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भाकृअनुप
ICAR

Training Manual for In-Plant Programme

Application of Geospatial Technologies for Land Use Planning

ICAR-National Bureau of Soil Survey and Land Use Planning

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About the ICAR-NBSS&LUP

The National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur, an institute of ICAR established in 1976, is responsible for preparing soil resource maps and providing research inputs in soil survey, classification, land evaluation, remote sensing, GIS-based database management and land use planning. The Bureau undertakes agro-ecological and soil degradation mapping at national, state, and district levels to assess and monitor soil health. Its research helps identify soil potentials and constraints, supporting sustainable agriculture and natural resource management. NBSS&LUP also plays a key role in capacity building through training programmes for students and professionals and contributes to advanced education and research in land resource management in collaboration with Dr. PanjabraoDeshmukhKrishiVidyapeeth, Akola.

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Content

FOREWORD

Land is a finite and vital resource supporting food security, livelihoods, and ecosystem stability. Rapid population growth, urbanization, climate change, and land degradation are intensifying pressure on land, especially in developing countries. Sustainable land use planning is therefore essential to balance agricultural productivity, environmental protection, and socio-economic needs. Geospatial technologies such as Remote Sensing, GIS, and GNSS play a crucial role by enabling accurate, data-driven assessment and monitoring of land resources.

A four-month In-Plant Training Programme on Application of Geospatial Technologies for Land Use Planning was conducted by the Division of Land Use Planning, ICAR-NBSS&LUP, Nagpur from 16^{th} June to 16^{th} October 2025. A total of 27 B.Tech. (Agricultural Engineering) students from agricultural universities of Maharashtra participated. This training manual has been prepared to provide theoretical knowledge and practical skills in applying geospatial tools for integrated land resource appraisal and sustainable land use planning, covering 12 key topics.

The manual aims to develop a holistic perspective among future agricultural engineers and strengthen their capacity to address land use and environmental challenges. The contributions of all authors, editors, and technical and administrative staffs involved in bringing out this publication are gratefully acknowledged.

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Soil Characteristics and Their Importance in Land Use Planning

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Introduction

Soil is one of the most fundamental natural resources and forms the foundation of terrestrial ecosystems. It supports a wide range of human and environmental activities, including agricultural production, forestry, grazing, infrastructure development, and the maintenance of ecological balance. The sustainable use and management of soil resources are therefore critical for food security, environmental protection, and long-term socio-economic development.

According to Soil Taxonomy (Soil Survey Staff, 1999), soil is defined as "a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons or layers that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter, or the ability to support rooted plants in a natural environment." This definition highlights soil as a dynamic and living system rather than an inert medium, continuously influenced by physical, chemical, and biological processes.

The inherent properties of soil largely govern its behavior under different land uses and management practices. These properties determine how soils respond to cultivation, irrigation, fertilization, grazing pressure, and engineering activities. Consequently, inappropriate land use without adequate consideration of soil characteristics often leads to land degradation in the form of erosion, salinization, nutrient depletion, compaction, and decline in soil productivity.

Soil–land use planning is a scientific and systematic approach aimed at allocating land resources to the most suitable uses while minimizing degradation and ensuring sustainable productivity. It involves matching the requirements of various land uses, such as crops, forests, pastures, or non-agricultural uses with the capability and limitations of the soil. A sound understanding of soil characteristics and their spatial variability is therefore essential for effective land use planning and decision-making.

Soil characteristics play a critical role in determining crop suitability, irrigation potential, erosion hazard, nutrient dynamics, water availability, and the overall resilience of land systems to climatic variability and environmental stress. These characteristics encompass the physical, chemical, and biological properties of soils, which together define their capacity to perform specific ecological and productive functions. Physical properties such as texture, structure, depth, bulk density, and water-holding capacity influence root penetration, moisture availability, aeration, and susceptibility to erosion. Chemical properties, including soil reaction (pH), salinity, cation exchange capacity, organic carbon content, and nutrient status, govern nutrient availability, toxicity risks, and fertilizer response.

Biological properties, such as soil organic matter dynamics, microbial activity, and faunal populations, regulate nutrient cycling, soil aggregation, and overall soil health.

These soil characteristics are primarily shaped by the soil-forming factors parent material, climate, organisms, relief, and time and thus exhibit spatial variability across landscapes. While many inherent soil properties remain relatively stable over short time scales, land use and management practices such as tillage, irrigation, fertilization, residue management, and cropping systems can significantly modify soil behavior and functional performance. In soil-land use planning, the integration of detailed soil information with physiography, climate, hydrology, vegetation, and socio-economic considerations enables the identification of suitable land use options and appropriate management interventions. Accordingly, soil characteristics are assessed using both qualitative descriptions and quantitative measurements to evaluate land capability, land suitability, and vulnerability to degradation, thereby supporting rational land allocation, sustainable resource use, and long-term agricultural productivity.

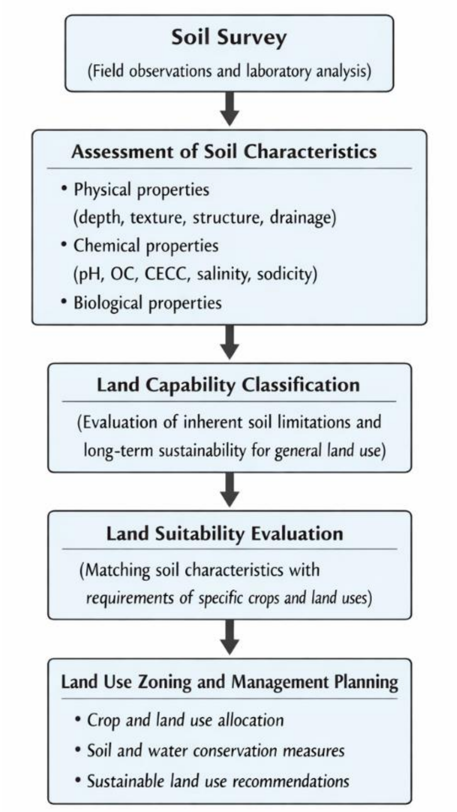

Fig. 1.1: Soil characteristics in land use planning

In the context of soil-land use planning, soil characteristics are evaluated using both qualitative (descriptive) and quantitative (measured) approaches. This evaluation forms the basis for assessing land capability, land suitability, and vulnerability to degradation. Such assessments support rational land use decisions, promote sustainable resource management, and contribute to long-term agricultural and environmental sustainability.

Physical soil characteristics and their importance

- **Soil texture**

Soil texture refers to the weight proportion of the separates (sand, silt and clay) for particles less than 2 mm in diameter as determined from a laboratory particle-size distribution (Table 1.1).

- **Sands -** Material has more than 85 % sand, and the percentage of silt plus 1.5 times the percentage of clay is less than 15.
  a) Coarse sand - Material has a total of 25 % or more very coarse and coarse sand and less than 50 % any other single grade of sand.
  b) Sand - Material has a total of 25 % or more very coarse, coarse, and medium sand, a total of less than 25 % very coarse and coarse sand, and less than 50 % fine sand and less than

50 % very fine sand; or material has 25 % or more very coarse and coarse sand and 50 % or more medium sand.

c) Fine sand **-**Material has 50 % or more fine sand, and fine sand exceeds very fine sand; or material has a total of less than 25 % very coarse, coarse, and medium sand and less than 50 % very fine sand.

d) Very fine sand -Material has 50 % or more very fine sand.

- **Loamy sands -** Material has between 70 and 90 % sand, the percentage of silt plus 1.5 times the percentage of clay is 15 or more, and the percentage of silt plus twice the percentage of clay is less than 30.

a) Loamy coarse sand - Material has a total of 25 % or more very coarse and coarse sand and less than 50 % any other single grade of sand.

b) Loamy sand - Material has a total of 25 % or more very coarse, coarse, and medium sand, a total of less than 25 % very coarse and coarse sand, and less than 50 % fine sand and less than 50 % very fine sand; or material has a total of 25 % or more very coarse and coarse sand and 50 % or more medium sand.

c) Loamy fine sand - Material has 50 % or more fine sand or less than 50 % very fine sand and a total of less than 25 % very coarse, coarse, and medium sand.

d) Loamy very fine sand - Material has 50 % or more very fine sand.

- **Sandy loams -**Material has 7 to less than 20 % clay and more than 52 % sand, and the percentage of silt plus twice the percentage of clay is 30 or more; or material has less than 7 % clay and less than 50 % silt, and the percentage of silt plus twice the percentage of clay is 30 or more.

a) Coarse sandy loam - Material has a total of 25 % or more very coarse and coarse sand and less than 50 % any other single grade of sand; or material has a total of 30 % or more very coarse, coarse, and medium sand, and very fine sand is 30 to less than 50 %.

b) Sandy loam - Material has a total of 30 % or more very coarse, coarse, and medium sand but a total of less than 25 % very coarse and coarse sand, less than 30 % fine sand, and less than 30 % very fine sand; or material has a total of 15 % or less very coarse, coarse, and medium sand, less than 30 % fine sand, and less than 30 % very fine sand with a total of 40 % or less fine and very fine sand; or material has a total of 25 % or more very coarse and coarse sand and 50 % or more medium sand.

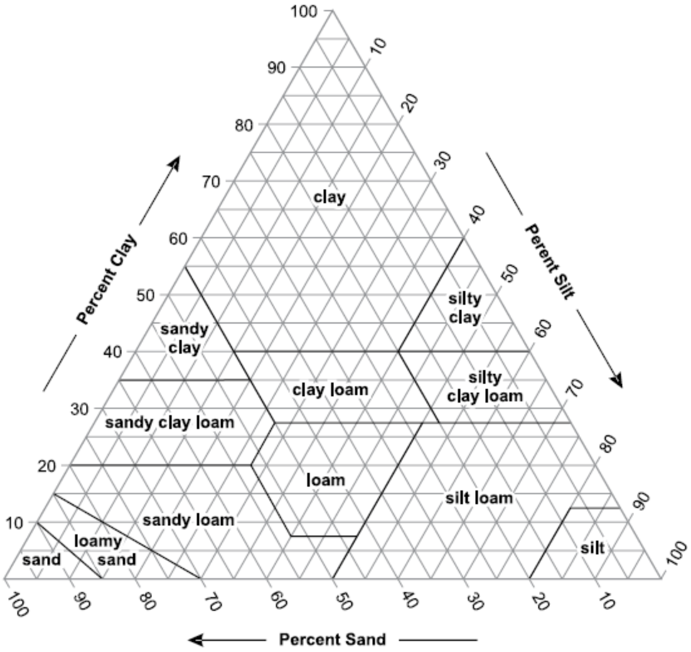

Fig. 1.2: USDA textural triangle showing the percentages of clay, silt, and sand in the 12 basic texture classes

Table 1.1: Soil textural classes

Sl. No.	USDA textural class	Approximate % sand (0.05-2mm)	Approximate % silt (0.002-0.05mm)	Approximate % clay (<0.002mm)	Corresponding IUSS/FAO textural class
1	Sand	85-100	0-15	0-10	Coarse
2	Loamy sand	70-90	0-30	0-15	Coarse
3	Sandy loam	43-85	0-50	0-20	Medium
4	Loam	23-52	28-50	7-27	Medium
5	Silt loam	0-50	50-88	0-27	Medium
6	Silt	0-20	88-100	0-12	Medium
7	Sandy clay loam	45-80	0-28	20-35	Fine
8	Clay loam	20-45	15-53	27-40	Fine
9	Silty clay loam	0-20	40-73	27-40	Fine
10	Sandy clay	45-65	0-20	35-55	Fine
11	Silty clay	0-20	40-60	40-60	Fine
12	Clay	0-45	0-40	40-100	Fine

c) Fine sandy loam - Material has 30 % or more fine sand, less than 30 % very fine sand, and a total of less than 25 % very coarse and coarse sand; or material has a total of 15 to less than 30 % very coarse, coarse, and medium sand and a total of less than 25 % very coarse and coarse sand; or material has a total of 40 % or more fine and very fine sand (and fine sand equals or exceeds very fine sand) and a total of 15 % or less very coarse, coarse, and medium sand; or material has a total of 25 % or more very coarse and coarse sand and 50 % or more fine sand.

d) Very fine sandy loam - Material has 30 % or more very fine sand and a total of less than 15 % very coarse, coarse, and medium sand, and very fine sand exceeds fine sand; or material has 40 % or more fine and very fine sand (and very fine sand exceeds fine sand) and a total of less than 15 % very coarse, coarse, and medium sand; or material has 50 % or more very fine sand and a total of 25 % or more very coarse and coarse sand; or material has a total of 30 % or more very coarse, coarse, and medium sand and 50 % or more very fine sand.

- **Loam -**Material has 7 to less than 27 % clay, 28 to less than 50 % silt, and 52 % or less sand.
- **Silt loam -**Material has 50 % or more silt and 12 to less than 27 % clay; or material has 50 to less than 80 % silt and less than 12 % clay.
- **Silt -**Material has 80 % or more silt and less than 12 % clay.
- **Clay loam -**Material has 27 to less than 40 % clay and more than 20 to 45 % sand.
- **Silty clay loam -**Material has 27 to less than 40 % clay and 20 % or less sand.
- **Sandy clay -**Material has 35 % or more clay and more than 45 % sand.
- **Silty clay -**Material has 40 % or more clay and 40 % or more silt.
- **Clay -**Material has 40 % or more clay, 45 % or less sand and less than 40 % silt.
- **Sandy clay loam -** Material has 20 to less than 35 % clay, less than 28 % silt, and more than 45 % sand.

It is a permanent soil property and exerts a strong influence on water retention, permeability, aeration, root penetration, and nutrient-holding capacity. Sandy soils have high permeability but low water and nutrient holding capacity, making them suitable for drought-tolerant crops and horticulture under assured irrigation. Clayey soils retain more water and nutrients but may suffer from poor drainage and workability problems. Loamy soils provide a balanced physical environment and are generally most suitable for intensive agriculture.

- **Soil structure**

Soil structure refers to the arrangement of soil particles into aggregates. Well-aggregated soils facilitate infiltration, aeration, and root growth, while poorly structured soils promote surface sealing, runoff, and erosion. Granular and crumb structures are desirable for agriculture, whereas massive and platy structures impose limitations on land use.

Types of soil structure

- **Platy -** The units are flat and plate-like. They are generally oriented horizontally.
- **Prismatic -** The individual units are bounded by flat to rounded vertical faces. Units are distinctly longer vertically, and the faces are typically casts or molds of adjoining units. Vertices are angular or sub-rounded; the tops of the prisms are somewhat indistinct and normally flat. (Fig. 1.3)
- **Columnar -** The units are similar to prisms and bounded by flat or slightly rounded vertical faces. The tops of columns, in contrast to those of prisms, are very distinct and normally rounded.
- **Blocky -** The units are block-like or polyhedral. They are bounded by flat or slightly rounded surfaces that are casts of the faces of surrounding peds. Typically, blocky structural units are nearly equi-dimensional but grade to prisms and plates. Angular blocky if the faces intersect at relatively sharp angles and sub-angular blocky if the faces are a mixture of rounded and plane faces and the corners are mostly rounded.
- **Granular -**The units are approximately spherical or polyhedral. They are bounded by curved or very irregular faces that are not casts of adjoining peds.
- **Wedge -**The units are approximately elliptical with interlocking lenses that terminate in acute angles. They are commonly bounded by small slickensides.
- **Lenticular -**The units are overlapping

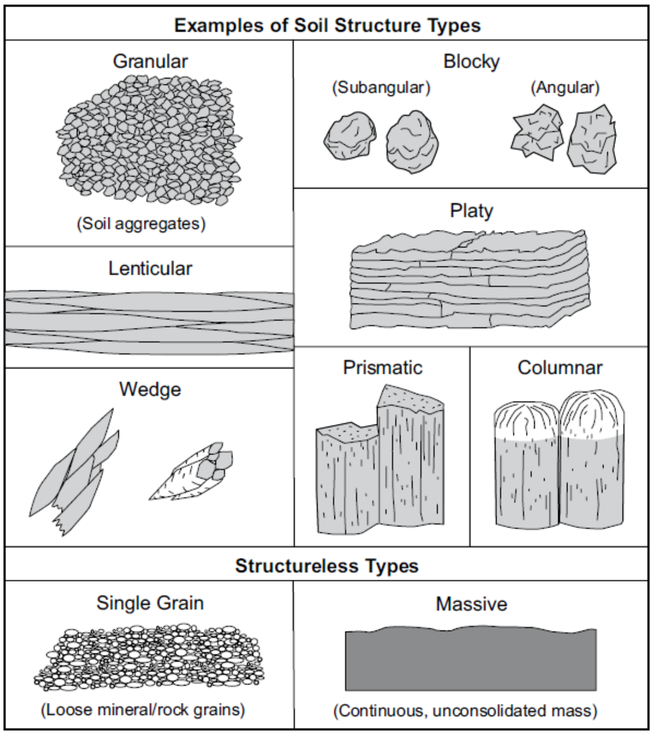

Fig. 1.3: Types of the soil structure

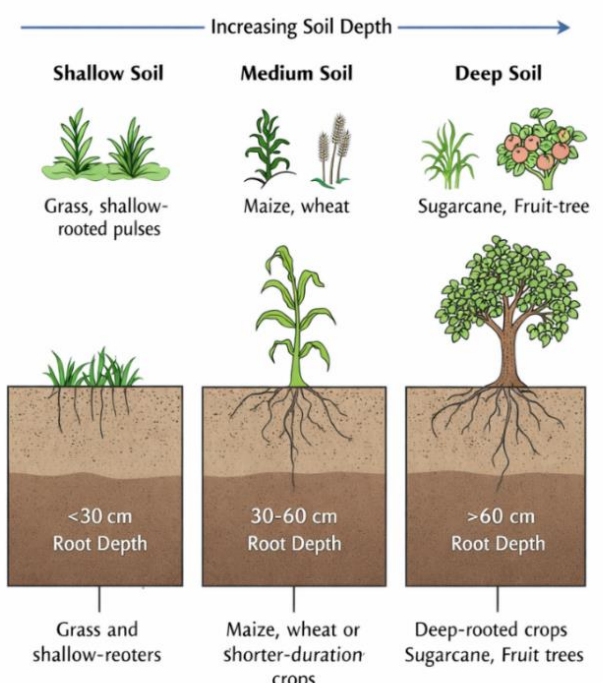

Fig. 1.4: Schematic relationship between soil depth and crop suitability

lenses parallel to the soil surface. They are thickest in the middle and thin towards the edges. Lenticular structure is commonly associated with moist soils, texture classes high in silt or very fine sand (e.g., silt loam), and high potential for frost action.

