in the visible and NIR spectral bands. These soils appear as bright white to dull white tones against the light red background of normal soils in standard false color composites

(FCC). Visual interpretation of salt-affected soils necessitates obtaining remote sensing data during the summer season when there is either no crop or the area lacks vegetation cover.

During the summer months (April - May), high evaporation rates facilitate capillary movement, causing salts to accumulate on the surface. Salt-affected areas are identified by scattered white patches of precipitated salt with small coverage areas, and higher spatial resolution data enhances the discrimination and mapping of these soils.

Digital Image Classification: Digital image classification involves two main methods: unsupervised and supervised classification. In unsupervised classification, image analysis software groups pixels with similar spectral characteristics into spectral classes automatically. These spectral classes are later interpreted by the user to assign them to different classes of salt-affected soils. In supervised classification, the user selects sample pixels based on ground truth data as training sites (input classes). This training data is used by image processing software to classify the entire image into various classes of salt-affected soils. Additionally, methods such as Principal Component Analysis and spectral indices are employed to classify and monitor salt-affected soils beyond traditional classification approaches.

Spectral indices: Various spectral salinity indices have been developed to detect salt-affected areas based on their spectral behaviors in different bands of remote sensing data. Crops stressed by soil salinity in the root zone exhibit increased reflectance in the blue (B), green (G), and red (R) wavelength regions, and decreased reflectance in the near-infrared (NIR) range. Vegetation indices (VIs) serve as proxies for salinity indicators to assess salt presence in the soil, given their impact on chlorophyll content, water stress, and overall plant growth. Commonly used VIs include the Normalized Difference Vegetation Index (NDVI), Soil-Adjusted Vegetation Index (SAVI), Enhanced Vegetation Index (EVI), and Normalized Differential Salinity Index (NDSI), which are employed to characterize crop growth conditions affected by salinity.

Salinity indicators are also employed to identify salt encrustations on bare soil surfaces and to map salt-affected areas. The Landsat-based Tasseled Cap Transformation (TCT), which includes the Soil Brightness Index (SBI), Green Vegetation Index, and Wetness Index, is also utilized to distinguish salinity from normal surroundings.

Thermal RS data can also be utilized to study and assess varying levels of soil salinity. This approach is based on the principle that the canopy temperature of plants in salt-affected areas will be higher than that of plants growing in normal soils.

11.4 Advanced analytical techniques

Hyperspectral remote sensing (HRS) data facilitates detailed identification, quantification, and mapping of surface salinity. Due to its numerous narrow contiguous bands, HRS data can capture the effects of salt concentration and mineralogy on absorption features across various wavelength regions. Regression techniques utilizing HRS-derived spectral indices are widely employed for characterizing and mapping soil salinity. Advanced classification techniques such as Artificial Neural Networks (ANN), SVM (Support Vector Machine), Random forest (RF), decision tree, spectral unmixing etc. are widely used for soil salinity studies using HRS data.

Hyperspectral data is also valuable for estimating salinity stress on agricultural crops by identifying stress-sensitive wavelengths. These wavelengths can be used for salinity quantification through various predictive modeling techniques, such as regression, multiple linear regression (MLR), absorption feature characterization, principal component regression, partial least squares regression (PLSR), spectral transformations, spectral feature fitting (SFF) etc.

Microwave RS data is considered effective for salinity detection due to the distinct behavior of the real and imaginary components of the dielectric constant in response to salt content. The imaginary component is highly sensitive to variations in electrical conductivity (EC) but insensitive to alkalinity, whereas the real component is independent of both salinity and alkalinity variations. Microwave data can also enhance the detection of saline water, monitor changes in dielectric constant, map surface roughness variations, and identify different types of salt-tolerant vegetation.

11.5 Proximal sensors for salinity

Proximal sensors using electromagnetic induction (EMI) offer simple, reliable, and rapid measurements of soil salinity across various scales, from field to landscape levels. These devices measure the apparent electrical conductivity (ECa) of the soil, often used as a proxy for soil salinity. EMI-based sensors can cover large areas quickly, either through manual field measurements or by on-the-go systems.

X-ray fluorescence based sensors such as pXRF spectrometers can provide total elemental composition of soil samples, thus helping in the identification and quantification of salt minerals (both cations and anions) as well as salinity levels in the field itself. This technique helps in reducing destructive sampling as well as minimizing the need for chemical analysis. Similarly, pH and EC sensors also help in quick and accurate characterization of salinity at field level. Multi-ion/nutrient analyzers also help in easy characterization of salinity parameters both in field as well as in laboratory. Figure 11.1 showing Resourcesat-1 LISS IV Std. FCC and field photo of salt-affected and waterlogged soils.

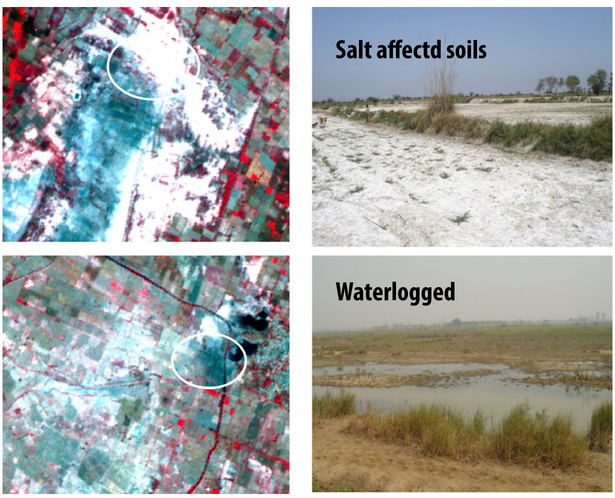


Fig 11.1: Salt-affected and waterlogged soils

12.0 Watershed Management

12.1 Watershed – concept, characterization

The concept of watershed management centres on the optimal utilization and conservation of natural resources within a specific area to ensure their prolonged and sustainable availability. Watersheds are recognized as the fundamental natural units for natural resource planning both globally and nationally.

A watershed is defined as a natural geo-hydrological unit that collects water and runoff, draining it to a common point or outlet. It is also known as a catchment area or drainage basin. The highest points within a watershed, which form the boundary between adjacent watersheds, are referred to as water divide lines or ridge lines.

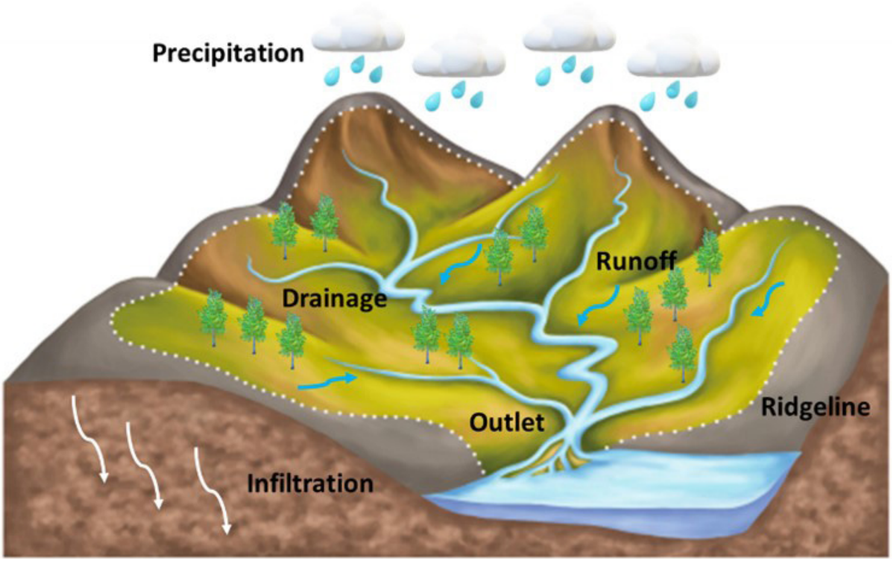


Fig 12.1: A Typical Conceptual Watershed

Watersheds can vary greatly in size, ranging from large river basins covering thousands of square kilometers to small farm micro-watersheds spanning just a few hectares. Smaller watersheds are always part of the larger watershed systems.

12.2 Watershed Management

A watershed, as a geographical unit, encompasses various physical and biological components such as water resources, soil resources, mineral resources, livestock, land use and land cover, pasture, human resources, and biomass, along with socio-political features. These diverse features and components need to be integrated during the planning and implementation of watershed management activities. Watersheds are considered the most suitable units for natural resource management and planning because soil, land, forest, and water resources can be effectively managed at this level. In the 1970s and 1980s, the Indian Council of Agricultural Research (ICAR) and subsequently the Ministry of Rural

Development and the Ministry of Environment and Forests initiated a series of integrated initiatives aimed at rural development, job creation, poverty eradication, and watershed development.

12.3 RS data use in watershed management

Remote sensing data, interpreted through various visual and digital techniques, helps in the identification and mapping of various watershed management components.

» Remote sensing data are universally utilized to create land use/land cover maps of watersheds through visual analysis and digital classification.

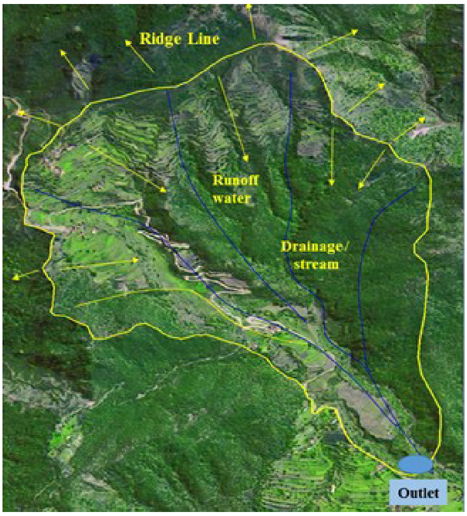


Fig 12.2. Watershed delineation with outlet showing ridge line & drainage lines on Natural Colour Composite of Resourcesat-1 LISS IV data

» Digital terrain analysis using DEMs facilitates the easy generation of drainage/stream networks, quick estimation of watershed area, slope, stream order, shape, drainage pattern, drainage density, and other parameters, which expedite the characterization and modeling of watershed processes (Fig 12.2).

» Geospatial technologies have advanced the characterization of diverse watershed components using various RS derived products like optical images, digital elevation models (DEMs), and microwave data.

12.4 Watershed characteristics

Watershed characteristics can be broadly categorized into *(a) Topographic characteristics (b) Geologic characteristics (c) Soil (d) Vegetation and Land Use.*

» ***Topographic Characteristics*** includes area and size, shape and pattern, relief and slope and drainage density are denoted as salient topographic characteristics and these individually and collectively influence watershed management. Drainage Characteristics of the watershed as: Stream length (Lu), Bifurcation ratio (Rb), Drainage density, Relief Ratio, Ruggedness Number, Elongation Ratio etc. Run-off & sediment estimation studies; operational schedules & conveniences.