- **Soil depth**

Effective soil depth determines the volume of soil available for root growth, water storage, and nutrient supply. Deep soils are suitable for a wide range of crops, plantations, and agroforestry systems, while shallow soils restrict rooting depth and moisture availability and are better suited for pasture, forestry, or conservation land uses.

The ICAR-NBSS&LUP classifies soil depth primarily for the purpose of understanding land capability, crop suitability, and erosion management. The standard classification is based on the depth of the solum (the A and B horizons, i.e., the weathered soil material above the parent rock or un-weathered material). It is typically measured in centimeters (Table 1.2).

Table 1.2: Soil depth class and their practical application for farmers and planners

Sl. No.	Depth class	Depth range (cm)	Recommended Land Use / Crops	Essential Management Practices
1	Very shallow	< 25	Pastures, silvi-pasture, social forestry, recreation.	Contour trenching, moisture conservation, avoid tillage.
2	Shallow	25 - 50	Millets (bajra, ragi), groundnut, grasses, some drought-tolerant horticulture (e.g., ber).	Contour bunding, mulching, in-situ moisture conservation, controlled grazing.
3	Moderately deep	50 - 75	Most cereals (wheat, maize), pulses, oilseeds, horticulture crops with medium root depth.	Contour cultivation, graded bunding, balanced fertilization.
4	Deep	75 - 100	All arable crops, sugarcane, cotton, deep-rooted fruits (mango, citrus), plantation crops.	Intensive agriculture, sub-surface drainage if needed, crop rotation, cover cropping to prevent nutrient mining.
5	Very deep	> 100		

- **Soil drainage and permeability**

Soil drainage refers to the frequency and duration of periods when soil is saturated or partially saturated with water under natural conditions. It reflects the soil's ability to remove excess water from the root zone and is influenced by texture, structure, depth, landscape position, permeability, and groundwater conditions. Poorly drained soils may suffer from waterlogging, reduced aeration, and salinity hazards, whereas excessively drained soils experience rapid moisture loss. Drainage characteristics strongly influence crop selection, irrigation planning, and infrastructure suitability. NBSS & LUP recognizes the following soil drainage classes (Table 1.3).

Table 1.3: Soil drainage classes			
Drainage class	**Soil moisture regime (Field condition)**	**Typical landscape position**	**Crop suitability (Indian context)**
Excessively drained	Water removed very rapidly; soil remains dry	Sand dunes, steep uplands	Pearl millet, cluster bean, fodder grasses (with irrigation support)
Somewhat excessively drained	Rapid removal of water; limited moisture storage	Upper uplands, gravelly plains	Groundnut, castor, sesame
Well drained	No waterlogging within rooting depth	Gently sloping uplands	Cotton, soybean, wheat, sorghum, maize
Moderately well drained	Short-term saturation in subsoil	Mid-slope positions	Cotton, pigeon pea, wheat (with surface drainage)
Imperfectly drained	Seasonal water stagnation; mottles present	Lower slopes, valley margins	Rice (medium duration), wheat (restricted), mustard
Poorly drained	Long-duration saturation; high water table	Low-lying plains, depressions	Rice, jute, fodder grasses
Very poorly drained	Prolonged ponding; marshy condition	Swamps, flood plains	Lowland rice, wetland vegetation

- **Soil permeability**

Soil permeability is the quality of soil that enables water to move downward through the soil profile. It is closely related to soil texture, structure, porosity, and presence of restrictive layers. NBSS & LUP classifies soil permeability into the following classes:

Table 1.4: Soil permeability classes			
Permeability Class	**Hydraulic Conductivity (cm hr^{-1})**	**Dominant Texture**	**Land Use Implication**
Very slow	< 0.13	Heavy clay	Severe drainage problem; suited to rice
Slow	0.13 - 0.5	Clay	Restricted infiltration; puddling possible
Moderately slow	0.5 - 2.0	Clay loam	Limited internal drainage
Moderate	2.0 - 6.3	Loam	Ideal for most field crops
Moderately rapid	6.3 - 12.7	Sandy loam	Good drainage; moderate moisture holding
Rapid	12.7 - 25.4	Loamy sand	High infiltration; frequent irrigation needed
Very rapid	> 25.4	Sand, gravel	Severe moisture stress

- **Bulk Density**

The mass of dry soil per unit volume. A measure of compaction. High bulk density restricts root growth and hydraulic conductivity, often a result of heavy machinery or overgrazing.

Chemical soil characteristics and their importance

- **Soil Reaction (pH)**

  Soil pH is a logarithmic measure of the hydrogen ion (H^+) activity in the soil solution. It indicates whether a soil is acidic, neutral, or alkaline. It ranges from 0 (extremely acidic) to 14 (extremely alkaline), with 7 being neutral and most crops prefer a pH between 6.0 and 7.5 (Table 1.5). High rainfall leaches basic ions (Ca^{2+}, Mg^{2+}, K^+, Na^+), increasing acidity. Soil pH governs nutrient availability, microbial activity, and the solubility of potentially toxic elements. Acid soils may exhibit aluminum and iron toxicity, while alkaline and calcareous soils often show micronutrient deficiencies. Rocks like granite weather to form acidic soils; limestone leads to alkaline soils. Soil–land use planning incorporates soil pH to recommend appropriate crops and soil amendments such as lime or gypsum.

Table1.5: Soil pH classification

pH range (in 1:2.5 soil: water)	Reaction class	Common Occurrence in India & Remarks
< 4.5	Ultra acid	Rare; in some highly leached forest soils or acid sulfate soils.
4.5 - 5.5	Extremely acid	Heavily leached soils of high rainfall areas (e.g., parts of Assam, Kerala, Western Ghats).
5.5 - 6.5	Strongly acid	Red and Lateritic soils of Odisha, Chhattisgarh, Eastern states.
6.5 - 7.5	Moderately acid to Neutral	Largest and most productive agricultural soils (e.g., Alluvial soils of Indo-Gangetic plains, deep black soils).
7.5 - 8.5	Moderately alkaline	Arid and semi-arid region soils (e.g., parts of Rajasthan, Haryana, Punjab), and many calcareous soils.
8.5 -9.5	Strongly alkaline	Saline-sodic or sodic soils (e.g., *Reh*, *Kallar*, *Usar* lands).
> 9.5	Very strongly alkaline	Highly sodic soils with high ESP (Exchangeable Sodium Percentage). Very poor for cultivation without reclamation.

- **Salinity and sodicity**

  The concentration of soluble salts and exchangeable sodium, respectively. Both are toxic to plants, degrade structure (sodicity causes dispersion), and are major constraints in arid and irrigated regions. Saline and sodic soils impose serious constraints on land use due to osmotic stress, poor soil structure, and reduced infiltration. Soil–land use planning identifies such soils for reclamation measures, salt-tolerant crops, or alternative land uses such as pasture and forestry. The standard international unit of measure for EC is decisiemens per meter (dS/m) corrected to a temperature of 25 °C. Table 1.6 shows the classes shows the classes of salinity

Table 1.6: Soil salinity classes

Salinity class	Electrical conductivity (ECe) dS m^{-1}
Non-saline	< 2
Very slightly saline	2 to < 4
Slightly saline	4 to < 8
Moderately saline	8 to < 16
Strongly saline	≥ 16

- **Cation exchange capacity (CEC)**

The soil's ability to hold and exchange positively charged nutrients (e.g., Ca^{2+}, Mg^{2+}, K^{+}). High CEC (clay and organic-rich soils) indicates high fertility and buffering capacity. Cation exchange capacity (CEC) represents the soil's ability to retain and exchange nutrient cations. High CEC soils, typically rich in clay and organic matter, possess greater buffering capacity against nutrient losses, whereas low CEC soils require careful nutrient management.

- **Soil organic carbon**

Soil organic carbon (SOC) is the carbon component of soil organic matter (SOM). SOM ≈ SOC × 1.72 (the conventional factor, though it can vary).It is the keystone of soil health-improving structure, water retention, CEC, and providing a reservoir of nutrients. It is also a major carbon sink. It enhances aggregate stability, water-holding capacity, nutrient availability, and biological activity. Land use systems that maintain or improve organic carbon levels are essential for long-term soil productivity. SOC classification into "high," "medium," and "low" is relative and depends on climate, soil texture, and land use (Table 1.7). The same SOC percentage can be "high" in an arid region but "low" in a humid, grassland area.

Table 1.7: Soil organic carbon classes

SOC %	Rating class	Typical occurrence in India & management need
< 0.5%	Low (L)	Intensively cultivated arid and semi-arid soils (parts of Punjab, Haryana, Rajasthan, Gujarat), heavily degraded soils. Critical need for organic matter addition.
0.5 - 0.75%	Medium (M)	Most intensively cropped alluvial and red soils of the Indo-Gangetic plains and peninsular India. Represents the "average" but sub-optimal level. Needs improvement.
> 0.75%	High (H)	Soils under conservation practices, soils with organic amendments, or those in high-rainfall/high-organic-matter zones (e.g., parts of Kerala, NE hill soils, alluvial soils under good management). Level to be maintained.

- **Soil calcium carbonate ($CaCO_3$)**

  Soil Calcium Carbonate is an inorganic carbon compound present in soils. It exists in two main forms:

  1. **Primary (Inherited) $CaCO_3$:** Derived directly from parent materials like limestone, marble, or calcareous sediments.
  2. **Secondary (Pedogenic) $CaCO_3$:** Formed in situ through pedogenic processes in arid/semi-arid regions. This often appears as distinctive soil features.

The most common and practical classification (Table 1.8) is based on the percentage of $CaCO_3$ equivalent in the soil, typically determined by acid neutralization (HCl treatment) or calcimeter methods.

Table 1.8: Classification of soil calcium carbonate ($CaCO_3$)

$CaCO_3$ % (in fine earth)	Calcareousness	Indian soil	Effervescence
< 1%	Non-calcareous	Lateritic soils (Kerala, Western. Ghats), Acidic hill soils (NE states), many alluvial soils of high rainfall areas.	None
1 - 10%	Slightly to moderately	Older alluvial soils (Bangar), some red soils, certain black soils (Regur).	Faint
10 - 25%	Strongly	Many black soils of peninsular India, Aridisols of Rajasthan and Gujarat.	Distinct
> 25%	Highly	Soils of arid regions (e.g., Rajasthan desert), soils derived from limestone (e.g., parts of Jammu & Kashmir, Himachal).	Violent

Biological Characteristics

- **Soil biodiversity**

The community of organisms (bacteria, fungi, earthworms, arthropods) that drive nutrient cycling, organic matter decomposition, and soil structure formation. A vibrant soil food web is essential for ecosystem services. Biological properties of soil include microorganisms, fauna, and root activity, which collectively drive nutrient cycling, organic matter decomposition, and soil structure formation. Biologically active soils are more resilient and better suited for sustainable land use systems. These soil characteristics serve as the foundational criteria for systematic land use planning through Land Evaluation Approaches.

- **Land evaluation approach**

Land evaluation systems translate core soil characteristics like depth, texture, pH, organic carbon, and calcium carbonate content into actionable land-use plans. The widely used USDA Land Capability Classification (LCC) classifies land into eight classes (I to VIII) based on limitations for agriculture, using a simple qualitative approach. Land is grouped by permitted use: cultivation (Classes I-III), occasional cultivation (IV), pasture/forestry (V-VII), and nature reserves (VIII). Subclasses (e, w, s, c) specify the type of limitation present, guiding conservation needs (Table 1.9 and 1.10).

Table 1.9: Arable land classes (I-IV)

Parameter	Class I (Few)	Class II (Moderate)	Class III (Severe)	Class IV (Very severe)
Definition	Few limitations	Moderate limitations	Severe limitations	Very severe limitations
Crops/yield	All crops, optimal	Most crops, near optimal	Limited crops, low yield	Marginal yield
Slope/erosion	Level, no erosion	Gentle, moderate erosion risk	Moderate steep, erosion	Steep, high erosion
Wetness/drainage	Well drained, no flooding	Occasional overflow, mod. permeability	Frequent overflow, waterlogging	Excessive waterlogging
Soil depth	Deep (>100 cm)	Moderately deep (50-100 cm)	Shallow (25-50 cm)	Very shallow (<25 cm)
Fertility	High	Responsive to fertilizers	Low	Very low
Salinity/alkalinity	None/Slight	Slight, easily correctable	Moderate hazard	Severe hazard
Management	Ordinary	Careful	Very careful	Very careful

Table 1.10: Non-arable land classes (V-VIII)

Parameter	Class V (Pasture)	Class VI (Pasture/range)	Class VII (Woodland)	Class VIII (Wildlife/recreation)
Definition	Not suited to cultivation	Severe limitations	Very severe limitations	Unsuitable for any exploitation
Use	Pasture	Pasture or range	Woodland	Recreation and wildlife
Limitations	Nearly level, drainage feasible	Very steep, severe erosion	Very steep, severe erosion, too wet	Extreme limitations (slope, stoniness, wetness)

More quantitative methods include the Storie index (1933) (Table 1.11) and productivity index (FAO, 1970), which multiply rated soil factors to generate a suitability score. Storie index rating (SIR) system was developed for the purposes of an appraisal according to land types. It is based on the product of the factors even one moderate factor reduces the value of index considerably. Its use, hence, is limited.

The basic concept of productivity index (Table 1.12) method is that agricultural soil productivity, under optimal management conditions, depends on the intrinsic characteristics. This is a multiplicative parametric method to evaluate soil productivity, from a scheme similar to the Storie index.

Table 1.11: Storie index rating (FAO, 1976a)		
Storie index rating (%)	**Grade**	**Category**
80-100	1	Excellent
60-79	2	Good
40-59	3	Fair
20-39	4	Poor
10-19	5	Very Poor
<10	6	Non-agricultural

Table 1.12: Productivity index rating		
Classes	**Grade**	**Use for**
P1	Excellent	All types of agricultural crops
P2	Good	
P3	Medium	Marginal agricultural use, suitable for non-fruiting trees
P4	Poor	Pasture or forestation or recreation
P5	Very Poor	Soils not adequate for any type of exploitation

Specialized systems like the Fertility capability classification (FCC) (Buol et al., 1975; Sanchez et al., 1982) focus on chemical constraints, while the Land irrigability classification (United States Bureau of Reclamation, 1953) assesses suitability for sustained irrigation (Table 1.13). It Assesses suitability for sustained irrigation based on soil, topography, drainage, and socioeconomics.

Table 1.13: Land irrigability classification	
Class 1(A)	Lands that have few limitations - Nearly level (<1%), deep (>90 cm), favourable permeability (5.0-50 mm hr^{-1}), texture (sl, cl) surface 30 cm, moisture holding capacity (12 cm)
Class 2(A-B)	Lands that have moderate limitations for sustained use under irrigation - 1-3% slope, 45-90 cm depth, texture (loamy sand, clay), permeability (1-3.5 mm hr^{-1}) (50-1300 mm hr^{-1}), moisture holding capacity (9-12 cm)
Class 3 (C)	Lands that have severe limitations for sustained use under irrigation. - Slopes (3-5%), unfavourable soil depth (22.5-45.0 cm), texture (sand, clay), permeability (0.3-1.3 mm hr^{-1}) (130-250 mm hr^{-1}), moderate severe salinity or alkalinity (8-12 mmhos cm^{-1}) (ESP >15%), unfavourable drainage (poor, ESP>15%, excessively drained), moisture holding capacity (6-9 cm)
Class 4 (D)	Marginal lands for sustained use under irrigation - Slope (5-10%), soil depth (7.5-22.5 cm), texture (sand, clay), permeability (0-3 mm hr^{-1}) (>250 mm hr^{-1}), moisture holding capacity (2-6 cm), very severe salinity (12-16 mmhos cm^{-1}) alkalinity (ESP> 15%)
Class 5	Lands that are temporarily classed as not suitable for sustained use under irrigation
Class 6(E)	Lands not suitable for sustained use under irrigation

Table 1.14: Land suitability classification (FAO framework)	
Order	**Sub- order**
S= Suitable (land in which the benefits exceed the costs and sustained use does not incapacitate the soil over a sufficiently long period of time)	S1 = Highly suitable. Without limitations for sustained use or minor limitations that do not affect productivity nor appreciably increase costs. S2 = Moderately suitable. Moderately serious limitations that reduce profits or involve risks of degradation in the sustained use of the soil. S3 = Marginally suitable. The limitations for the sustained use are serious and the balance between the costs and benefits make the use only marginally justifiable. Its use is normally justified on other than economic grounds.
N=Not Suitable	N1 = Not currently suitable. Land with limitations that could be eliminated by technical means or investment, but that these changes are at present unfeasible. N2 = Permanently unsuitable. Serious limitations of generally a physical nature, which are assumed to be beyond solving over the long term.

The comprehensive FAO Framework (1976b) provides a flexible structure, evaluating land for specific uses under orders of Suitable (S) or Not suitable (N), with subclasses indicating limiting factors (Table 1.14). Together, these systems form the foundation for sustainable soil-land use planning, increasingly supported by GIS and modeling tools to address complex environmental and socio-economic challenges.

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Soil-landscape Relationships

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Introduction

Landform and soil variations are directly linked with geomorphological expressions. The inter relationships between spatial and temporal sequences were frequently studied by establishing landform-soils or pedo-geomorphic relationship. Thus, the geomorphological work of landform analysis and the study of soils need to be closely co-coordinated. The fact that the soils develop in an organized manner on any given landform and that a close association exists between different elements/segments of landforms and soils along the slope from the waxing crests to the waning valley floor is now recognized. Thus, geomorphology has strong influence on the distribution of soils in an area and plays an important role in the stage of soil development as evidenced from the soil profiles. Often the soils are not directly derived from the underlying bedrock, but develop in slope deposits or other covering materials that pre-date soil formation. Such deposits may be related to earlier geomorphological situations when relief, climate and other situations differed from the present ones. The relief in itself is an important geomorphological factor in soil formation. Rain water tends to collect in depressions; shallow ground water may also occur resulting into the hydromorphic soils with gley development. At the higher level, however, in the drier parts of the relief, relatively different soil characteristics prevail and a good correlation exists between landforms and soil patterns. The inter relationships that exist between landforms and that of soils are examined in detail with respect to the particular region.

Basic concept of soil mapping

Soil maps are used to evaluate land for different uses depending upon the potential and limitations of the soils. The primary purpose of soil map is to predict soil properties at site of interest. Its utility depends on the precision and accuracy of the statements made about the map units (Beckett, 1968). Some of terminology used in study of soil landscape are defined below.