» ***Geologic Characteristics:*** Rock type is significant in the watershed both statically and dynamically. Due to permeability and porosity, different tock types vary in their ability to store water.

» ***Soils:*** Remote sensing data are widely utilized for mapping soil resources. Run-off & sediment studies; treatment details; water balance study; production potential (crop & vegetation); land use planning; soil irrigability assessment, operational convenience.

» ***Vegetation and Landuse / Land Cover:*** The production of sediments by erosion will necessarily depend upon the vegetation cover as this determines the exposure of the soil surface. The significance of vegetation in a watershed can thus be visualized in its influence over modifying net input to the basin, through interception and evapotranspiration.

12.5 Watershed prioritization

Prioritizing watersheds is essential for effectively implementing major schemes, allowing planners and policymakers to adopt a strategic approach considering the size of the catchment area, severity of issues, funding constraints, political system and local manpower demands. Irrespective of the different schemes' objectives, the prioritization framework remains the same and categorizes areas into very high, high, medium, low, and very low vulnerability levels, enabling targeted conservation and management efforts to maximize benefits.

Various empirical equations, such as the Universal Soil Loss Equation by Wischmeier and Smith (1978), and models like the Sediment Yield Index (SYI) and Runoff Potential Index (RPI) developed by the Soil and Land Use Survey of India, are utilized for prioritization. These models aid in identifying delineating priority areas and conducting surveys in specific catchments like RVP & FPR.

12.6 Watershed Modelling

A watershed model provides a comprehensive simulation of hydrological processes, offering a more holistic approach compared to models that typically focus on individual or multiple processes at smaller scales, such as field-scale models. Watershed-scale modelling has become a crucial scientific research and management tool, especially in endeavours aimed at comprehensively understanding and managing water pollution.

Watershed-scale models can be categorized into event-based and continuous-process models. Event-based models simulate individual precipitation-runoff events, emphasizing infiltration and surface runoff dynamics. In contrast, continuous process models comprehensively account for all runoff components and include soil moisture redistribution between storm events.

Geographic Information Systems (GIS) have become a robust tool for managing spatially referenced information, facilitating data preparation, visualization, and interacting with models. When integrated with environmental models, GIS enables simulations and spatial interpretation of results. GIS technology allows extraction of information from satellite imagery and digital elevation models (DEMs), as well as processing large datasets efficiently. It offers significant advantages in identifying spatial patterns of soil loss within watersheds. Models like the widely used USLE and RUSLE are examples of factor-based models that benefit from GIS applications.

Assessing surface runoff and sediment loss is crucial for implementing effective soil and water conservation strategies within watersheds. Various soil erosion models are employed to simulate runoff, sediment, and nutrient loss at watershed scales such as soil water assessment tool (SWAT), WEPP, APEX, and agricultural non-point source pollution (AGNPS). Widely used watershed models integrated with RS and GIS described as:

Soil and Water Assessment Tool (SWAT) Model

The SWAT model is a physically-based, spatially distributed conceptual model designed to simulate water, sediment, nutrient, and pesticide transport at the catchment scale on a daily time step. It is a continuous time, distributed parameter hydrologic simulation model that computes hydrologic components including runoff, stream flow, and evapotranspiration.

SWAT employs a modified version of the SCS-CN method for runoff prediction (USDA-SCS 1972) and calculates the landscape's water balance components on a daily basis. The model requires terrain, soil, land cover, and daily weather data. SWAT simulates watershed runoff volumes using the SCS-CN equation, but spatially distributes the curve number (CN). HRUs (Hydrological Response Units) in SWAT are delineated based on land use and soil types.

The Agricultural Policy / Environmental eXtender (APEX) model

APEX, a process-based model offers numerous choices to predict hydrology, erosion and sedimentation processes and delivers the flexibility to characterize weather, land use, soil, topography and various management practices. It is conditioned to perform all these functions within multifaceted landscapes through the channel to the watershed outlet. It facilitated quick assessment of the spatial distribution of surface runoff and sediment loss for large areas.

Water Erosion Prediction Project (WEPP)

The Water Erosion Prediction Project Model (WEPP) is a recent model designed to simulate water erosion and sediment yield. It is a process-based, distributed parameter model suitable for continuous simulation of soil erosion on personal computers. WEPP can be applied to small watersheds and hillslope profiles within larger watersheds. The model calculates both detachment and deposition processes on hillslopes, which can vary from storm to storm. It incorporates factors such as residue cover, crop growth, soil water content, surface roughness, and soil parameters over time using a daily time step. WEPP is available in both Hillslope and Watershed versions, and it has been integrated with GIS, known as the GeoWEPP model.

13.0 Soil Conservation Measures

Soil erosion control hinges on effective management practices, which involve establishing adequate crop cover and selecting suitable tillage methods. Therefore, soil conservation heavily relies on biological and mechanical approaches. Biological methods mainly include vegetative measures such as forestry, agro-forestry, horticulture, and agronomic practices. On the other hand, mechanical methods involve the construction of permanent and semi-permanent structures like bunding, terracing, check dams, gabion structures, and crib walls. Typically, a combination of both biological and mechanical measures is integrated for comprehensive conservation planning to achieve effective erosion control.