- **Geomorphology**: It is a branch of physical geography. The term geomorphology originates from the Greek words i.e., *ge* (meaning earth) *morphe* (meaning form) and *logos* (meaning discourse). Therefore the term geomorphology may be defined as the scientific study of surface features of the earth's surface involving interpretative description of landforms, their origin, development, nature, mechanism of geomorphological processes which evolve the landforms (Singh, 1998).

- **Physiography:** It includes considerably landform, climatology, meteorology, oceanography and mathematical geography. Physiography is concerned with landform. In soil survey perspective, physiographic units are used for such terms as plain, plateau and valley of a region/place.
- **Landform:** It refers to the shape of land surface.
- **Relief:** Relief is the irregularities of surface such as sloping, undulating etc.
- **Landscape:** It is a group of bodies of soil, non-soil and associated items, including cultural features.

Major landforms

- **Mountain:** It is a feature of the earth's surface that rises high above the base and generally has steep slopes and relatively a small summit area. They result in localized differences in climate, drainage, soils, flora and fauna.
- **Volcanic mountain:** A mountain originating through volcanic activity. The resulting main landforms are cones or cone shaped relief. Generally, high and intense degradation takes place on the slopes of young volcano. A characteristic centrifugal drainage pattern develops on their tops.
- **Hills:** A land surface feature characterized by strong relief rising straight from plain or surrounding areas, usually not exceeding a height of about 300 m.
- **Plateau:** An extensive flat or almost flat surface found in upland regions, considerably elevated above the adjacent landscape and limited by an abrupt descent scrap on at least one side.
- **Plains:**An extensive, generally broad tract of land, flat or gently sloping, unconfined, low-lying with low relief intensity (varying up to 10 m) and gentle slopes (generally <3%). They can occur around mountain/hill bases, along primary river valleys or along coast lines.
- **Escarpment:** Escarpment is a steep, exposed slope where the land falls from a higher to lower level. Usually, escarpment can be caused by vertical displacement of the earth's surface along fault lines.
- **Ridge:** An elongated, narrow, steep sided elevation of the earth's surface. It has single crest, which may have a more or less constant elevation, or may contain number of peaks.
- **Pediment:** A term defined as a smooth concave upward erosion surface, typically sloping down from the foot of a highland area and graded to either a local or more general base level. The pediment is an erosion surface with shallow rock floor.
- **Delta:** Accumulation of river-borne sediment deposited at the coast where a river enters a receiving body of water such as an ocean, lagoon, estuary or lake. Deltas result from the interaction of fluvial and marine forces and their development involves pro-gradation of river

mouths and delta shorelines, producing a sub-aerial deltaic plain surmounting delta front deposit which have accumulated to seaward.

Landscape model

Soil maps are mostly prepared taking into consideration the factors of soil formation as outlined by (Jenny, 1941). This well-known model identifies the five factors of soil formations *viz.* climate, parent material, topography/relief, living organism and time. This model implies that by watching for changes in one or more of these factors as the landscape is crossed, one can predict where changes in the soil continuum are likely to occur. Both short and long range variations can be characterized as continuous, with no well-defined inflections in the lateral rate of change or discontinuous where two distinct but relatively uniform bodies of soil adjoin.

Soil-landscape model is most frequently used by the scientist for soil mapping. In soil-landscape model, the information about soils and site characteristics are inferred from visible landscape features. The major concepts used in this model are:

1. Soil-landscape units are natural terrains resulting from the five factors conventionally cited in the functional equation for soil formation. A soil-landscape unit has a recognizable form and shape on the surface of the earth. A soil-landscape unit is similar to landform, but is more narrowly defined.
2. Soil-landscape units have a predictable spatial relationship to one another. For example, one kind will always be located below another, *etc.*
3. In a given area, there are relatively few soil-landscape units. These few units are replicated again and again.
4. Generally, the more difference in two adjacent soil-landscape units are, the more abrupt and striking the discontinuity separating them. An example is the boundary between a steep side slope and an alluvial flat at its base. Conversely, the more nearly alike two adjacent soil-landscape units are, the less striking the discontinuity separating them.
5. The boundaries between distinct soil-landscape units can be observed and mapped as discontinuities on the earth's surface. As a result, they can be delineated accurately by trained mappers.
6. A distinctive, relatively homogenous soil cover develops on each soil-landscape unit. Two distinctively different soil-landscape units typically support soil covers that are significantly different from each other in appearance and behaviour. The more stable the landscapes, the higher the co-variance between soil and landscape unit. Once, the soil-landscape relationships are determined for an area, the soil cover can be inferred by examining the landscape. Soil is examined directly only as needed to validate this relationship.

7. Since the boundaries between distinctly different landscape units tend to be abrupt and prominent, the boundaries between their associated soils tend to be abrupt and prominent.
8. Adjacent soils that are distinctly different will tend to be on distinctly different landscape units separated by abrupt discontinuities. As a general rule, the more different two adjacent soils are, the easier it is to locate the boundary between them accurately and precisely. This is a fortuitous relationship. Because of it, adjacent soils that differ markedly in appearance and behaviour tend to be separated in mapping with precision and accuracy.
9. Within a given soil-landscape unit, soil variation at the human scale of perception, is most cyclic. Adjacent soils tend to be similar and the boundaries between them tend to be indistinct and gradational. Soils within the same landscape unit normally cannot be separated with precision.

Soil mapping unit

The name of the map unit (type and constituents) provides shorthand to describe the map unit. The kind of map units (Table 2.1) normally used for mapping soils at different scales is described in USDA soil survey manual (Soil Survey Division Staff, 1998).

- **Consociation**: Only one soil type is named. This named soil type and closely-related soils that differ in only a few unimportant properties that do not significantly affect interpretations make up at least 75 per cent of the area of a consociation. Therefore, up to 25 per cent of the total area may contain soils that differ significantly from the named soil in one or more properties. Up to 15 per cent of the total area may contain soils that differ significantly from the named soil, and that in addition are significantly more limiting for one or more land uses.
- **Association:** Several important soil types that occur in the map unit are named. These soils occur in a regular pattern in the landscape that can be seen in the field and on aerial photographs, but cannot be mapped due to scale limitation. The named soil types and closely-related soils that differ in only a few unimportant properties that do not significantly affect interpretations make up at least 75 per cent of the area of the association. Therefore, up to 25 per cent of the total area may contain soils that differ significantly from all of the named soil in one or more properties. Up to 15 per cent of the total area may contain soils that differ significantly from all of the named soils, and that in addition are significantly more limiting for one or more land uses.
- **Complex:** Similar to an association except that the named soils do not occur in a regular pattern in the landscape that can be seen in the field and on aerial photographs at normal map scales. Instead, they occur together in a very intricate pattern that can be discovered only by detailed on-site inspection.

Table 2.1: Key for identifying kinds of soil surveys				
Level of data needed	**Field procedures**	**Typical components of map units[2]**	**Kind of map units**	**Appropriate scales for mapping and publications**
1st order - Very intensive (i.e., experimental plots or individual building sites)	The soils in each delineation are identified by transecting or traversing. Soil boundaries are observed throughout their length. Remotely sensed data are used as an aid in boundary delineation.	Phases of soil series, miscellaneous areas.	Mostly consociations, some complexes, miscellaneous areas.	1:15,840 or larger
2nd order - Intensive (e.g. general agriculture, urban planning)	The soils in each delineation are identifies by field observations and by remotely sensed data. Boundaries are verified at closely spaced intervals.	Phases of soil series, miscellaneous areas, few named at a level above the series.	Consociations, complexes; few associations and undifferentiated groups.	1:12,000 to 1:31,680
3rd order - Extensive (i.e., range or community planning	Soil boundaries plotted by observation and interpretation of remotely sensed data. Soil boundaries are verified by traversing representative areas and by some transects.	Phases of soil series or taxa above the series; or miscellaneous areas.	Mostly associations or complexes, some consociations and undifferentiated groups.	1:20,000 to 1:63,360
4th order- Extensive (e.g., general soil information for broad statements concerning land-use potential and general land management)	Soil boundaries plotted by interpretation of remotely sensed data. Boundaries are verified by traversing representative areas and by some transects.	Phases of soil series or taxa above the series or miscellaneous areas.	Mostly associations; some complexes, consociations and undifferentiated groups	1:63,360 to 1:250,000
5th order - Very extensive (e.g., regional planning, selections of areas for more intensive study)	The soil patterns and composition of map units are determined by mapping representative ideas and like areas by interpretation of remotely sensed data. Soils verified by occasional onsite investigation or by traversing.	Phases of levels above the series, miscellaneous areas.	Associations; some consociations and undifferentiated groups.	1:250,000 to 1:1,000,000 or smaller

Landform-soil relationship in basaltic terrain

The soil-landform relationship in Seloo taluka of Wardha district is presented in Fig. 2.1.

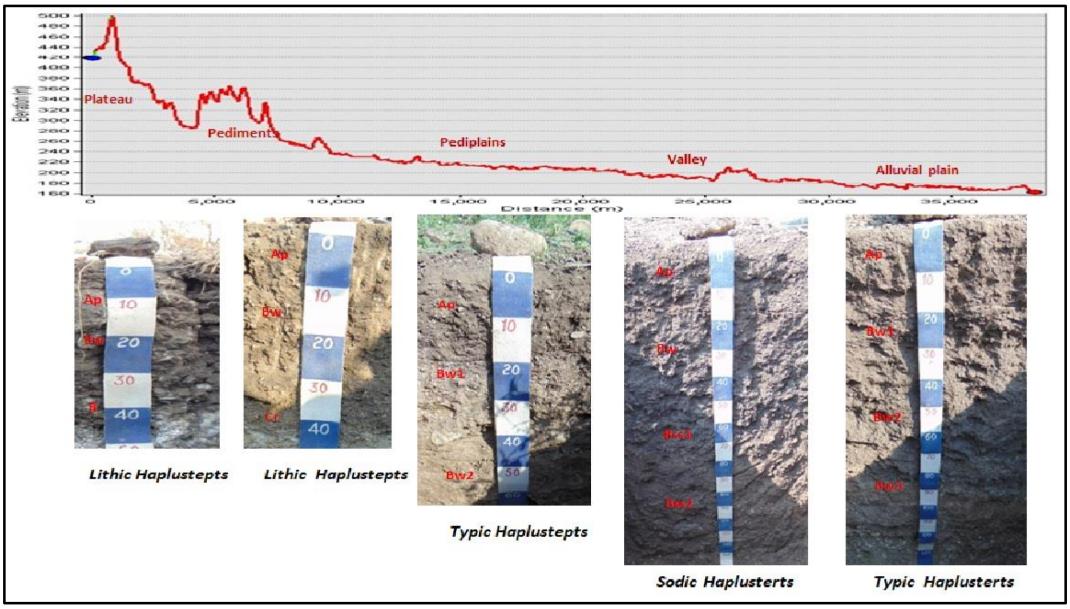

Fig. 2.1: Landform-soil relationship on basaltic terrain in Seloo tehsil, Wardha district, Maharashtra

The soils of the plateau were shallow, well drained, clay loam to clay, neutral to slightly alkaline (pH 7.1-7.4), low to medium in organic carbon (0.32-0.64%) content due to degraded forest cover. They were classified as Lithic Haplustepts. The soils of the pediments were shallow, clay loam to clay in texture, moderately alkaline classified as Lithic Haplustepts. The soils occurring on pediplains were moderately shallow to moderately deep, well drained clayey soils classified as Typic Haplustepts. The soils of the valley plain were very deep, moderately well drained, clay in texture, strongly alkaline, Sodic Haplusterts. The soils of the alluvial plain were very deep, well drained, clay in texture, calcareous, moderate to strongly alkaline classified as Typic Haplusterts (Fig. 2.1).

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Remote Sensing and GIS Applications for Land Use Planning

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Introduction

Land use and land cover (LULC) are often used as the same terms, but they have different meanings. Land cover refers to what is physically present on the Earth's surface, such as vegetation, buildings, water bodies, or bare soil. Land cover mapping is important for understanding natural resources, environmental conditions and for monitoring changes over a time period. It provides basic information needed for planning and management activities. Land use, on the other hand, describes how people use the land, such as for agriculture, housing, industry, recreation, or wildlife protection. Information on land use helps planners understand changes caused by human activities like urban growth, loss of farmland and deforestation. Remote sensing (RS) mainly observes LULC is interpreted from this information using additional knowledge (Turner et. al, 2007). Together, LULC studies support sustainable development, environmental monitoring and proper land resource management.

In developing countries like India, rapid population growth and increasing demand for food, housing and infrastructure have placed enormous pressure on limited land resources (Ramachandra et al., 2015). In many regions, land is being used without considering its capability, leading to serious environmental and socio-economic problems. Therefore, scientific land use planning (LUP) has become an essential to ensure balanced development, environmental protection and sustainable use of land resources.

However, traditional LUP methods mainly depend on ground-based field surveys and manual map preparation. Although these methods provide detailed local information, it is very time-consuming, costlyand limited to small areas. Moreover, it is difficult to frequently update land use maps and monitor changes over large regions using conventional techniques (Lillesand et al., 2015). As a result, these methods are not suitable for rapid assessment and long-term monitoring of land resources. In this context, RS and Geographic Information System (GIS) have emerged as powerful and efficient tools for LUP. RS provides up-to-date, repetitive and synoptic information about land surface features over large areas, while GIS enables systematic storage, analysis, integration, and visualization of spatial data from different sources (Jensen, 2016). The combined use of RS and GIS has greatly improved the accuracy, speed and reliability of LUP and supports informed decision making for sustainable land resource management.

Recap of remote sensing (RS) technology

Remote sensing plays a vital role in LUP by providing timely, reliable and spatially extensive information. RS is defined as the science and art of obtaining information about an object, area or phenomenon without direct contact, using data recorded by sensors (Lillesand, 2004).It involves sensing the Earth's surface from space using electromagnetic energy that is emitted, reflected, or scattered by surface features. This capability makes RS especially useful for LUP, as it allows continuous observation of land cover such as vegetation, water bodies, built-up areas and wastelands over large regions. The instruments used to detect electromagnetic radiation from the Earth's surface are known as sensors and examples include cameras and scanners. These sensors are mounted on platforms such as aircraft or satellites, which carry them over the Earth's surface to collect data. Thus, the combined use of sensors and platforms allows accurate mapping and monitoring of land cover, forming a strong foundation for effective LUP.

Types of remote sensing

Passive sensors: RS systems which measure energy that is naturally available are called passive sensors. Sun is the source of natural energy for passive RS systems (Fig. 3.1). Passive sensors detect energy that is reflected or emitted from the Earth's surface without generating their own energy. In the case of reflected energy, data can be collected only during daytime when sunlight illuminates the Earth, as no reflected solar energy is available at night. However, naturally emitted energy, such as thermal infrared radiation, can be recorded both during day and night, and provided the emitted energy is sufficient to be detected by the sensor.

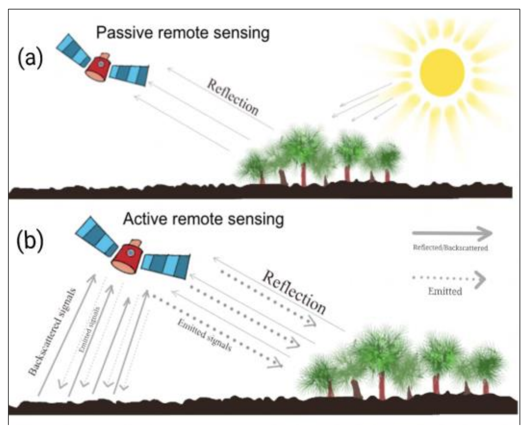

Fig. 3.1: Passive and active remote sensing

Active sensors: Active sensors generate their own source of energy to illuminate the target. The emitted radiation interacts with the target, and the reflected or backscattered energy is detected by the sensor (Fig. 3.1). A major advantage of active sensors is their ability to collect data at any time, regardless of day, night, or season and to operate at wavelengths such as microwaves that are not sufficiently provided by the Sun. However, active systems require a large amount of energy for operation. Examples of active sensors include laser fluorosensors and synthetic aperture radar (SAR).

Stages in remote sensing

The process of RS involves a number of processes starting from energy emission from source to data analysis and information extraction.

The mechanisms of RS is depicted in Fig. 3.2 and describes below:

- **Energy source or Illumination:** The first requirement for RS is to have an energy source which illuminates or provides electromagnetic energy to the target of interest.
- **Radiation and atmosphere:** As the energy travels from its source to the target, it will come in contact with and interact with the atmosphere, as it passes through. This interaction may take place a second time as the energy travels from the target to the sensor.
- **Interaction with the target:** Once the energy makes its way to the target through the atmosphere, it interacts with the target depending on the properties of both target and radiation.
- **Recording of energy by the sensor:** After the energy has been scattered by, or emitted from the target, a sensor collects and records the electromagnetic radiation.
- **Transmission, reception and processing:** The energy recorded by the sensor has to be transmitted, often in electronic form, to a receiving and processing station where the data are processed into an image (hardcopy/digital).
- **Interpretation and analysis**: The processed image is interpreted, visually and digitally or electronically, to extract information about the target which was illuminated.
- **Application:** The final element of the RS process is achieved when we apply the information, we have been able to extract from the imagery about the target in order to better understand it, reveal some new information, or assist in solving a particular problem.

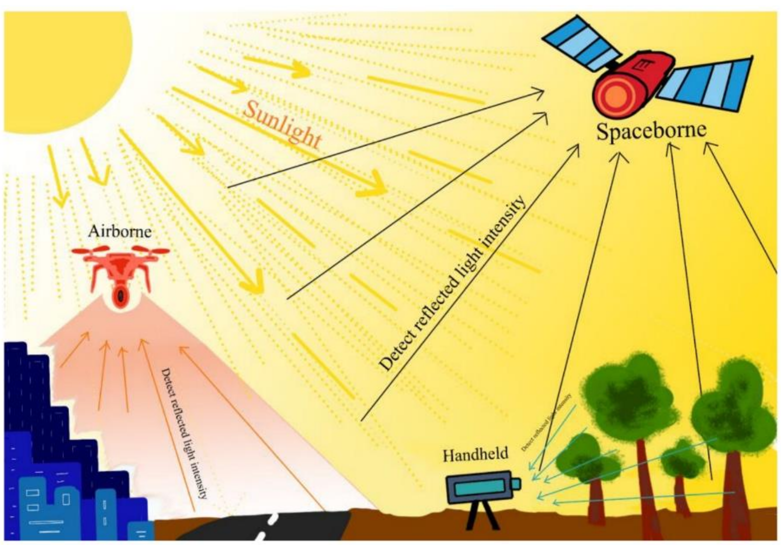

Fig. 3.2: Basic mechanism of remote sensing: Sensor record information received as a function of wavelength and atmospheric condition

Electromagnetic radiation

The electromagnetic (EM) spectrum is the continuous range of electromagnetic radiation, extending from gamma rays (highest frequency and shortest wavelength) to radio waves (lowest frequency and longest wavelength) and including visible light. The EM spectrum can be divided into seven different regions - gamma rays, X-rays, ultraviolet, visible light, infrared, microwaves and radio waves (Fig. 3.3).Each region differs in wavelength, frequency and has specific applications in science and technology.