13.1 Approaches to soil conservation

13.1.1 Biological measures

Agronomic techniques are implemented on gentle to undulating slopes to mitigate the impact of raindrops on the soil surface and protect soil aggregates from erosion. These methods aim to increase the soil's infiltration rate and enhance water absorption capacity. The root systems of agronomic plants effectively reduce runoff velocity, thereby shielding the soil from erosion caused by surface water runoff. The principal agronomic measures are cover crops, strip cropping, intercropping, contour farming, tillage system and mulching etc.

Cover crops

Legume cover crops are widely used throughout the tropics and are recognised for their consider¬able benefit in fixing soil nitrogen with their creeping and trailing characteristics, they not only provide a good cover, but also smother vigorous weeds and grasses.

Strip cropping

It involves cultivating alternate strips of erosion-permitting and erosion-resistant crops within the field. By planting crops with deep root systems and dense canopies, it effectively reduces runoff velocity and mitigates erosion processes.

Mulching

Mulch involves covering the soil surface with organic or non-organic materials to protect it from erosion, reduce evaporation, increase infiltration, improve soil structure, and conserve soil moisture. It also prevents crust formation on the soil surface during rainy periods. Farmers commonly use crop residue, such as cut grass or other vegetation residues, to create a protective layer on the ground.

Conservation tillage

Conservation tillage involves leaving at least 30% of the soil surface covered with crop residue before and after planting the next crop, aimed at reducing soil erosion and surface runoff. It is an umbrella term, which includes all methods of soil preparation that leave most residues on the surface of the soil. Included are no-till and direct drilling systems which plant immediately into undisturbed soil; they give the maximum erosion control and good soil moisture conservation.

Contour farming

All the agricultural operations viz. plowing, sowing, inter-culture, etc., are practiced along the contour line. The ridges and furrows are made across the slope to build a series of small barriers, so that it reduces the flow of runoff water and minimize soil erosion and nutrient loss. It helps to increase infiltration rate and reduces runoff water protecting soil from erosion and conserves soil fertility and moisture, and thus improves overall crop productivity.

Contour farming involves conducting all agricultural operations such as plowing, sowing, and inter-culture etc along contour lines. Ridges and furrows are created across the slope to form a series of small barriers, which slow down the flow of runoff water, thereby minimizing soil erosion and nutrient loss. This method also enhances infiltration rates, reduces runoff water, protects soil from erosion, conserves soil fertility and moisture, and ultimately improves overall crop productivity.

Agroforestry measures

Agroforestry measures encompass a range of practices aimed at effective soil and water conservation as well as soil erosion control. This approach involves cultivating trees or shrubs alongside agricultural crops and livestock production on the same land. The addition of leaf litter acts as a protective layer against soil erosion, enhances soil health, improves soil moisture retention capacity, and boosts crop productivity.

Various types of agroforestry systems include:

- Agri-Silviculture: Growing agricultural crops together with multipurpose trees (MPTs) on the same field.
- Agri-Horticulture: Cultivating agricultural crops alongside fruit trees on the same field.
- Silvi-pasture System: Integrating grasses or livestock with multipurpose trees on the same field.

Grass species like Cenchrus ciliaris (buffel grass), Cenchrus setigerus (birdwood grass), Dichanthium annulatum (marvel grass), Panicum antidotale (blue panicgrass), Panicum maximum (Guinea grass), Brachiaria mutica (para grass), and Pennisetum purpureum (elephant grass) play crucial roles in the restoration of ravines.

Reduced tillage

It refers to minimum disturbance of soil while growing crops. Ploughing operation is not recommended. It usually involve a light discing which forms a seedbed without burying the plant residues; again, compaction can be a problem especially if the discing is repeated when the soil, is wet. It includes zero tillage, minimum tillage as most effective to conserve soil and soil moisture.

13.1.2 Mechanical Soil Conservation

The fundamental concept guiding mechanical soil and water conservation measures is the management and safe disposal of runoff water. This is accomplished by a wide array of types of earthen embankments - often called 'bunds', and associated channels or waterways. Because these physical measures tend to concentrate water into channelized flow, it is essential that all waterways are carefully protected. Mechanical measures commonly recommended are:

Bunding

Bunding is employed to manage runoff water for its effective disposal. Contour bunding is suitable for areas with slopes ranging from 2-6% and mean rainfall less than 750 mm, with permeable soils (Fig 13.1). The spacing between bunds varies based on slope steepness, rainfall intensity, and the type of crops grown. Graded bunds are constructed in areas with slopes of 6-10% and rainfall exceeding 750 mm. Peripheral bunds are built around gully heads to prevent runoff water from entering.

Contour trenching

Trenches are dug along contour lines to slow down runoff velocity and conserve soil moisture on slopes less than 30%. There are two types: continuous contour trenches, used in low rainfall areas, and staggered contour trenches (STCs), where trenches in alternate rows are staggered beneath each other, typically implemented in high rainfall regions.

Terracing

Terraces are earthen embankments constructed in a stepped manner across fields with a uniform slope (Fig 13.1). These structures are integrated with channels to guide runoff at reduced velocities towards the main outlet. Terraces effectively decrease the steepness and length of slopes, thereby reducing surface runoff velocity, soil erosion, and enhancing water infiltration. They are suitable for lands with slopes up to 33%, and can be adapted for slopes ranging from 50% to 60%.

Crib structures

Crib structures are frequently employed to stabilize steep slopes exceeding 40%. These structures consist of log wood filled with stones and are interconnected using 20–25 cm long nails. The height of these structures typically ranges from 1.5 to 2 m above the ground, adjusted according to the slope of the land.

Geo-textiles

Geotextiles, typically made from materials like jute or coir, are employed to stabilize degraded slopes in areas such as mine spoils and landslide-prone zones. They assist in initially establishing vegetation on highly degraded sloping lands by holding the vegetation in place and conserving soil moisture. Geotextiles are biodegradable and come in varying thicknesses ranging from 3 to 25 mm, featuring an open mesh design.

Check dams

Check dams are effective structures designed to reduce runoff velocity and control severe erosion in steep and wide gullies, particularly in high elevation areas. These dams feature a spillway at the center to safely discharge excess runoff water.

Brushwood check dams

Brushwood check dams involve staking branches of tree and shrub species in two parallel rows across a gully or runoff pathway. The space between the rows is filled with brushwood. Tree species are planted in 0.3 m $\times$ 0.2 m trenches across the gully, effectively reducing runoff velocity.

Diversion drains

Diversion drains are channels constructed to protect downstream areas and ensure the safe disposal of runoff water. They are primarily recommended in high rainfall areas to control runoff and prevent soil erosion.

Gully Erosion Control Structures

Types of mechanical measures adopted for soil and water conservation include grassed waterways, gabions, chute spillways, pipe spillways, drop structures, and culverts.

Fig 13.1: Field photographs showing soil conservation using contour bunding and terracing in the agricultural fields

14.0 Land Use Planning

Land use planning plays a crucial role in achieving sustainable development. It enables the allocation of land to uses that offer the greatest sustainable benefits, ensuring that development stays within the carrying capacity of the supporting ecosystems.

14.1 Land Evaluation and Land Use Planning

Land evaluation is integral to the land use planning process, serving as a tool to aid in this planning. Most land evaluation methods are qualitative and rely on expert judgment. Typically, soil surveyors and agronomists interpret their field data, making it comprehensible for planners, engineers, extension officers, and farmers.

Land evaluation plays a crucial role in (i) formulating alternative forms of land use and identifying their primary requirements, (ii) recognizing and delineating the different types of land in the area, and (iii) comparing and assessing each type of land for various uses. The fundamental principles of Land Evaluation are:

- The fundamental principles of Land Evaluation are:
- Assessing and classifying land suitability for specific types of use.
- Conducting evaluations relevant to the physical, economic, and social context of the area.
- Determining land suitability for alternative uses on a sustained basis.
- Comparing multiple types of land use.

Most commonly used Land Evaluation methods are Land Capability Classification and Crop Suitability Analysis using FAO Framework of Land Evaluation.

14.2 Land Capability classification

Land capability classification is a system used to assess and map the suitability of land for various uses based on its physical characteristics. It considers factors such as slope, soil type, drainage, and climate to identify the most suitable potential uses for a given area of land. Under this classification system land is classified into eight land capability classes (Table 14.1) under two broad groups as:

- Land suitable for agriculture and other uses which include class I to class IV lands.
- Land not suitable for agriculture but very well suited for forestry, grass land and wild life which include class V to class VIII lands.

Each land group is further sub-divided into four capability classes based on intensity of hazards and limitations of use.

Table 14.1: Salient features of Land Capability Classes (LCC)

Land Capability Class (LCC)	Characteristics
Land Suitable for Cultivation	
I	Highly productive, very good cultivable, deep, nearly level land with no or minimal limitations or hazards. Soils in this class are suitable for a wide range of crops and do not require any special cultivation practices.
II	Good cultivable land on almost level plain or on gentle slopes, moderate depth, subject to occasional overland flow, may require drainage, moderate risk of damage when cultivated, use crop rotations, water control system or special tillage practices to control erosion.
III	Soils are of moderate fertility on moderate steep slopes subject to more sever erosion and severe risk of damage but can be used for crops provided adequate plant cover is maintained, hay or other sod crops should be grown instead of row crops.
IV	These are good soils on steep slopes, subject to severe erosion, with severe risk of damage but may be cultivated occasionally if handled with great care, keep in hay or pasture but a grain crop may be grown once in 5 or 6 years.
Land unsuitable for cultivation but suitable for permanent vegetation	
V	Land is too wet or stony which make it unsuitable for cultivation of crops, subject to only slight erosion if properly managed, should be used for pasture or forestry but grazing should be regulated to prevent cover from being destroyed.
VI	These are shallow soils on steep slopes, used for grazing and forestry; grazing should be regulated to preserve plant cover; if the plant cover is destroyed, use should be restricted until cover is re-established.
VII	These are steep, rough, eroded lands with shallow soils, also includes droughtly and swampy land, severe risk of damage even when used for pasture or forestry, strict grazing or forest management must be applied.
VIII	Very rough land, not suitable even for woodland or grazing, reserve for wild life, recreation or wasteland consideration.

Land capability classes (except Class I) are further subdivided into subclasses based on specific limitations, including erosion (e), wetness (w), soil (s), and climatic conditions (c). These limitations can occur individually or in combination.

14.3 FAO Framework of Land Evaluation

It is widely used for evaluating the suitability of soils for different Land Utilization Types (LUTs). According to FAO (1983), land suitability is defined as "the fitness of a given type of land for a specified kind of land use." Suitability measures how well the characteristics of a land unit align with the requirements of a particular land use. The suitability is assessed for each relevant use and each land unit identified in the study.