Human eyes can detect only a small portion of the electromagnetic spectrum known as the visible region, which ranges approximately from 0.4 to 0.7 micrometers (μm). Although this is the only part, human can see, a large amount of radiation exists beyond this range that is invisible to the human eye. RS instruments are designed to detect these invisible wavelengths and use them to study the earth's surface. In RS applications, commonly used regions of the electromagnetic spectrum include near ultraviolet (0.3-0.4 μm), visible light (0.4-0.7 μm), near and shortwave infrared and thermal infrared (0.7-14 μm) and microwave regions (1 mm - 1 m). These regions are especially useful for observing land cover, vegetation, water bodies, soil conditions and atmospheric properties.

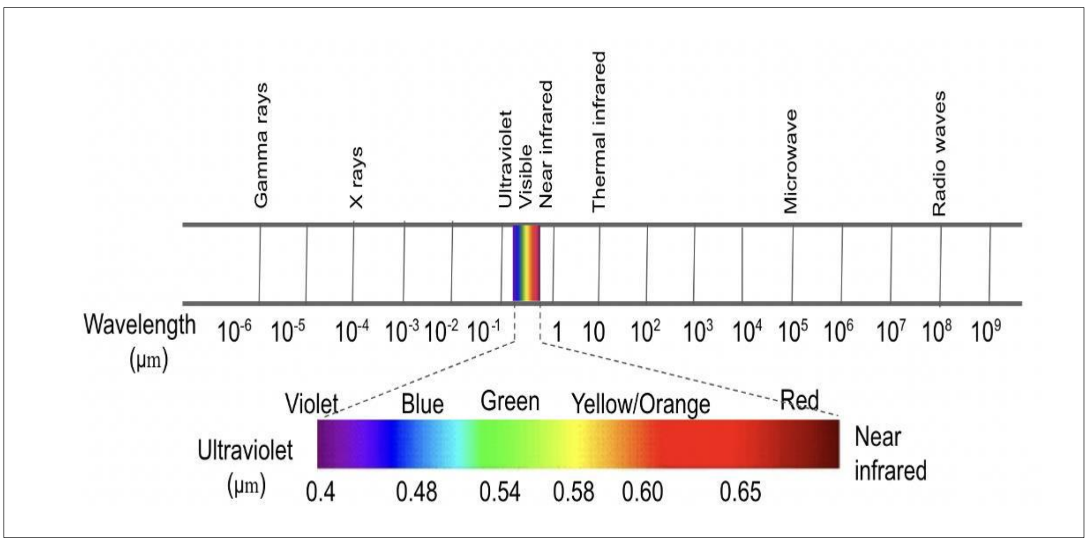

Fig. 3.3: Simplified representation of the electromagnetic spectrum

Spectral signature

Spectral reflectance varies with different types of land coverand this principle allows land cover identification using RS. A spectral band is a specific interval of the electromagnetic spectrum defined by a range of wavelengths. The spectral signature is the unique pattern of reflectance or radiance of an object measured over one or more spectral bands and helps in distinguishing features such as vegetation, water and soil. A spectral reflectance curve shows the percentage of incident energy reflected at different wavelengths. Vegetation shows very high reflectance in the near-infrared region due to leaf structure; water shows strong absorption in the near-infrared region and soil reflectance generally increases with increasing wavelength.

Spectral reflectance of vegetation, water and soil

Soil generally shows relatively high reflectance values across most spectral regions, while water exhibits very low reflectance, especially in the infrared region. Fig.3.4illustrates the spectral reflectance curves of vegetation and water. In vegetation, chlorophyll strongly absorbs radiation at wavelengths around 0.45 µm (blue) and 0.67 µm (red), while it shows high reflectance in the near-infrared region (0.7-0.9 µm). This absorption and reflection pattern creates a small reflectance peak in the green region (0.5-0.6 µm), which is why vegetation appears green to the human eye. The sharp increase in reflectance in the near-infrared region is unique to vegetation, making it very useful for vegetation mapping and surveys. In addition, due to the water content in plant leaves, absorption bands occur near 1.5 µm and 1.9 µm, which are used to assess vegetation health and vigor.

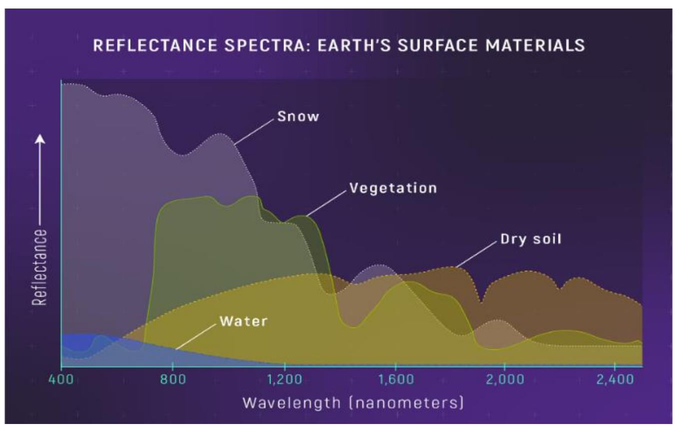

Fig. 3.4: Simplified representation of the electromagnetic spectrum

Thus, understanding the electromagnetic spectrum and the spectral behavior of different land cover features forms the scientific basis of RS. The information derived from various spectral bands is converted into thematic maps such as LULC, vegetation, water bodies, and soil maps. To efficiently store, analyze, integrate, and interpret these spatial datasets for planning and decision-making, GIS is used, which acts as a powerful complementary tool to RS.

Sensors use in remote sensing

RS sensors are instruments designed to detect, measure and record electromagnetic energy reflected or emitted from the Earth's surface and atmosphere. These sensors operate across different regions of the electromagnetic spectrum, such as visible, infrared, microwave, and laser wavelengths, and are broadly classified into optical, thermal, microwave (active and passive), hyperspectral, and Light Detection and Ranging (LiDAR) sensors. Major operational RS sensor uses in worldwide is listed in Table 3.1.

Table 3.1: Major operational RS sensors

Sl. No.	Sensor / Instrument	Satellite / platform	Sensor type	Spectral band(s)	Spatial resolution (m)	Key applications
1	OLI-2	Landsat-9	Optical (MS)	VIS-NIR-SWIR	30	LULC& agriculture
2	MSI	Sentinel-2A/B	Optical (MS)	VIS-NIR-SWIR	10-20	Crop& vegetation
3	WorldView-3	Maxar	Optical + SWIR	VIS-SWIR	0.31	Urban& minerals
4	Planet Scope (Super Dove)	Planet	Optical	VIS-NIR	3	Daily crop mapping
5	MODIS	Terra/Aqua	Optical	VIS-TIR	250-1000	Climate monitoring
6	DESIS	ISS (NASA-DLR)	Hyperspectral	400-1000 nm	30	Precision Agriculture
7	Sentinel-1	ESA	SAR	C-band	10	Flood & soil moisture
8	NISAR	NASA-ISRO	SAR	L & S band	10-100	Biomass& soil moisture
9	SAOCOM-1A/1B	Argentina	SAR	L-band	10	Flood & soil moisture
10	RADARSAT-RCM	Canada	SAR	C-band	5-100	Disaster management
11	ECOSTRESS	ISS	Thermal IR	TIR	70	Crop water stress
12	ICESat-2 (ATLAS)	NASA	LiDAR	Green laser	17	Elevation& ice
13	Cartosat-3	ISRO	Optical (PAN)	PAN	0.25	Urban mapping
14	Resourcesat-2/2A (LISS-III)	ISRO	Optical (MS)	VIS-NIR-SWIR	23.5	Agriculture
15	Resourcesat-2/2A (AWiFS)	ISRO	Optical	VIS-NIR	56	LULC& crops
16	Oceansat-3 (OCM-3)	ISRO	Optical	VIS	360	Ocean color
17	INSAT-3D/3DR Imager	ISRO	Optical + Thermal	VIS-TIR	1000-4000	Weather

Recap of GIS

As an option to a more traditional approach for different kinds of planning work and studies GIS has become more frequently applied. This is due to the increasing capacity of modern computers and the development of specialized and user-friendly software.

In simple terms, a GIS has the ability to handle both spatial and non-spatial (attribute) data. The spatial component represents real-world features with a specific location and shape on the Earth's surface, defined by geographic coordinates. These features are represented as points, lines, or areas, such as a point for a water source, a line for a river or road, and an area for a lake, forest, or city. Along with location and shape, GIS also stores attribute information that describes these features, such as name, type, or size. By linking spatial data with attribute data, GIS allows effective storage, analysis, and visualization of geographic information.

GIS are systems designed to capture, store, manipulate, analyze, manage, and present spatial or geographic data. GIS allows users to visualize, question, and interpret data to understand relationships, patterns and trends in the form of maps, reports and charts.

Key components of GIS

- **Spatial data:** Data that represents the location and shape of geographic features (roads, rivers, land use).
- **Attribute data:** Descriptive information about spatial features (population, temperature, land use type).
- **Maps:** Visual representations of spatial data, often used to analyze and communicate findings.
- **Layers:** Each dataset (roads, buildings, rivers) is stored in a separate layer, which can be stacked and analyzed together.

Type of GIS data

GIS data is mainly of two types: 1) spatial data and 2) attribute (non-spatial) data. Spatial data represents the location, shape and size of real-world features on the Earth's surface and is stored in the form of vector data (points, lines and polygons) or raster data (grids or pixels such as satellite images). Attribute data provides descriptive information about these spatial features, such as land use type, soil characteristics, crop name, population, or area. In a GIS, spatial and attribute data are linked together, which allows effective mapping, analysis and decision-making for LUP and resource management.

Data capture and editing

Data capture and editing is an important step in GIS, where geographic and attribute information is collected and converted into digital form for further analysis. Spatial data can be obtained through manual digitizing of existing maps, automatic scanning, importing coordinates from global positioning system (GPS), or by directly using satellite data, which is already available in digital format (Burrough and McDonnell, 2011). During the data capture process, spatial features are first entered into the computer system, followed by the input of attribute data and finally both are linked using GIS software (Fig. 3.5). Digitized features are stored as points, lines, or polygons with unique identification numbers and associated attributes. Scanned maps are stored in raster format and often require editing to remove errors and improve accuracy. GIS software also provides tools for edge matching, coordinate transformation and interpolation to generate accurate datasets such as Digital Elevation Models (DEM), which are widely used in terrain and land use analysis (Ramachandra et al., 2015). Proper data capture and editing improve data quality, reduce positional and attribute errors, and ensure reliable spatial analysis and effective decision-making in GIS applications.

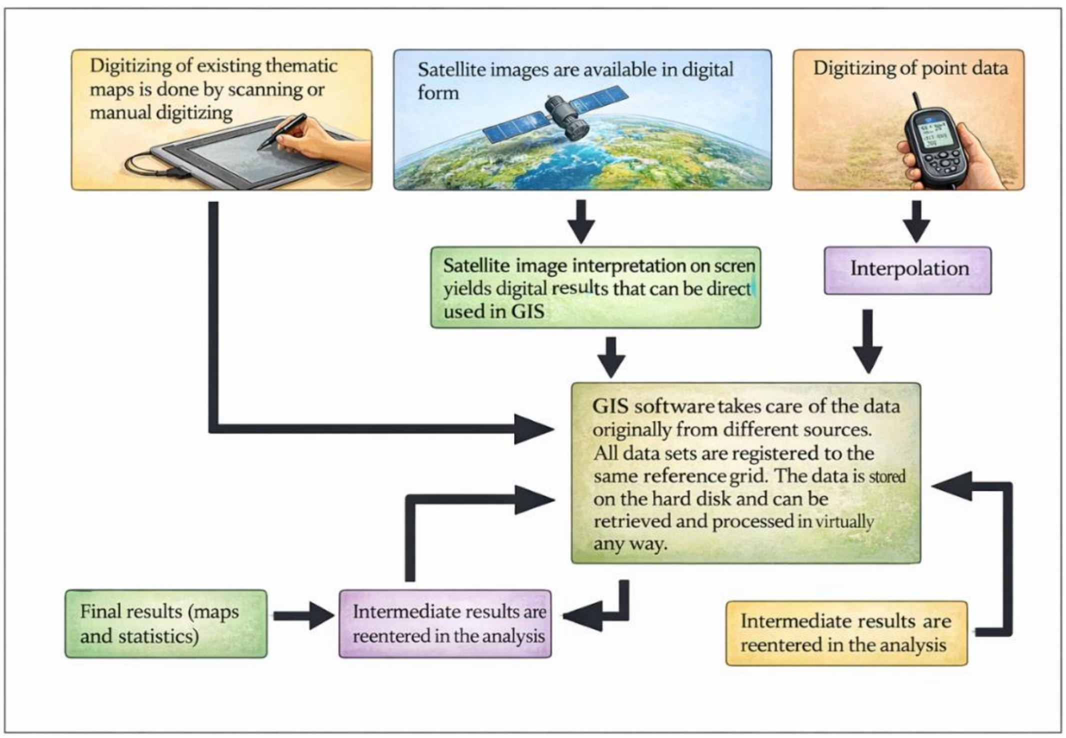

Fig. 3.5: Data acquisition procedure and storing in a GIS

Data analysis in GIS

In a manual GIS, information is drawn on separate maps, with each map representing a single thematic layer such as soil, rainfall, roads, or land use (Fig. 3.6). In GIS-based data analysis, these thematic layers are collected from different sources and integrated to solve specific problems, such as identifying suitable arable land. For example, rainfall data (interpolated from point stations), soil and geology maps, road and drainage networks, and existing land use layers are used as input data. These layers are first registered to a common coordinate system and then overlaid using GIS software. The overlay analysis combines corresponding spatial units (cells in raster GIS or features in vector GIS) to produce intermediate results, which are stored as new layers. These intermediate layers can be further analyzed to generate final outputs such as arable land suitability maps. Unlike manual overlaying, which is time-consuming and difficult to update, GIS performs all operations efficiently on a computer, allows easy updating, and enables the results to be printed or reused for further analysis. In raster GIS, overlay is performed cell-by-cell at the same spatial position, while vector overlay operations are more complex due to the absence of a regular grid.

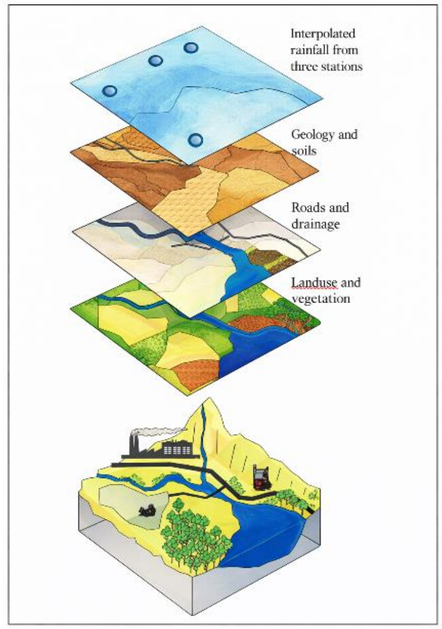

Fig. 3.6: Multiple layers of information from various sources are combined in the GIS

RS, GIS techniques for LULC change assessment

Satellite RS provides synoptic and multi-temporal observations of the Earth's surface, enabling detection and analysis of LULC changes based on variations in spectral reflectance (Lillesand and Kiefer, 2006; Navalgund, 2001). GIS facilitates the storage, integration, and analysis of RS and ancillary data, supporting accurate spatial modeling and informed decision-making in LUP and environmental management. Satellite systems such as Landsat, Sentinel, and Indian Remote Sensing (IRS) satellites are widely used for LUP applications.

The LULC mapping from satellite data consists of four steps: date acquisition, data processing, classification/ analysis, product generation and documentation / report generation (Fig. 3.7).

- **Data acquisition**: Data acquisition is the first step in satellite RS and involves collecting satellite imagery of the Earth's surface using sensors mounted on satellites. These sensors record electromagnetic energy reflected or emitted by surface features in different spectral bands. The data may be acquired at different spatial, spectral, and temporal resolutions depending on the purpose of the study, such as LUP, agriculture, or environmental monitoring.

- **Data processing:** Data processing involves converting raw satellite data into a usable and accurate form. This includes radiometric correction to remove sensor and atmospheric errors, geometric correction to align the data with real-world coordinates, and image enhancement to improve visual interpretation. Proper data processing ensures that the satellite images are spatially accurate and suitable for further analysis.
- **Classification/analysis**: In this step, the processed satellite data are analyzed to extract meaningful information. Classification techniques, either supervised or unsupervised, are used to categorize pixels into LULC classes such as vegetation, water bodies, built-up areas, and soil. Spatial analysis may also be performed to detect changes, assess suitability, or evaluate environmental conditions.
- **Product generation and documentation:** The final step involves generating output products such as thematic maps, statistics, graphs, and tables based on the analysis. These products are documented through reports that describe the data sources, methodology, accuracy assessment, and results. Proper documentation ensures that the outputs can be used effectively for planning, decision-making, and future reference.

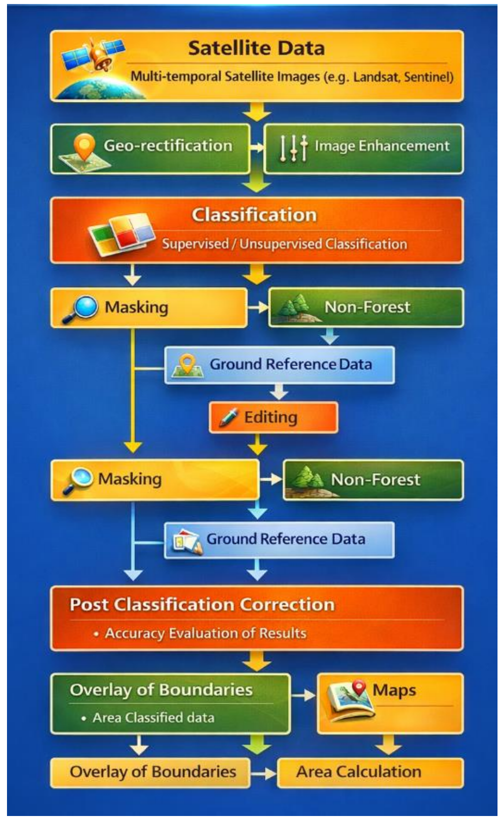

Fig. 3.7: Flow chart of image processing for LULC mapping using RS and GIS

Land use land cover classification system

The LULC classification system in India has been developed through a series of national-level projects using RS and GIS techniques. Major national level LULC mapping projects in India are listed in Table 3.2. These projects vary in scale, methodology and thematic detail, ranging from broad national assessments to detailed urban and decentralized planning studies. Visual interpretation and digital classification of multi-temporal satellite data have been widely used to generate consistent and reliable LULC information for LUP, resource management and policy formulation across the country.