FAO Framework classification describes the suitability of an evaluation unit for a land use in four categories, namely. Orders, Classes, Subclasses and Units:

I. Suitability orders: All land is divided into two suitability orders, according to whether the land is suitable or not for a given LUT.

S' = suitable, 'N' = not suitable, for the land use.

II. Suitability classes: These are divisions indicate the degree of suitability, not simply suitable vs. not suitable.

S1: Highly suitable: Represents land having no significant limitations to sustained application of the defined use.

S2: Moderately suitable: Represents land having limitations, which will reduce production levels and /or increase costs, but is physically and economically suitable for the defined use.

S3: Marginally Suitable: Represents land having limitations, which will reduce production levels and / or costs such that it is economically marginal for the defined use.

*Ns: Not suitable**:*** It mainly distinguish land that is unsuitable for a particular use at present but which might be useable in future (N1), from land that offers no prospect of being so used (N2).

III. Suitability subclasses

It indicates not only the degree of suitability (as reflected in the suitability class) but also the specific limitations that make the land less than completely suitable. For instance, suitability class S1 has no subclasses. However, moderately and marginally suitable classes may have limitations such as soil erosion, fertility issues, or physical soil constraints.

14.4 Parametric methods of Land Evaluation

There are some parametric methods are used to assess soil potential in quantitative terms. Among the most commonly used methods are:

Land Productivity Index- Also known as the Storie index can be stated as:

$$\text{Land productivity index} := A \times B \times C \times X \times Y \times 100 \;\ldots\ldots\ldots\ldots\ldots\; \text{Eq 14.1}$$

Where, A = percentage rating tor the general character of the soil profile

B = percentage rating for the texture of the surface horizon

C = percentage rating for the slope of the land

X = percentage rating for site conditions other than those covered by the factors A, B, and C (e.g., salinity, soil reaction, freedom from damaging winds)

Y = percentage rating for rainfall

Land productivity rating (index) describes the potentiality of land for general agriculture use.

Soil Productivity Index

The morphological and physico-chemical properties of pedons were analyzed to assess their productivity using the parametric approach described by Ricquier et al. (1970). The productivity index was calculated considering nine factors that determine soil productivity: moisture (H), drainage (D), effective soil depth (P), texture/structure (T), base saturation (N), soluble salts (S), organic matter (O), nature of clay (A), and mineral reserves (M). Each factor was rated on a scale from 0 to 100. The individual scores for each factor were multiplied together and expressed as a percentage to derive the final index.

Index of Productivity (IP)=H x D x P x T x S or N x O x A x M ....Eq 14.2

Where, H= soil moisture; D = drainage conditions; P = effective soil depth

T = texture/structure; N = base saturation; S = soluble salts

O = organic matter content A =nature/CEC of clay mineral M=mineral reserve

According to the resulting index of productivity the soil is assigned to one of five productivity classes:

Class 1 = excellent with rating	65-100
Class 2 = good with rating	35-64
Class 3 = *average* with rating	20-34
Class 4 = poor with rating	8-19
Class 5 = extremely poor to nil. with rating	0-7

15.0 Land Degradation Neutrality

Land degradation refers to the decline in the inherent capacity of soil to produce economic goods and services due to natural or human-induced actions. This phenomenon poses a significant threat to the sustainable development of agriculture.

According to the United Nations Convention to Combat Desertification (UNCCD), land degradation is defined as "Any reduction or loss in the biological or economic productive capacity of the land resource base. It is generally caused by human activities, exacerbated by natural processes, and often magnified by and closely intertwined with climate change and biodiversity loss."

In contrast, soil degradation specifically refers to the deterioration in soil quality and fertility due to physical, chemical, or biological damage. This includes loss of organic matter, changes in soil structure, chemistry, and biology.

The UNCCD defines desertification as "land degradation in arid, semiarid, and dry sub-humid areas resulting from various factors, including climatic variations and human activities." Desertification poses a serious global threat, impacting both developed and developing countries.

Land degradation leads to significant nutrient loss and reduced crop output, which has profound consequences for food security, livelihoods, and environmental stability. Moreover, it is a major contributor to biodiversity loss and changes in species abundance.

15.1 Land Degradation Neutrality (LDN)

It is defined as a "state whereby the amount and quality of land resources necessary to support ecosystem functions services and enhance food security remain stable within specified temporal and spatial scales and ecosystems (UNCCD)".

There a strong connection between LDN and other Sustainable Development Goal (SDG) like poverty eradication, food security, health, gender, water, energy and climate change. SDG-15 deals with life on land. It states that "this goal aims to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably mange forests, combat desertification and reverse land degradation and hold biodiversity loss".

15.2 Land Degradation and SDGs

Land degradation is prominently addressed within the United Nations Sustainable Development Goals (SDGs), particularly under SDG 15.3, which aims to restore degraded lands and soils affected by desertification, droughts, and floods to achieve land degradation neutrality.

India, as a signatory to the United Nations Convention to Combat Desertification (UNCCD), has committed to reducing land degradation and desertification. The country has set a target to reclaim 26 million hectares of land by 2030. This effort includes reclaiming approximately 21 million hectares of forest land and the remaining outside forest areas.

The indicators of land degradation vary depending on the type of degradation under consideration, the severity of the process, and the extent of its impact. For instance, common indicators of desertification include changes in vegetation and land use, occurrences of drought, soil erosion, and urbanization.

Using NDVI as a proxy of land degradation: Monitoring changes in vegetation (including cover, composition, structure, and function) through NDVI can provide valuable insights into the condition, health, and overall quality of environmental resources and services within a region.