Table 3.2: Major national level LULC mapping projects in India: Scale, approach and focus					
Sl. No.	**Project**	**Scale of mapping**	**Approach**	**No. of classes**	**Focus**
1	Nationwide LULC analysis for agro-climatic zone planning (1988-89)	1:250,000	Visual interpretation of multi-temporal data	22	LULC information for entire country
2	National wastelands inventory (1980-82)	1:1 Million	Visual interpretation of satellite data	Wasteland classes only	Wasteland mapping for entire country
3	LULC mapping of India (2005-06)	1:50,000	Visual interpretation of multi-temporal data	79	National LULC information
4	LULC mapping of India (2012-13, II cycle)	1:50,000	Visual interpretation of multi-temporal data	54 (ongoing)	National LULC information
5	National LULC mapping using multi-temporal AWiFS data (2004-05 onwards)	1:250,000	Digital classification	18	Seasonal net sown area & LULC
6	National urban information system (NUIS)	1:10,000	Visual interpretation	113 (Level II–V)	Urban & peri-urban areas
7	Space-based inputs for decentralized planning	1:10,000 & 1:2,000	Visual interpretation	28	Decentralized planning across India

Global LULC datasets

- IGBP–DISCover - Global land cover dataset at 1 km spatial resolution, derived from AVHRR data.
- University of Maryland (UMD) - Global land cover dataset at 1 km resolution, widely used for climate and land surface studies.
- Global Land Cover 2000 (GLC-2000) -Global dataset at 1 km resolution, developed using SPOT-VEGETATION data.
- MODIS Land Cover Product (MCD12Q1) -Global land cover dataset at 250 m and 500 m resolution, updated annually.
- ESA Climate Change Initiative (CCI) Land Cover -Global land cover maps at 300 m resolution, multi-year time series.
- Copernicus Global Land Service (CGLS) -Global land cover products at 100 m resolution.

National LULC datasets (India)

- NRSC, ISRO LULC Database -National level land use and land cover maps prepared under the National Land Use/Land Cover Mapping Programme (NLULCMP) using IRS satellite data.
- Bhuvan, LULC (ISRO) -Web-based LULC datasets available through the Bhuvan Geoportal.

- NBSSLUP (ICAR) -Land use and land resource databases integrated with soil and agro-ecological information.
- Ministry of Agriculture and Farmers Welfare (India) -LULC data used for agricultural planning and policy support, in collaboration with NRSC and ICAR institutes.

Digital classification

- **Supervised classification:** Supervised classification is a digital image classification technique in which the analyst provides prior knowledge of LULC in the form of training samples. These training samples represent the spectral characteristics of known surface features such as vegetation, water, built-up areas and soil. Based on this information, classification algorithms assign each pixel in the image to one of the predefined classes. Commonly used supervised classification algorithms include Maximum Likelihood, Minimum Distance, and Parallelepiped classifiers. Among these, the Maximum Likelihood algorithm is the most widely used due to its higher classification accuracy and statistical robustness (Richards, 1993).
- **Unsupervised classification:** Unsupervised classification is a digital image classification method in which no prior knowledge of land cover classes is required. In this approach, the computer automatically groups image pixels into clusters based on their spectral similarity using statistical algorithms such as K-means or ISODATA. After clustering, the analyst interprets and labels these clusters into meaningful LULC classes using field knowledge or reference data. Unsupervised classification is useful when limited ground information is available or for preliminary analysis of large and unknown areas.

After supervised or unsupervised classification, the next important step in LULC is post-classification processing and accuracy assessment.

Post classification processing

The post-classification processing is performed to enhance thematic accuracy and spatial coherence of the classified image. This involves noise reduction, reclassification, and smoothing of class boundaries using filtering and editing techniques. Visual interpretation supported by ancillary data and high-resolution imagery is applied to correct misclassifications and improve class consistency.

Ground truth verification

Ground truthing is undertaken to validate the classified LULC categories against actual field conditions. GPS-based observations, field surveys, and reference datasets are used to compare classified outputs with real-world features, thereby identifying classification discrepancies and improving thematic reliability.

Accuracy assessment

Accuracy assessment quantitatively evaluates the reliability of the classification results. This is achieved by constructing an error matrix that compares classified data with reference information. Statistical measures such as overall accuracy, producer's accuracy, user's accuracy, and the kappa coefficient are derived to assess classification performance.

GIS integration and spatial analysis

Validated LULC map is subsequently integrated into a GIS environment. Spatial analysis techniques such as overlay analysis, area computation, and change detection are applied in conjunction with ancillary spatial datasets to support LUP and resource management.

Map production and documentation

The final stage involves generation of thematic maps, spatial statistics, and comprehensive documentation of methodologies and results. These outputs provide essential inputs for planning, policy formulation, and decision-making, and ensure transparency and reproducibility of the LULC assessment.

Key applications

- Urban planning: Managing city growth, site selection for facilities, and infrastructure mapping (roads, power, & water).
- Agricultural management: Estimating crop acreage, predicting yields, and planning irrigation based on soil and water availability.
- Natural resource conservation: Identifying endangered habitats, monitoring forest health, and preventing encroachment on protected lands.

- Disaster management: Delineating flood-prone areas, assessing damage from natural disasters (e.g., tornadoes or earthquakes), and planning mitigation strategies.

Conclusions

LUP aims to achieve multiple objectives such as environmental conservation, control of urban sprawl, reduction of land use conflicts, minimization of transportation costs, and reduction of environmental pollution. Effective LUP is therefore essential for ensuring balanced development and sustainable utilization of land resources. In recent decades, India has experienced rapid and largely unplanned population growth, which has exerted significant pressure on limited land resources. This situation has resulted in inefficient land use patterns, environmental degradation, and increased socio-economic challenges. Consequently, there is an urgent need for stakeholders, planners, administrators, and policy makers to adopt modern and innovative technologies to address these issues and promote sustainable LUP.

RS and GIS provide powerful tools for the assessment, monitoring, management, and planning of land use. These technologies overcome the limitations of conventional mapping by enabling efficient analysis of large spatial datasets and offering advanced data acquisition techniques such as optical, radar, and LiDAR sensing. The integration of these technologies supports informed decision-making and optimal utilization of land resources for the welfare of society.

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Meteorological Data: Principles, Measurement Techniques, and Applications in Natural Resource Management

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Introduction

Meteorological data forms the cornerstone of climate-smart and sustainable natural resource management (NRM) (Murthy, 2002; WMO, 2017). The variability and uncertainty in weather and climate directly influence soil moisture, water availability, vegetation growth, land degradation, and agricultural productivity (Reddy & Pereira, 1996).Therefore, understanding, measuring, and applying meteorological data are fundamental for planning, managing, and conserving natural resources effectively (FAO, 1998). In India, the management of natural resources such as land, water, and vegetation is highly dependent on the monsoon-driven climatic system (Das, 2015). Rainfall variability, temperature extremes, and evapotranspiration patterns affect both the quantity and quality of natural resources (MoES, 2020). For example, erratic rainfall can lead to droughts or floods; high-intensity rainfall may cause soil erosion; and prolonged dry spells can reduce groundwater recharge (Tripathi and Singh, 2017). Hence, accurate meteorological data serves as the basis for assessing these phenomena and developing adaptive management practices (Maidment, 1993).

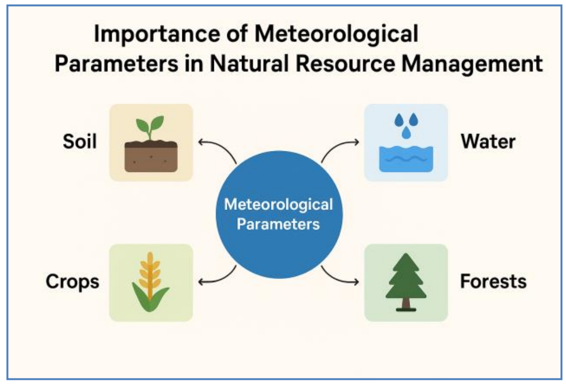

Fig.4.1: Relationship between meteorological data and natural resources

Meteorological observations provide quantitative information about the state and dynamics of the atmosphere at a given place and time (IMD, 2023). This information supports applications such as irrigation scheduling, soil erosion estimation using USLE/RUSLE models, crop-weather relationship analysis, drought and flood monitoring, and climate trend detection (FAO, 1998; Singh and Woolhiser, 2002).

With advancements in instrumentation, automation, and remote sensing, meteorological data is now available at finer temporal and spatial resolutions (NASA, 2021; ISRO, 2022). This has significantly improved the ability of scientists, planners, and resource managers to model, predict, and manage natural resources under changing climate conditions (WMO, 2018).

Definition and concept

Meteorological data refers to quantitative information collected about atmospheric variables describing the state of weather and climate over space and time (Murthy, 2002). It includes parameters such as rainfall, temperature, humidity, wind speed and direction, solar radiation, and atmospheric pressure (IMD, 2023).

These parameters determine the energy and moisture balance of the Earth's surface, influencing evapotranspiration, infiltration, plant growth, and soil erosion (FAO, 1998; Tripathi & Singh, 2017). Meteorological data generally refers to short-term observations, while climatological data consists of long-term records (30 years or more) used for trend analysis (WMO, 2017).

Both types are essential: meteorological data supports real-time decision-making, while climatological data provides the context for sustainable resource management and climate adaptation planning (MoES, 2020).

Meteorological data can be categorized as:

- **Real-time data:** Recorded and transmitted immediately for operational uses such as weather forecasting or disaster warning.
- **Historical data:** Long-term archived records used for trend analysis, climatology, and model calibration.
- **Derived data:** Computed values such as evapotranspiration, dew point, or rainfall erosivity, based on observed parameters.

The discipline of meteorology thus forms the foundation for climate science and environmental management, offering insights into how atmospheric conditions interact with land and water resources.

Time and space scales of meteorological data

Meteorological data operates across multiple spatial and temporal scales, each relevant to different NRM applications (Reddy and Pereira, 1996; Maidment, 1993).The detail of these is presented in Table 4.1.

Table 4.1: Spatial extent, temporal resolution of meteorological data and its application			
Scale	**Spatial extent**	**Temporal resolution**	**Application in NRM**
Micro	Field / plot level	Hourly / daily	Irrigation, crop microclimate
Meso	District / watershed	Daily / weekly	Watershed management, rainfall analysis
Macro	Regional / national	Monthly / seasonal	Drought/flood monitoring, climate planning
Global	Continental / planetary	Seasonal / annual / decadal	Climate change studies, policy assessment

Key meteorological parameters and its measurement

The Table 4.2 below summarizes the major meteorological parameters, their standard measurement units, the instruments used for observation, and their relevance to natural resource management. In this chapter only, details of rainfall measurement have been described. Standard measurement units, instruments, and relevance follow guidelines of IMD (2023) and WMO (2018).

Table 4.2: Important meteorological parameters, instruments, and their role in NRM			
Parameter	**Unit**	**Instrument / Sensor**	**Relevance in NRM**
Rainfall (Precipitation)	mm(or) cm	Rain gauge (manual/automatic)	Determines surface runoff, infiltration, soil erosion; key input for hydrological and watershed models
Relative humidity (RH)	%	Hygrometer, Psychrometer, Capacitive humidity sensor	Affects evapotranspiration, dew formation, and plant stress levels
Solar radiation	MJ m^{-2} day^{-1} or W m^{-2}	Pyranometer, Radiometer	Determines potential evapotranspiration, crop photosynthesis and radiation balance
Wind speed and direction	m s^{-1} (or) km h^{-1}, degrees	Anemometer, Wind vane	Important for estimating wind erosion, pollutant dispersion and evapotranspiration
Atmospheric pressure	Pa (or) mb	Barometer	Used for weather forecasting and understanding atmospheric circulation
Evaporation / Evapotranspiration	mm/day	Class A pan evaporimeter, Lysimeter	Crucial for water balance studies and irrigation planning
Sunshine duration	Hours/day	Sunshine recorder (Campbell–Stokes)	Determines solar energy availability and aids in estimating crop water requirement
Dew point temperature	°C	Calculated from temperature and RH	Indicates condensation, fog and potential water availability to plants
Soil temperature	°C	Soil thermometer or Thermistor probe	Influences germination, microbial activity and nutrient cycling
Soil moisture/suction	% (Volumetric)	TDR sensor, Tensiometer, Gravimetric method	Determines irrigation scheduling, drought assessment and hydrological modeling

Rainfall

Rainfall measurement is the quantitative estimation of precipitation over a given area and period, expressed in mm. Rainfall is measured by a network of rain gauges and remote sensing instruments that record the depth of rainfall reaching the ground surface.

A. Non-recording rain gauge (Symon's raingauge)

Operation: It consists of a funnel, receiver bottle, and graduated measuring cylinder housed inside a metal casing (Fig. 4.2a).The funnel collects rain and directs it into a container. At a fixed time (usually 08:30 IST daily), the collected water is poured into a measuring cylinder to determine the rainfall amount.

Advantages:

- It is simple in design and has a low cost.
- Suitable for long-term climatological observations.

Limitations*:*

- Requires manual reading; not suitable for remote or automated monitoring.
- Measurement errors during strong winds or evaporation loss if not properly covered.

B. Tipping bucket rain gauge

Operation: It issued in Automatic Weather Stations (AWS) (Fig. 4.2b). It consists of a funnel, two small buckets, and a reed switch sensor. Each time one bucket fills (typically 0.2 or 0.5 mm of rainfall), it tips, emptying and triggering an electrical pulse that is digitally recorded. Data are stored or transmitted for real-time monitoring.

Advantages:

- Provides continuous and automatic data.
- Suitable for remote sites and real-time flood forecasting.

Limitations:

- May underestimate rainfall during intense events due to tipping delay.
- Requires regular calibration and maintenance to prevent clogging.

C. Weighing type rain gauge

Operation: It collects rainfall in a container placed on a weighing platform (Fig. 4.2c). The increase in weight corresponds to the amount of rainfall, which is recorded automatically. Suitable for both liquid and solid precipitation (snow).

Advantages:

- Very accurate and ideal for research stations.
- Works for snow and mixed precipitation.

Limitations:

- High cost and complex maintenance.

D. Floating type rain gauge

The Floating type rain gauge**,** also known as the Natural Syphon rain Gauge, is a recording-type instrument that continuously records rainfall intensity and duration over time. It operates on the principle of afloat mechanism that rises with the increasing water level as rainfall collects in the gauge.

Operation:

The instrument consists of a funnel, float chamber, syphon arrangement, and a pen-and-drum recorder (Fig. 4.2d). Rainwater enters through the funnel and collects in the float chamber. As the water level rises, the float moves upward, which is mechanically connected to a pen that traces the water level rise on a rotating chart drum driven by a clock. When the chamber is full, the syphon mechanism automatically empties the water, and the float drops back to the bottom, starting a new recording cycle. The slope of the trace on the chart indicates rainfall intensity**,** while the total vertical rise shows cumulative rainfall.

Advantages:

- Provides a continuous graphical record of rainfall over time.
- Useful for intensity–duration–frequency (IDF) studies and hydrological analysis.
- No need for electrical power; mechanical operation.

Limitations:

- Requires frequent maintenance and calibration to ensure proper functioning of the syphon.
- Mechanical parts can be affected by dust, debris, or algae growth in the chamber.
- Less suitable for remote or automated systems compared to tipping bucket types.

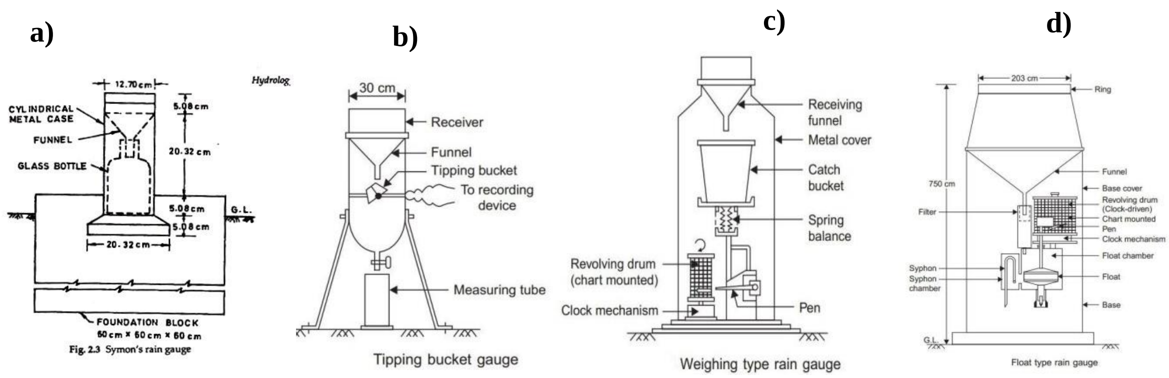

Fig. 4.2: Types of rain gauges used for rainfall measurement

Many variables/parameters used in resource management are derived from primary meteorological data through empirical or analytical relationships. The details of derived parameters, its source and use are presented in Table 4.3.

Table 4.3: Derived parameters and their use in NRM

Derived variable	Derived from	Use in NRM
Potential Evapotranspiration (PET)	Temperature, humidity, radiation, wind	Used for irrigation planning, drought monitoring
Rainfall erosivity (R-factor)	Rainfall intensity and energy	Used in soil erosion models (USLE/RUSLE)
Drought index (SPI, PDSI)	Rainfall, temperature	For drought monitoring and early warning
Heat index / growing degree days	Temperature	For crop growth modeling and agro-advisories
Wind erosion index	Wind speed, soil texture, vegetation cover	Used in wind erosion assessment and land degradation studies

Automatic weather stations (AWS)

Modern meteorological data collection relies increasingly on AWS, which records, store sand transmits data automatically using sensors and data loggers.