NDVI's potential as a proxy for land productivity (an indicator of the state of land degradation) stems from studies that have established a robust correlation between NDVI and Net Primary Productivity (NPP).

The NDVI formula is presented as:

$$NDVI = (NIR-RED)/(NIR+RED) \ldots\ldots\ldots\ldots\ldots \text{ Eq 15.1}$$

Where NIR is reflectance in the near infrared band and RED is reflectance in the visible red band.

The NDVI algorithm utilizes the ratio of reflectance characteristics from different spectral bands, making it a useful index for assessing photosynthetic activity. NDVI values range from -1 to +1, where only positive values indicate vegetated areas. Higher NDVI values indicate greater chlorophyll content in the target vegetation.

In studies on desertification, NDVI has been applied to (a) monitor the current status and trends of desertification, (b) classify areas based on the severity of desertification, and (c) assess the impact of policies and interventions aimed at mitigating desertification.

Researchers have leveraged the established relationship between NDVI and biomass productivity to detect and monitor the status and trends of desertification. This relationship serves as the foundation for utilizing satellite data, particularly NDVI, to analyze and assess biomass dynamics on a global scale.

Multi-temporal satellite datasets enable the application of remote sensing imagery and techniques to assess relevant indices for land degradation (LD) assessments. These datasets vary in resolutions-spatial, spectral, temporal, and radiometric-along with spatial coverage and cost, facilitating comprehensive analysis.

16.0 Soil Information Systems and Ecosystem Services

Timely and accurate information about the nature, extent, and spatial distribution of soils is essential for assessing their potential and limitations in preparing agricultural development plans aimed at increasing food grain production and managing soil resources. Traditionally, soil maps were generated using remote sensing or earlier with aerial photographs to establish soil resource databases. These databases are crucial for monitoring soil resource degradation. Soil resource inventories are conducted globally and nationally at various scales based on specific purposes. These databases are utilized for evaluating land suitability for different crops, classifying soil and land suitability, assessing land capability, categorizing soil hydrological properties, and developing watershed management plans. Soil maps are integrated with other thematic maps such as climate, geology, topography, land use/land cover, surface water resources, and groundwater resources to create robust digital databases for diverse applications. Today, Geographic Information System (GIS) is employed to store, retrieve, manipulate, and analyze large volumes of spatial and attribute data, offering significant utility for various users and planners due to its effectiveness. There is a growing need to establish a comprehensive soil information system to meet national and global requirements. Here, we discuss two databases available to users.

16.1 Indian Soil Information System

Over the past three decades, the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), India's premier soil research institute under the Indian Council of Agricultural Research (ICAR), has systematically mapped the soil resources of the country. Initially, soil mapping was conducted at a scale of 1:7 million, focusing on the level of sub-order associations, thus recognizing 103 sub-orders. Recognizing the importance of sustainable resource management, a comprehensive three tier approach was adopted in 1986, which included image interpretation, field mapping, and laboratory analysis across different climatic zones. Subsequently, maps were cartographically prepared and printed for all states and union territories at a scale of 1:250,000. A total of 176 false color composite (FCC) and black and white (B/W) infrared imageries at the 1:250,000 scale were visually interpreted to create pre-field physiography-cum-photomorphic maps. Special attention was given to detailed mapping of regions like Sikkim, Goa, Lakshadweep, and Andaman and Nicobar Islands, which were mapped at a more detailed scale of 1:50,000 using Landsat Thematic Mapper (TM) false color composites.

16.2 Global Soil Database

The Harmonized World Soil Database v 1.2 is a collaborative effort involving the FAO, IIASA, ISRIC-World Soil Information, Institute of Soil Science-Chinese Academy of Sciences (ISSCAS), and the Joint Research Centre of the European Commission (JRC). This database comprises a 30 arc-second raster format containing more than 15,000 different soil mapping units. It integrates regional and national updates of soil information from various sources such as SOTER, ESD, Soil Map of China, and WISE, along with data from the FAO-UNESCO Soil Map of the World (1:5,000,000 scale, FAO, 1971-1981). The database employs a standardized structure that enables linking of attribute data with the raster map. This facilitates the display and querying of soil unit compositions and the characterization of key soil parameters. These parameters include organic carbon content, pH, water storage capacity, soil depth, cation exchange capacity, clay fraction, total exchangeable nutrients, lime and gypsum contents, sodium exchange percentage, salinity, textural class, and granulometry. For downloading the database, please visit the following website - ***https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/***

The Global Soil Map initiative is a consortium aimed at creating digital maps of essential soil properties on a global scale. These maps encompass six soil layers ranging from 0–5 cm to 100–200 cm depth (i.e., 0–5, 5–15, 15–30, 30–60, 60–100, and 100–200 cm). Numerous countries have developed soil maps following the specifications set by the Global Soil Map consortium. Another significant global soil mapping project is the SoilGrids system (https://www.soilgrids.org, last accessed: 3 July 2019). The latest version offers maps at a resolution of 250 meters. This version was developed using an ensemble of machine-learning methods, utilizing data from approximately 150,000 soil profiles and 158 soil covariates. This represents one of the most detailed estimations available of global soil distribution to date.