Components of AWS (Fig. 4.3):

- **Sensors:** Measure temperature, humidity, rainfall, solar radiation, wind speed/direction, and pressure.
- **Data logger:** Records and stores sensor

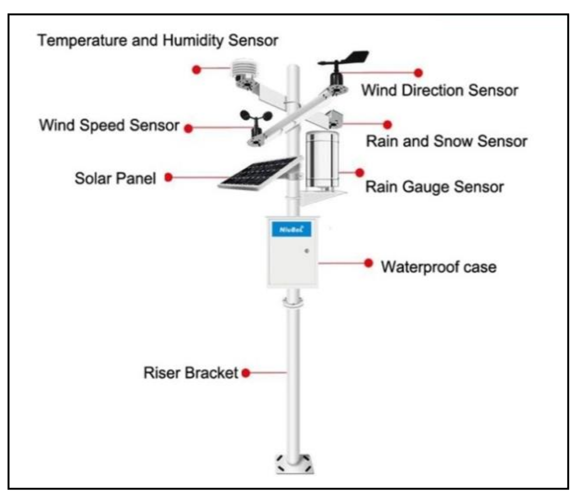

Fig. 4.3: Automatic weather station and its components

data at predefined intervals (15 minutes or hourly).

- **Power supply:** Solar panel with battery backup ensures continuous operation.
- **Communication system:** Global System for Mobile Communications/General Packet Radio Service (GSM/GPRS), satellite or radio for remote data transmission.

Advantages of AWS:

- High-frequency data recording (hourly to sub-hourly)
- Reduced human error and maintenance effort
- Real-time data accessibility via telemetry
- Integration with digital platforms for visualization and forecasting

The manual weather station involves the collection of meteorological data by human observers using standard instruments; in contrast, an automatic weather station uses electronic sensors and data loggers to continuously record, process and transmit meteorological parameters. The major difference in functionality of manual and automatic weather stations is presented in Table 4.4.

Table 4.4: Functionality difference between manual and automatic weather station

Feature	Manual station	Automatic weather station
Data frequency	Daily	Hourly or higher
Observation method	Manual	Automated (sensor-based)
Manpower requirement	High	Minimal
Data transmission	Paper records	Telemetry (GSM, Internet)
Accuracy and precision	Moderate	High (depends on calibration)
Maintenance	Simple but regular	Technical (requires trained personnel)

Remote sensing and satellite-based meteorological observations

When ground-based data are sparse, satellite observations provide valuable large-scale meteorological information. Satellites measure radiation reflected or emitted from the Earth's surface and atmosphere to estimate parameters such as rainfall, temperature and humidity. The following Table 4.5 informs major satellite and reanalysis data sources and key parameters they give, along with their spatial resolution that can be used in NRM.

Table 4.5: Summary of commonly used satellite and reanalysis data sources for NRM			
Data source	**Agency / origin**	**Key parameters**	**Spatial/temporal resolution**
INSAT-3D / 3DR	ISRO (India)	Rainfall, cloud cover, temperature	4 km / 30 min
MODIS (Terra & Aqua)	NASA	Land surface temperature, NDVI, albedo	1 km / daily
CHIRPS	USGS/FEWSNET	Rainfall	0.05° / daily
ERA5 / MERRA-2	ECMWF / NASA	Reanalysis of multiple meteorological variables	0.25° / hourly
TRMM / GPM	NASA -JAXA	Precipitation	0.1° / 3-hourly
NASA POWER	NASA	Radiation, temperature, humidity, wind	0.5° / daily

ISRO: Indian Space Research Organization, INSAT: Indian National Satellite System, MODIS: Moderate Resolution Imaging Spectro-radiometer, CHIRPS: Climate Hazards Group InfraRed Precipitation with Station Data, ERA5 / MERRA-Modern-Era Retrospective analysis for Research and Applications, NASA: National Aeronautics and Space Administration, ECMWF: European Centre for Medium-Range Weather Forecasts, FEWS NET – Famine Early Warning Systems Network, NDVI: Normalized Difference Vegetation Index, USGS: United States Geological Survey.

Such datasets are extremely valuable for regional hydrological modeling, drought analysis and climate impact assessment especially in data-scarce regions. Datasets such as MODIS, CHIRPS, ERA5, TRMM /GPM are widely used for hydrological modeling and drought analysis (ECMWF, 2021; USGS/FEWS NET, 2020).

Importance of accurate measurement

Accurate measurement is essential for reliable forecasting, modeling, and agricultural planning (WMO, 2018; IMD, 2023). Errors in data lead to incorrect estimation of water availability and crop response (FAO, 1998). Whatever may be the source of data, it is essential to have accurate measurement of meteorological parameters for understanding and managing the interactions between weather, climate, and natural resources. Precise data on temperature, rainfall, humidity, wind speed, and solar radiation form the foundation for reliable weather forecasting, climate modeling, and agricultural planning. In NRM, even small errors in measurement can lead to incorrect estimation of water availability, soil moisture, crop growth, and ecosystem responses. Accurate measurements ensure that derived indices such as evapotranspiration, drought severity, or vegetation health (Normalized Difference Vegetation Index: NDVI) reflect true field conditions. Moreover, they enhance the calibration and validation of remote sensing products and hydrological models, enabling informed decision-making in areas like irrigation scheduling, flood forecasting, and drought mitigation. Hence, standardization of methods as per guidelines of the World Meteorological Organization (WMO) and India Meteorological Department (IMD) is essential for reliable data collection. Further, maintaining accuracy of data with well-calibrated instruments and their proper maintenance is critical. The following points should be followed for calibration and maintenance of instruments.

- Instruments must be regularly calibrated against standards approved by WMO/IMD.
- Rain gauges should be checked for level and leaks.
- Thermometers and sensors should be cleaned and protected from radiation errors.
- AWS sensors should be validated using parallel manual readings periodically.
- Proper capacity building in instrument handling, data validation and troubleshooting is essential for maintaining long-term data quality.

Application of meteorological data for NRM

Meteorological inputs are fundamental for hydrological modeling (Maidment, 1993; Singh & Woolhiser, 2002). Long-term rainfall records support water conservation planning (Tripathi & Singh, 2017).Meteorological data form the backbone of effective NRM, as they provide essential information about the dynamic interactions between the atmosphere, land, and biosphere. The accurate and continuous monitoring of meteorological parameters such as rainfall, temperature, humidity, solar radiation, wind speed, and evapotranspiration is vital for understanding and managing natural systems. These data help assess how weather and climate influence the availability, quality, and sustainability of resources like water, soil, crops, and forests, which are interdependent components of the environment.

Water resource management

Rainfall intensity and wind velocity influence erosion (Tripathi & Singh, 2017). Long-term data help identify vulnerable zones (Reddy & Pereira, 1996).Water is one of the most climate-sensitive natural resources, and meteorological data are indispensable for its effective planning and management. Rainfall and evaporation data form the basis for estimating runoff, infiltration, and groundwater recharge. Hydrological models use these inputs to predict stream flow, reservoir inflow, and flood potential. Accurate rainfall data help in delineating watersheds, assessing drought severity, and developing irrigation schedules. For example, long-term rainfall records enable water resource planners to design check dams, percolation tanks, and other conservation structures in semi-arid regions. Meteorological data also play a key role in flood forecasting, drought early warning systems, and climate-resilient water allocation. Seasonal and sub-seasonal forecasts based on meteorological modeling help decision-makers prepare for extreme events, thus reducing water-related risks and ensuring sustainable utilization of available water resources.

Soil resource management

Soil health and stability are closely linked to climatic and meteorological factors. Parameters such as rainfall intensity, wind velocity and temperature influence soil erosion, moisture retention and fertility dynamics. For instance, high-intensity rainfall leads to greater surface runoff and soil loss, especially on unprotected slopes. By analyzing long-term meteorological data, areas prone to erosion or desertification can be identified and managed through appropriate soil conservation measures like contour bunding, vegetative barriers and mulching. Soil moisture estimation, derived from rainfall and evapotranspiration data, assists in irrigation planning and crop suitability assessment. Temperature and humidity data also influence soil microbial activity, organic matter decomposition and nutrient availability, which are crucial for maintaining soil productivity. Thus, integrating meteorological data into soil management ensures better conservation practices and promotes sustainable land use planning.

Crop management

Agriculture is the sector most directly influenced by meteorological conditions. Crop growth, its yield, and quality depend on weather parameters such as temperature, rainfall, humidity, and solar radiation. Meteorological data support agro-advisory services, which guide farmers on the optimal time for sowing, irrigation, fertilizer application, and pest control. Agro-advisories depend on meteorological data (FAO, 1998; Murthy, 2002). Growing degree days support phenological analysis (Reddy & Pereira, 1996).For example, temperature-based growing degree days help determine crop phenological stages, while rainfall forecasts aid in choosing drought-tolerant or flood-resistant crop varieties. Real-time meteorological monitoring is essential for precision agriculture, where irrigation and input application are fine-tuned according to local weather variations. Additionally, meteorological indices like NDVI and reference evapotranspiration (ETo) derived from satellite data are used for assessing crop stress, estimating yield, and managing water use efficiency. Hence, meteorological data ensure climate-smart farming and enhance agricultural resilience to weather variability and climate change.

Forest and ecosystem management

Forests are sensitive indicators of climatic variability and play a major role in maintaining environmental balance. Meteorological parameters such as temperature, humidity, wind speed, and precipitation strongly influence forest productivity, species distribution, and biomass accumulation. Long-term meteorological datasets help in assessing the impact of climate change on forest ecosystems, biodiversity, and wildlife habitats. They are also crucial for predicting and managing forest fires, which depends on wind, temperature, and dry conditions. Remote sensing data integrated with meteorological information support forest cover mapping, deforestation detection, and carbon sequestration assessment. Furthermore, microclimate monitoring within forested areas assists in understanding energy and water exchanges that regulate ecosystem functioning. Meteorological parameters regulate forest productivity and fire risk (WMO, 2017). Remote sensing integration supports carbon assessment (NASA, 2021).Thus, meteorological data serve as a key tool for forest conservation planning, ecosystem health assessment, and climate change adaptation strategies.

Integrated approach to NRM through meteorological data

Meteorological data provide the linkage between all components of natural resources. For example, rainfall influences soil moisture, which in turn affects crop productivity and groundwater recharge. Similarly, temperature and humidity affect evapotranspiration rates, impacting both agricultural and water management practices. By integrating ground-based observations (from manual or AWS) with satellite-derived information (such as MODIS, CHIRPS, and ERA5), comprehensive spatial and temporal datasets can be developed for NRM planning. These datasets are essential for creating decision support systems (DSS) that enable real-time monitoring, forecasting, and sustainable resource allocation. Integration of ground and satellite datasets (MODIS, CHIRPS, ERA5) enables DSS development (ECMWF, 2021; USGS/FEWS NET, 2020). Meteorological data help mitigate climatic risks and improve productivity (MoES, 2020).Therefore, meteorological data serve as a cornerstone for sustainable NRM. They help to predict and mitigate the effects of climatic variability, improve productivity, and protect ecosystems. The systematic collection, analysis, and application of meteorological information empower the planners, researchers, and policymakers to make informed decisions that promote environmental sustainability, resilience, and long-term resource security.

Conclusions

Meteorological data forms the foundation of climate-smart and sustainable NRM by linking atmospheric processes with land, water, soil, crops, and ecosystems. The accurate observation and interpretation of meteorological parameters such as rainfall, temperature, humidity, solar radiation, wind speed, and evaporation enable a scientific understanding of environmental dynamics and resource behavior. In India, where resource management is highly influenced by the monsoon system, reliable meteorological data are indispensable for addressing challenges like droughts, floods, and land degradation.

The integration of ground-based instruments, including manual and AWS with remote sensing and satellite datasets has revolutionized the spatial and temporal resolution of meteorological information. This advancement facilitates precise hydrological modeling, crop forecasting, soil erosion assessment, and climate monitoring. Derived parameters such as evapotranspiration, drought indices, and rainfall erosivity further enhance the analytical power of meteorological datasets for applied natural resource planning.

Each resource domain: water, soil, crops, and forests depend on accurate meteorological observations. Rainfall and temperature data support water balance estimation and irrigation design; humidity and wind data guide evapotranspiration and soil moisture modeling; and long-term climatic records assist in forest ecosystem assessment and climate change impact analysis. The role of meteorological data thus extends from real-time operational management (e.g., irrigation scheduling, flood warning) to long-term strategic planning (e.g., climate adaptation, conservation policy).

Ensuring accuracy, calibration, and standardization of instruments as per WMO and IMD guidelines remains critical for generating reliable data. Capacity building in data handling, quality control, and model integration further strengthens the utility of meteorological datasets in decision-making. In conclusion, meteorological data serve as the scientific backbone of NRM, enabling an integrated approach that connects atmosphere–land–water interactions. By harnessing accurate, continuous, and spatially rich meteorological information, planners and policymakers can design adaptive, resilient, and sustainable management strategies that safeguard natural resources under changing climatic conditions.

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Rainfall and Hydrograph Analysis for Land Use Planning

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Introduction

Effective land-use planning within any watershed or physiographic region requires a rigorous understanding of the underlying hydrological processes that govern water movement and sediment dynamics. The hydrological cycle (Fig. 5.1) determines how rainfall is partitioned upon reaching the land surface through various processes such as infiltration into the soil profile, evaporation and evapotranspiration to the atmosphere, groundwater recharge through percolation, and surface runoff generation when rainfall intensity exceeds infiltration capacity or soil saturation occurs (Chow et al., 1988). The portion of rainfall that becomes surface runoff mobilizes soil particles and other sediments, initiating erosion and contributing to sediment transport within the catchment.

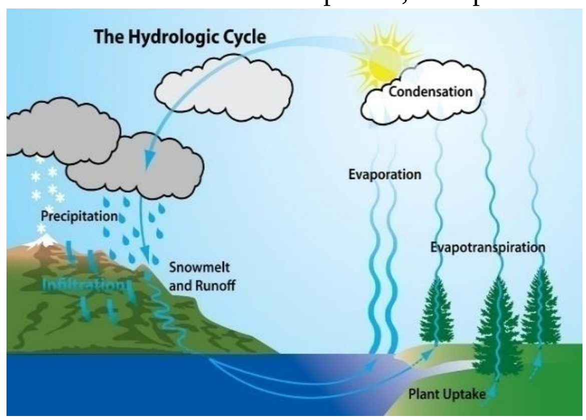

Fig. 5.1: Hydrological cycle depicting its components

These interrelated processes involving rainfall characteristics, runoff behavior, and soil loss or sediment yield are integral components of the watershed's hydrological response system (Singh, 1988). Quantitative assessment of each is critical for developing sustainable land-use strategies, designing soil and water conservation (SWC) measures and implementing integrated watershed management. Moreover, understanding these linkages supports effective flood mitigation, reservoir sedimentation control and maintenance of ecological stability. Consequently, hydrological analysis serves as the scientific foundation upon which rational land-use planning, agricultural zoning and water resources management decisions are built (Ward and Robinson, 2000; Viessman, and Lewis, 2003).

Rainfall

Rainfall is the key input to the land-surface hydrological system. Therefore, understanding rainfall patterns through its magnitude (depth), intensity (rate), duration and temporal distribution is foundational.

Rainfall depth (P): It is the total depth of precipitation collected on a horizontal surface during a specified period, expressed in millimeters (mm).

Rainfall intensity (I): It is the rate of rainfall occurrence over a unit time period expressed in (mm h^{-1})

$$I = \frac{P}{t} \tag{1}$$

where, P is rainfall depth (mm) and t is duration of rainfall (h).Rainfall intensity is the critical parameter influencing infiltration excess, runoff initiation and rainfall erosivity. High intensities over short durations are especially significant for flood and soil-erosion analysis.

Rainfall duration (t): The time period from the start to the end of a single rain event. This includes any shorter periods of no rain within the overall event and is a critical factor for understanding how much water falls and how it affects soil moisture, runoff and flood risk. It is often used in conjunction with rainfall intensity in hydrological models and analysis.

Rainfall chart types and their uses

Hyetograph

The graphical representation of rainfall intensity over time with time on the x-axis and rainfall intensity on the y-axis is known as hyetograph. Its primary use is in hydrological engineering for calculating runoff, designing storm drainage systems and forecasting floods by providing a realistic model of a storm's temporal pattern. The total area under the hyetograph represents the total amount of rainfall from a storm. An example is given in the Table 5.1 and the hyetograph for the rainfall is presented in Fig. 5.2.

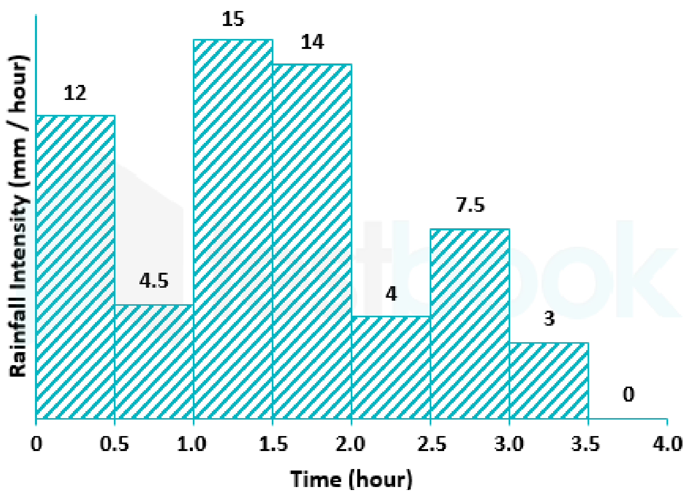

Fig. 5.2: Rainfall hyetograph

Table 5.1: Rainfall data for hyetograph depiction		
Time interval (min)	**Rainfall depth (mm)**	**Intensity (mm h^{-1})**
0-30	6	12
30-60	2.25	4.5
60-90	7.5	15
90-120	7	14
120-150	2	4
150-180	3.75	7.5
180-210	1.5	3
210-240	0	0

Cumulative mass curve: The mass curve of rainfall is a plot of the cumulative depth of rainfall against time plotted in chronological order (Fig. 5.3). The steepness of the curve indicates the intensity of rainfall. The horizontal line of the curve indicates that there is no rainfall during that period. It shows the total depth accumulating through the storm. Useful for infiltration and runoff modelling, because the shape influences runoff generation.

Intensity-duration-frequency (IDF) curve: IDF curves express the statistical relationship between rainfall intensity (I), duration (D),frequency (F) or return period (T).It provides a concise representation of extreme rainfall behavior at a specific location and is derived from long-term precipitation records through frequency analysis. The IDF curve helps quantify the expected rainfall intensity for a given duration and recurrence interval, serving as a critical input in the design of hydraulic structures such as storm water drainage systems, culverts and flood control facilities. The mathematical relationship between intensity (I), duration (t) and return period (T) is often expressed empirically as follow:

$$I = \frac{KT^a}{(t+b)^n} \tag{2}$$

Where, I is rainfall intensity (mm h^{-1}), is return period (yr), t= rainfall duration (h), K, a, b, n are empirical constants determined from observed data. This relationship reflects that rainfall intensity decreases with increasing duration, while longer return periods correspond to rarer, more intense storms (Fig. 5.4). By analyzing IDF relationships, engineers and planners can estimate design storms that ensure the reliability and resilience of water management infrastructure under varying climatic conditions.

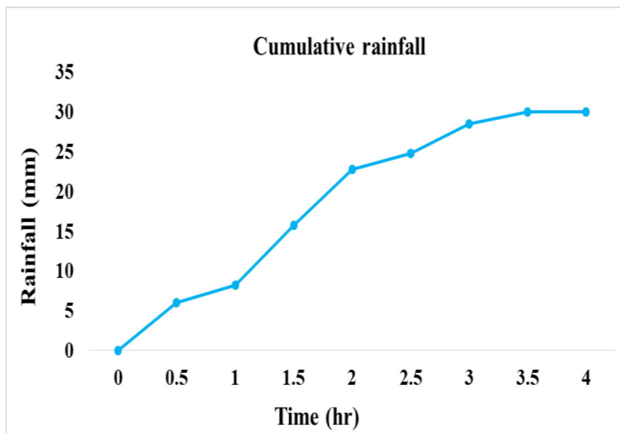

Fig. 5.3: Rainfall mass curve

Procedure to derive IDF curves:

- Extract annual maximum rainfall intensities for various durations (5 min, 10 min, 30 min, 1 h, 3 h, etc.).
- Fit probability distributions (Gumbel, Log-Pearson Type III, etc.).
- Determine rainfall intensity for selected return periods (T = 2, 5, 10, 25, 50 years).
- Plot intensity (I) vs duration (t) for each T.
- Use curves to design structures and assess storm severity.

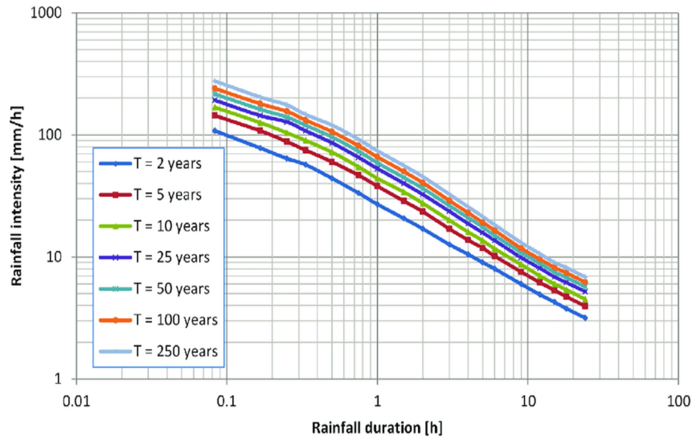

Fig. 5.4: IDF curve

Rainfall histogram or seasonal chart: Shows long-term monthly or seasonal rainfall totals, useful for broader land use planning (e.g., for agriculture, recharge and water harvesting).

Rainfall characteristics and its implication for land use plan: Rainfall characteristics exert a profound influence on land use decisions by determining surface runoff potential, soil moisture dynamics and erosion susceptibility. The nature of rainfall-whether it occurs as short, intense storms or as long, gentle showers dictates the type of land management and conservation measures required. Table 5.2 summarizes the relationship between key rainfall characteristics and their corresponding implications for sustainable land use planning.

Table 5.2: Rainfall characteristics and its implication in land use plan

Rainfall characteristic	Implication for land use
High intensity and short-duration rainfall	Causes rapid surface runoff and soil erosion; hence avoid bare slopes and promote vegetative cover, contour farming, or terracing to reduce runoff velocity
Long duration, low-intensity rainfall	Encourages infiltration and groundwater recharge; suitable for groundwater recharge zones, percolation tanks, and infiltration trenches.
High annual rainfall with high erosivity (R-factor)	Increases soil erosion risk; therefore prioritize soil conservation practices such as contour bunding, vegetative barriers, and cover cropping.
Seasonal rainfall concentration	Requires seasonal land use planning, such as crop rotation and maintenance of contour structures before monsoon onset; plan land use activities according to rainfall calendar.

Runoff

Runoff is that part of precipitation that appears in a drainage channel as surface flow in a perennial or an intermittent form (Fig.5.5). It is also known as yield of catchment. As runoff is an important factor, its quantification is required. The quantification of runoff can be done ether by its measurement or estimation of using some equations. Among various estimation methods, the hydrograph analysis is one.

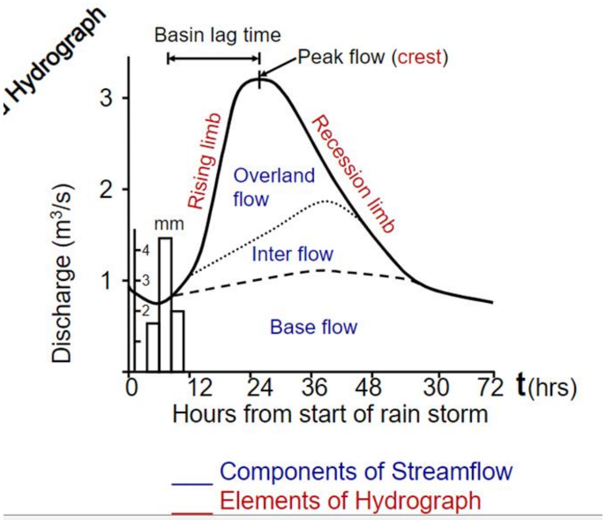

Fig. 5.5: Components of hydrograph

Hydrograph

A hydrograph is a graphical representation showing the variation of discharge (flow rate) of a river or stream with respect to time at a specific location (Subramanya, 2013). It is a fundamental tool in hydrology, used to analyze watershed response to rainfall events and to design hydraulic structures such as dams, reservoirs and drainage systems. The shape of a hydrograph reflects the combined effects of rainfall characteristics, catchment properties, infiltration and storage conditions. Hydrograph analysis allows us to understand how quickly and strongly a watershed or an area responds to rainfall.

Components of hydrograph: A typical storm hydrograph consists of three main parts- the rising limb, the peak (or crest segment) and the recession (or falling limb) (Chow et al., 1988).

- **Rising limb (concentration curve):** The portion of the hydrograph that shows the increase in discharge following the onset of rainfall. It represents the accumulation of surface runoff reaching the stream channel. The steepness of the rising limb depends on rainfall intensity, catchment slope and drainage density.
- **Crest segment (peak stage):** The highest point on the hydrograph corresponds to the peak flow representing the maximum flow rate during the storm event. This point is critical for flood estimation and hydraulic design.
- **Recession limb (falling limb):** This segment shows the decline of discharge after the peak, as surface runoff decreases and only subsurface and base flow contributions remain. The slope of the recession limb indicates how quickly the catchment drains; a gentle slope suggests a large storage capacity or flat terrain.

- **Lag time:** The time difference between the center of mass of rainfall excess (effective rainfall) and the peak discharge on the hydrograph. It indicates the delay in watershed response due to infiltration, storage, and flow routing.
- **Time to peak (Tp):** The time interval between the start of rainfall and the occurrence of peak discharge. It is a key parameter in hydrologic modeling and flood forecasting.
- **Base flow**: The portion of the stream flow that is sustained between rainfall events, originating from groundwater discharge or delayed subsurface flow. It forms the lower envelope of the hydrograph.
- **Direct runoff (Quick flow):** The portion of flow generated directly from rainfall excess, represented by the area above the base flow line during the storm event. It includes both surface and near-surface flow components.
- **Total runoff volume:** The total area under the hydrograph curve (above the time axis) represents the volume of water that passed through the gauging station during the storm event.

Among the fundamental tools in hydrograph analysis are the direct runoff hydrograph (DRH), the unit hydrograph (UH), and methods for base flow separation. Each of these components provides unique insights into the rainfall-runoff process and the hydrological behavior of an area.

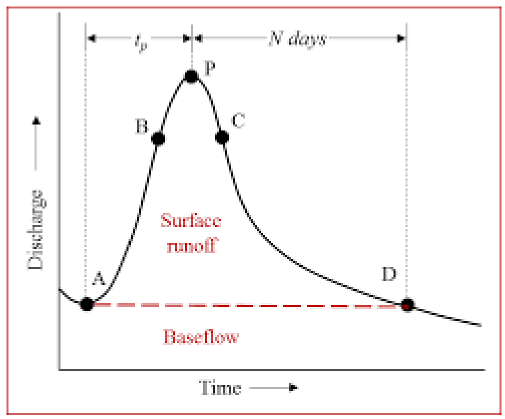

Fig. 5.6: Straight line method of base flow separation

Methods of base flow separation

Base flow is the portion of stream flow that is sustained between rainfall events and originates mainly from groundwater or delayed subsurface flow. Separating base flow from total stream flow is essential to obtain the direct runoff hydrograph. Accurate base flow estimation allows better understanding of watershed hydrology, recharge characteristics, and water availability during dry periods (Singh, 1988). There are three main methods for base flow separation as follows:

I. Straight line method
II. Two lines method
III. Curve extension method

Straight line method

In the straight-line method, the base flow separation is achieved by joining the starting point of

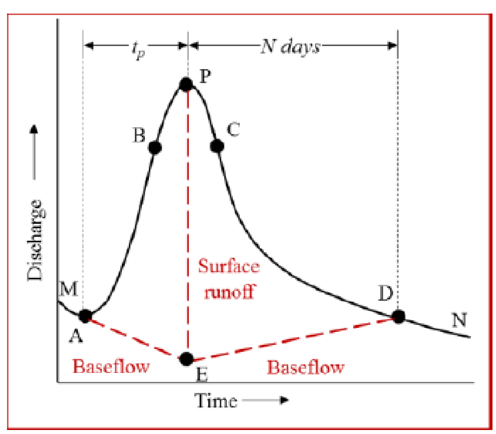

Fig. 5.7: Two-line method of base flow separation

the hydrograph or the starting point of the rising limb that is point A and the ending point of the recession limb that is point D as shown in Fig.5.6.Point A can be identified easily but sometimes it is difficult to identify where point D is and where we can say that, the effect of rainfall has stopped and runoff is coming from the groundwater contribution that is as a base flow. The approximate position of point D is achieved by an empirical equation as follows:

$$N = 0.83A^{0.2}$$

Where, N is in days and A is the drainage area in km^2.

Two line method

In this method, the separation of base flow is performed with the help of two lines AE and ED as shown in Fig.5.7. The line AE is obtained by extending the base flow recession curve MA (recession curve before the commencement of the surface runoff) up to the ordinate of the peak discharge (point P). Point D is obtained using the same formula as discussed in the straight-line method, and thereafter, the lines AE and ED are joined to separate the base flow.

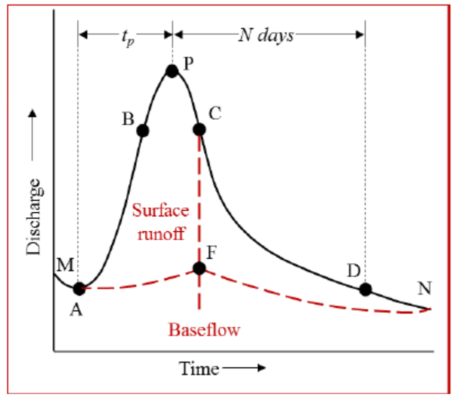

Fig. 5.8: Curve extension method of base flow separation

Curve extension method

This procedure for separation of base flow starts by drawing an arbitrary smooth curve, i.e., and extension of the MA curve till it intersects the ordinate of point of inflection (C) at point F as shown in Fig.5.8. Thereafter, a curve between F and N is drawn by extending it backward from N to F. Thus, the two segments marked by the curves AF and FN demarcate the base flow and surface/direct runoff. This method is applicable in a region where the groundwater contributions are significant and reach the stream quickly. The demarcations, obtained by various methods, separating the base flow and direct runoff (DR), i.e., either the straight line AD or the curves denoted by AED or AFN may not always represent the actual site condition.

Direct runoff hydrograph (DRH)

After the separation of base flow from the storm hydrograph, the resulting hydrograph is known as a direct runoff hydrograph (DRH). So, the total area under the DRH is indicating that how much total volume of the runoff has come out from the basin due to a storm that is what is called the direct runoff volume.

The direct runoff can also be expressed in terms of depth. If the volume is divided by the area that gets in terms of the depth also. So, runoff sometime is expressed in terms of depth as the rainfall is also expressed in terms of depth.

Example 1: Suppose a watershed experiences a storm. The observed stream flow data over time is given below, calculate the ordinates of DRH.

Answer:

Solution			
Time (h) **Col.1**	**Total stream flow (m^3s^{-1})** **Col.2**	**Base flow (m^3s^{-1})** **Col.3**	**Direct runoff (m^3s^{-1})** **Col.4= Col.2- Col. 3**
0	5	5	0
1	8	5	3
2	15	5	10
3	20	5	15
4	18	5	13
5	12	5	7
6	7	5	2
7	5	5	0

Unit Hydrograph (UH)

The unit hydrograph (UH) is one of the most fundamental tools in surface hydrology, representing the relationship between rainfall excess and direct runoff for a given watershed. It provides a means of transforming rainfall input into stream flow output using linear systems theory. The concept was first introduced by L.K. Sherman (1932),who defined the unit hydrograph as the direct runoff hydrograph (DRH) resulting from one unit depth (usually 1 cm or 1 inch) of effective rainfall occurring uniformly over a catchment and at a constant rate for a specified duration. The UH is, therefore, a characteristic response function of a watershed to a standardized rainfall input. The unit hydrograph is based on two principal assumptions of linearity and time invariance.

- **Linearity (proportionality):** The magnitude of direct runoff is directly proportional to the magnitude of effective rainfall. Hence, if 1 cm of effective rainfall produces a certain hydrograph, 2 cm of rainfall will produce a hydrograph of the same shape but with twice the ordinates.
- **Time invariance:** The watershed's response to rainfall does not change with time; the same effective rainfall occurring at any other time will produce an identical hydrograph (apart from a time shift).

An additional assumption is that the effective rainfall is uniformly distributed both in time (during its duration) and space (over the entire catchment). The total direct runoff from a complex storm can then be obtained by superposition and time-shifting of several unit hydrographs corresponding to successive pulses of rainfall excess.

Derivation of a unit hydrograph

The derivation of a unit hydrograph typically involves the following steps:

- Selection of a single, well-defined rainfall-runoff event where losses (infiltration, evaporation, etc.) can be estimated.
- Separation of the base flow from the total stream flow to obtain the direct runoff hydrograph.
- Determination of the effective rainfall (ER) hyetograph corresponding to the event.
- Division of the ordinates of the DRH by the total depth of effective rainfall to obtain the unit hydrograph ordinates.

The unit hydrograph is widely used in hydrologic modeling and water resources engineering (Ward and Robinson, 2000). Its main applications include: a) flood estimation and forecasting, b) design of drainage and flood control structures, c) derivation of synthetic hydrographs for ungauged basins, and d) conversion of design storms into runoff hydrographs for engineering design.

Limitations:

- Assumption of linearity may not hold for extreme rainfall events.
- Assumes uniform rainfall - spatial variability in rainfall can lead to errors.
- Ignores dynamic watershed changes - urbanization, soil moisture variations.
- Cannot directly apply for very long storms without S-curve or convolution techniques.

Example 2: Derivation of a unit hydrograph from observed data

A catchment with a drainage area of 50 km² experienced a short-duration storm, with a rainfall of 6 cm, and losses of 2 cm. The recorded rainfall and corresponding stream flow hydrograph are given below. Determine the 3-hour Unit Hydrograph (UH) for the basin. Assume the base flow increases linearly from 0 to 10 $m^3 s^{-1}$ over the first 12 hours and remains constant thereafter.

Time interval (h)	Rainfall (cm)
0-3	2.0
3-6	3.0
6-9	1.0

Time (h)	0	3	6	9	12	15	18	21	24
Discharge ($m^3 s^{-1}$)	0	15	40	65	50	30	15	5	0

Answer:

Step 1: Estimation of base flow			
Time (h)	**Total Q ($m^3\ s^{-1}$)**	**Base flow ($m^3\ s^{-1}$)**	**Direct runoff ($m^3\ s^{-1}$)**
0	0	0	0
3	15	2.5	12.5
6	40	5.0	35.0
9	65	7.5	57.5
12	50	10.0	40.0
15	30	10.0	20.0
18	15	10.0	5.0
21	5	10.0	0
24	0	10.0	0

Step 2: Determination of effective rainfall (ER)

The total rainfall is 2 + 3 + 1 = 6 cm

Assume losses (infiltration + interception) = 2 cm

So, the effective rainfall is 4 cm.

Step 3: Determination of ordinates of UH:				
Time (h)	**Total Q ($m^3\ s^{-1}$)**	**Baseflow ($m^3\ s^{-1}$)**	**Direct runoff ($m^3\ s^{-1}$)**	**Unit hydrograph ($m^3\ s^{-1}$)**
0	0	0	0	0
3	15	2.5	12.5	3.13
6	40	5.0	35.0	8.75
9	65	7.5	57.5	14.38
12	50	10.0	40.0	10.00
15	30	10.0	20.0	5.00
18	15	10.0	5.0	1.25
21	5	10.0	0	0
24	0	10.0	0	0

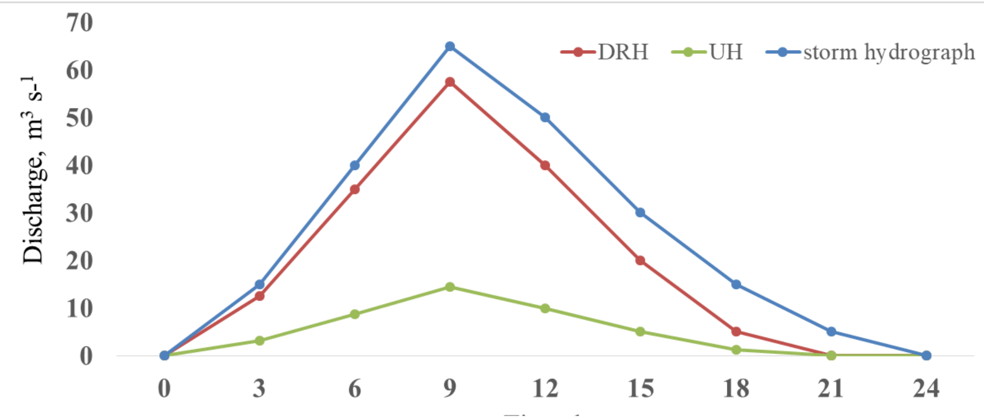

Fig. 5.9: Storm, direct runoff and unit hydrograph

Conclusions

Rainfall and hydrograph analysis are essential components of hydrologic assessment for effective land use planning and sustainable watershed management. By examining the temporal and spatial distribution of rainfall and the corresponding runoff response, planners and engineers can understand how different land uses such as urbanization, agriculture, or forest cover affect surface runoff, infiltration, and flood potential. The hydrograph serves as a critical tool for quantifying these relationships, illustrating how rainfall inputs translate into stream flow outputs under existing or proposed land use conditions.