16.3 Soil Ecosystem Services

Soil, an essential natural resource, profoundly impacts human life and ecological balance. Despite its critical role in sustaining the environment, the significance of soils is often underestimated in global sustainability efforts. They facilitate vital ecosystem processes such as plant growth, water regulation, nutrient cycling, and support diverse biodiversity. However, soils are currently confronted with unprecedented challenges related to degradation from human activities. Factors like deforestation, intensive and unsustainable agriculture, and soil pollution are exerting immense pressure, leading to soil degradation. This degradation stems from land use changes, poor agricultural practices, erosion, salinization, and desertification, all of which threaten the soil's ability to continue providing essential ecosystem services.

16.4 Role of Soils in Ecosystem Services

Soil supports a diverse range of flora and fauna, including numerous microorganisms that play crucial roles in biogeochemical processes. The ecosystem services provided by soil can be categorized into four main groups:

I. ***Provisioning services:*** refers to the tangible products derived from soils, such as food, fiber, fuel, medicinal plants, and more.

II. ***Regulating services:*** It encompass the control of ecological processes and systems. Soils play a crucial role in water regulation by absorbing, storing, and purifying water through soil-water interactions. This helps mitigate flood risks and ensures the provision of clean water for both human and ecological use.

III. ***Supporting services:*** It plays a crucial role in maintaining biodiversity, facilitating global nutrient cycling, supporting complex interactions among plants, microorganisms, and soil minerals.

IV. Cultural services: Soil provides intangible benefits derived from ecosystems-spiritual enrichment, intellectual development, education, recreation, and aesthetic enjoyment. It shapes landscapes, supports and enhances local traditions and practices, spiritual endeavors, and helps in developing a sense of place and cultural identity.

16.5 Soil and Climate Change

Soils and climate change are closely intertwined. They interact in various ways, such as carbon sequestration, water regulation, temperature modulation, and support for biodiversity. Soils serve as significant carbon sinks, playing a crucial role in the global carbon cycle. Enhancing soil carbon sequestration can be achieved through practices like cover cropping, reduced tillage, crop rotation, agroforestry, and organic amendments such as manuring. This not only improves soil health but also enhances microbial diversity and stabilizes organic matter. According to the IPCC, the rise in global temperatures and changes in precipitation patterns are expected to profoundly impact the physical, chemical, and biological properties of soils.

16.6 Climate change Impact on Ecosystem services

Climate change has the potential to reduce soil fertility by disrupting the balance of soil-water-gas interactions and decreasing soil organic carbon levels. Additionally, soil serves as the largest terrestrial carbon sink, but improper management can lead to significant greenhouse gas emissions. Accelerated soil degradation due to agricultural expansion, unsustainable practices, conversion of natural habitats to rural and urban areas, and urban sprawl poses serious threats to soil health and ecosystem services. Ensuring the provisioning and regulating ecosystem services of soils is crucial for poverty alleviation efforts.

16.7 Sustainable Development and Food Production

Projected population growth estimates suggest that the world's population could approach 10 billion by 2050, necessitating a 70% increase in food production. Meeting this demand requires enhancing food productivity on current croplands while minimizing environmental impact and bolstering resilience to climate change. Enhancing soil health is pivotal in meeting food grain requirements while mitigating land degradation. Adopting sustainable agricultural practices like organic farming, conservation agriculture, agroforestry, and crop rotation, along with promoting biodiversity, will be essential to improving the resilience of agricultural systems overall.

The complex interplay among soils, sustainable development, and food production highlights the importance of embracing sustainable soil management and transitioning to more sustainable agricultural practices. Soils affect not only agriculture and ecology but also influence our dietary choices and environmental impact. Recognizing these connections provides valuable perspectives on sustainability, climate change, and the services ecosystems provide.

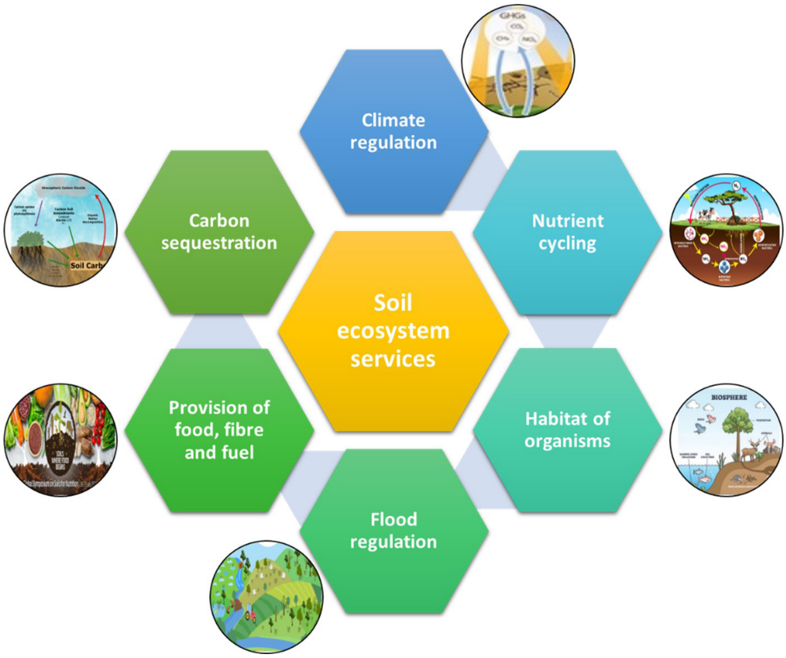


Fig 16.1: Schematic Diagram of Soil Functions and ecosystem services

"To forgot how to dig the earth and to tend the soil is to forget ourselves"

-Mahatma Gandhi

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