Through such analyses, it becomes possible to identify areas prone to flooding, estimate peak discharge rates and evaluate the impacts of impervious surfaces or deforestation on catchment hydrology. Integrating rainfall-runoff relationships into land use planning helps in designing drainage networks, storm water management systems and flood control structures that are both efficient and environmentally sound.

In conclusion, rainfall and hydrograph analysis provide the scientific foundation for balancing development and environmental protection. They enable planners to predict hydrologic consequences of land use changes, promote resilient urban design and ensure that future land development is guided by the principles of hydrological sustainability and risk mitigation.

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Soil and Water Conservation Measures in Arable and Non-arable Land

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Introduction

Soil erosion is the detachment of soil from its original location and transportation to a new location by the erosive agents. The word erosion has been derived from the Latin word 'erodere' which means eating away or to excavate. Erosion process involves the three phases (i) detachment of individual soil particle from soil mass (ii) transporting it from one place to another (iii) its deposition when sufficient energy is not available to transport a particle.

Agents of soil erosion

Mainly water is responsible for this erosion although in many locations wind, glaciers are also the agents causing soil erosion. Water in the form of rain, flood and runoff badly affects the soil. When the rain falls on the land surface, the water detaches the soil particles and takes away the soil particles along with the flowing water. Similarly, when wind blows in the form of storms, its speed becomes too high to lift off the entire upper layer soil and causes soil erosion. Other factors responsible for soil erosion are human and animal activities.

Causes of soil erosion

No single unique cause can be held responsible for soil erosion or assumed as the main cause for this problem. There are many underlying factors responsible for this process, some induced by nature and others by human being. The main causes of soil erosion can be enumerated as:

a. **Destruction of natural protective cover by**
    - Indiscriminate cutting of trees
    - Overgrazing of the vegetative cover
    - Forest fires

b. **Improper use of land**
    - Keeping the land barren subjecting it to the action of rain and wind
    - Growing of crops that accelerate soil erosion
    - Removal of organic matter and plant nutrients by injudicious cropping patterns
    - Cultivation along the land slope

- Faulty methods of irrigation

Types of soil erosion

Soil erosion can be broadly classified into two types (a) According to origin (b) According to erosive agents

a) **According to origin:** Soil erosion can broadly be categorized into two type's i.e. geologic erosion and accelerated erosion.

- **Geological erosion:** It is the soil erosion in natural environment. Equilibrium conditions is established between the climate of a place and the vegetative cover that protects the soil layer under natural undisturbed conditions. Vegetative covers reduce the transportation of soil material and also act as a barrier against erosion. Still, a certain amount of erosion takes place even under the natural condition. This erosion is called geologic erosion, and a slow process compensated by the formation of soil under the natural weathering process.
- **Accelerated erosion**: When cultivation is done in the land, the balance between the soil, its vegetation cover and climate is disturbed. Under such condition, the removal of surface soil due to natural agencies takes places at faster rate than it can be built by the soil formation process. Erosion occurring under this condition is referred to as accelerated erosion. Its rates are higher than geological erosion.

b) **According to erosive agents:** Depending on the erosive agents, soil erosion is broadly categorized into different types. There are of four types.

- **Water erosion:** Running water is the most common agent of soil erosion. Water erosion can further be divided based on different actions of water such as: (i) splash erosion caused by raindrop (ii) sheet erosion (iii) rill erosion (iv) gully erosion (v) stream bank erosion and (vi) slip erosion.
- **Wind erosion**: Wind erosion generally occurred in the dry areas wherein strong winds observed, it brush against various landforms, cutting through them and loosening the soil particles, which are lifted and transported towards the direction in which the wind blows. The best example of wind erosion is sand dunes and mushroom rocks structures, typically found in deserts.
- **Coastal erosion**: Due to the action of sea waves and advancement of ocean, the nearby area and sea coast are eroded and eroded material deposited in the sea. It is very difficult to control.

- **Glacial erosion**: Glacial erosion, also referred to as ice erosion, is common in cold regions at high altitudes. When soil comes in contact with large moving glaciers, it sticks to the base of these glaciers. This is eventually transported with the glaciers, and as they start melting it is deposited in the course of the moving chunks of ice.

Factors affecting soil erosion

For planning of soil conservation measures, it is essential to identify the factors affecting the soil erosion. The major factors affecting the soil erosion are climate, soil type, vegetation, topography and the cultivation practices. Climatic factors like, precipitation, wind, humidity and solar radiation directly or indirectly influence the soil erosion. The soil properties such as soil structure, texture, organic matter content, moisture content, and density or compactness influence the process of soil erosion.

Vegetation plays an important role in soil erosion. It reduces the kinetic energy of falling raindrops and reduces the surface velocity of flowing water which reduces the soil erosion. However, the benefit given by the vegetation mainly depends upon the type of vegetation on the land. Topographical features that influence erosion are degree and length of slope, size and shape of watershed.

Soil and water conservation measures in watershed

The important soil and water conservation measures, used either to reclaim the land degradation or to maintain the land suitable for cultivation for sustainable crop production are categorized under following two groups:

- Measures for arable lands
- Measures for non arable lands

The different types soil and water conservation measures implemented in arable and non arable lands for watershed management is given in Table 6.1.

Table 6.1: Suitability of various soil and water conservation measures in watershed			
Sl. No.	**Measures**	**Suitable in**	
		Plain land and mild slope	**Hilly land**
A.	**Suitable for arable land**		
A.1.	**Mechanical or Engineering**		
	1. Bunding		
	a. Narrow based terracing		
	a_1. Contour bund	√	
	a_2. Graded bund (uniformly and variable graded)	√	
	2. Trenching		
	a. Contour trenching		
	a_1. Continuous	√	√
	a_2. Staggered	√	√
	b. Graded trenching	√	√
	3. Terracing (Bench)		
	a. Level		√
	b. Inward sloping		√
	c. Outward sloping		√
	d. Puertorican type		√
	4. Zing terracing	√	√
	5. Conservation bench terracing	√	√
	6. Land levelling/grading	√	√
	7. Silt detention tank	√	√
	8. Water ways or disposal drain	√	√
	9. Revetment		√
A.2	**Agronomical Practices**		
	1. Contour cultivation	√	√
	2. Strip cropping	√	√
	3. Inter or mixed cropping	√	√
	4. Green manuring	√	√
	5. Crop Rotation	√	√
	6. Use of crop residue	√	√
	7. Mulching	√	√
	8. Relay cropping	√	√
	9. Seasonal crop cover	√	√
	10. Improved crop management practices	√	√
A.3	**Vegetative measures**		
	1. Grassed contour barrier	√	
	2. Grassed waterway	√	√
	3. Agro-forestry	√	√
	4. Agri-pasture	√	√
	5. Agri-horticulture	√	√
B.	**Suitable for non-arable land**		
B.1	**Mechanical or Engineering**		
	1. Trenching		
	a. Contour trenching		
	Continuous	√	√
	Staggered	√	√
	b. Graded trenching	√	√
	2. Stonewall		

		a. Contour	√	√
		b. Graded	√	√
	3.	Silt detention tank	√	√
	4.	Diversion drain	√	√
	5.	Toe wall/Toe drain	√	√
	6.	Interceptor drain	√	√
	7.	Channel is action of flow or stream training	√	√
	8.	Waterways	√	√
	9.	Retaining wall		√
B.2	**Gully control structures**			
	1.	Brushwood check dam		
	2.	Loose boulder check dam		
	3.	Gabion check dam	Used for controlling erosion and stabilization of gully	
	4.	Drop structure		
	5.	Drop inlet structure		
	6.	Chute structure		
B.3	**Biological measures**			
	1.	Afforestation/reforestation	√	√
	2.	Social forestry	√	√
	3.	Silvipasture	√	√
	4.	Pasture development	√	√
	5.	Leguminous pasture plant	√	√
	6.	Farm and range plant	√	√
	7.	Meadow grasses	√	√
	8.	Stream training	√	√
	9.	Wattling	√	√
	10.	Mulching	√	√

Estimation of soil loss

The factors affecting soil erosion were based on the empirical formula developed by Wischmeir and Smith (1978) widely known as USLE. The factors are (i) rainfall erosivity factor (R) (ii) soil erodibility (K) (iii) topographic factor (LS) (iv) vegetative cover (C) (v) management measures (P). The USLE is expressed as:

$$A = R \times K \times L \times S \times C \times P \tag{1}$$

Where, A is annual soil loss (t ha^{-1}), R is rainfall erosivity factor (MJ mm ha^{-1} hr^{-1} yr^{-1}), K is soil erodibility factor (t ha hr Mj^{-1} ha^{-1} mm^{-1}), L is slope length factor, S is slope gradient factor, C is cover factor, and P is management measures factor.

K factor measures under standard unit plot condition of 72.6 ft long, 9% steep slope, tilled continuous fallow, up and down hill till age. The major soil parameters are used in soil loss estimation equation are soil texture, organic matter, soil structure and permeability and the equation is presented below:

$$K = 2.77M^{1.14} \times (10^{-7}) \times (12-\alpha) + 4.28(10^{-3})(\beta - 2) + 3.29(10^{-3}) \times (\gamma - 3) \quad (2)$$

Where, M is calculated as (% silt + % very fine sand) (100-% clay), a is percent organic matter, b is structure code, and c is profile permeability class.

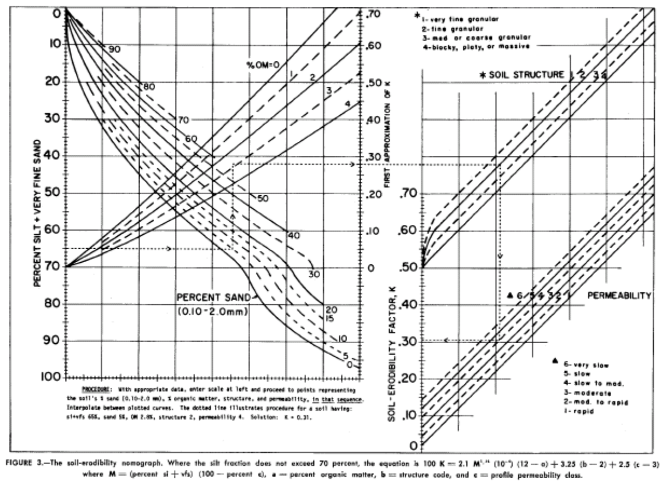

Fig. 6.1: Soil erodibility nomograph

Estimation of Runoff

Following formula is used for estimation of runoff,

- Rational method

$$Q_p = \frac{CIA}{360} \quad (3)$$

Where, Q_p is peak rate of runoff (m^3/sec) for the design frequency of rainfall, C is rational runoff coefficient having values ranging from zero to one depending upon watershed condition, I is rainfall intensity (mm hr^{-1}) for the design frequency and for the duration at least equal to the time of concentration of the watershed, and A is watershed area (ha).

Table 6.2: Value of runoff coefficient 'C' in Rational formula

Land use / vegetation cover	Slope (%)	Sandy loam	Clay and silt loam	Stiff clay
Cultivated Land	0-5	0.30	0.50	0.60
	5-10	0.40	0.60	0.70
	10-30	0.52	0.72	0.82
Pasture Land	0-5	0.10	0.30	0.40
	5-10	0.16	0.36	0.55
	10-30	0.22	0.42	0.60
Forest Land	0-5	0.10	0.30	0.40
	5-10	0.25	0.35	0.50
	10-30	0.30	0.50	0.60

- **Hydrological soil cover complex method**

$$Q_p = \frac{0.0208 \times A \times Q_d}{T_p} \tag{4}$$

Where, Q_p is peak rate of flow (m^3/sec), A is area of the watershed (ha), Q_d is runoff depth (cm) in cm for the given area of the watershed, T_p is time to peak (hr). Tp is calculated as

$$T_p = 0.6T_c + \sqrt{T_c} \tag{5}$$

Where, T_c is time of concentration (hr)

$$Q = \frac{(P - 0.3S)^2}{P + 0.7S} \text{ for black soil region under AMC I and other soil} \tag{6}$$

$$Q = \frac{(P - 0.1S)^2}{P + 0.9S} \text{ for black soil region AMC II and AMC III} \tag{7}$$

Where, Q is actual runoff (mm), P is rainfall (mm), and S is potential maximum retention, which is calculated by following equation.

$$Q = \frac{25400}{CN} - 254 \tag{8}$$

Where, CN is curve number

Measures for control of erosion in arable land

1. **Bunding**

This is adopted up to 6-8 % land slope and therefore is an engineering measure for mild sloppy land. The main objective of construction of bund is to reduce the slope length. It reduces the length of slope, which in turn reduce the soil erosion. It impounds water in the up-stream portion and permits more water to recharge into the soil. Contour bunds can be adopted on most types of relatively permeable soil i.e. alluvial, red , laterite, brown, shallow, medium black except the clayey deep black soils.

Data required for design: The following data are required for its design.

- Rainfall

- Soil type and its characteristics
- Slope length and slope
- Crop Conservation practices to be adopted

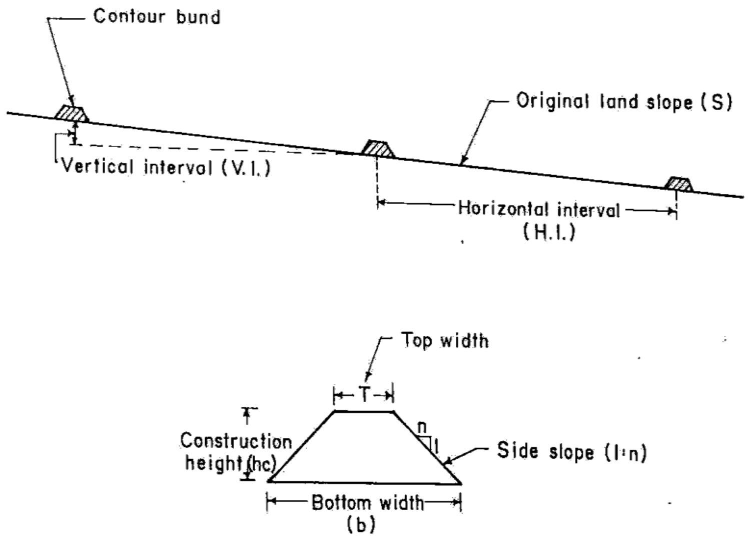

Fig. 6.2: Cross section of bund

Specifications: Following information's are needed for its construction

- Spacing of bund: the spacing of bund depends on slope length, slope steepness, amount of rainfall, cropping pattern and conservation practices to be adopted
- Deviation from contour line for getting better alignment in undulating areas: The grade along the contour bund should be zero along its length. The deviation may cause uneven impounding of water and there is a chance of breach. The limits of deviation are prescribed as 10 cm on higher side and 20 cm on for crossing depression.
- Cross section of bund: It depends depth water standing against the bund, rate of infiltration water into the soil, vertical interval between two bund.
- Alignment of bund: The contour bunds should have zero grade along its length and local ridges and depression should be removed before contour bunding.

2. Graded bunding

The main purpose of these bunds is to make safe disposal of runoff by slow movements instead of rushing off. The graded bunds are along a predetermined longitudinal grade.

Suitability

These bunds are adopted in areas receiving rainfall exceeding 750 mm particularly in soils having infiltration rate less than 8 mm hr^{-1}. Graded bund is also recommended in areas receiving less rainfall where rain water is not readily absorbed into the soil due to low infiltration rates such as clayey soils.

Factors to be considered

- Location of the most desirable terrace outlets
- Straight natural waterways have the advantage of terrace outlets
- Mechanical measures need to be constructed to encounter sudden drop, excessive velocities and poor grass cover if vegetation is not capable to conduct concentrated water down the slope

3. Grade

Channel grade depend on soil type and length of the terrace. The following grade are suitable in different type of soils,

Table 6.3: Slope of graded bund in different type of soil, gradient (%)

Soil type	Gradient (%)
Clayey soil	0.1 to 0.2
Medium soil (Loamy soil)	0.3 to 0.4
Sandy soil	0.5

4. Terracing

It is an engineering soil conservation practice, used to control the soil erosion in highly sloped area (greater than 10%). The effective length and degree of the slope is changed by constructing steps like structures across the land slope to check the flow of runoff and to reduce soil loss. Large quantity of surface soil is moved from one place to another place in terracing. Bench terrace is recommended for slopes up to 33% but due to socio-economic compulsions, this practice is being adopted up to 50-60% land slope. The bench terrace can be classified in to three categories and each of them explained below,

- **Level terraces:** When the terrace is made table top, without any slope in any direction, then it is called as level terrace and usually used for paddy cultivation. This used in areas which receive medium rainfall and have highly permeable soil.
- **Inward sloping terrace**: When the terrace is made with mild inward slope to facilitate quick disposal of rain water from the field, it is called as inward sloping terrace. This is used in the areas of heavy rainfall and less permeable soil. These are usually preferred for crops which cannot withstand water

logging such as potato, maize etc. These terraces help in quick and safe disposal of runoff through the drain provided on the inner side

- **Outward sloping terrace**: When the terraces are made with a mild outward grade, it is called outward sloping terrace. These are made in areas of shallow soil depth and low rainfall. Shoulder bund is essential. The rainfall coming over the area is to be conserved by retaining the shoulder bund
- **Puertorican type terrace**: In this type of terrace, soil is not disturbed for making a terrace. Hedge of suitable grass is planted on contour at pre-determined spacing. The inter-space between two hedge lines of grass planted (termed as vegetative hedge) is cultivated and tilled to take crops. The tilled soil slowly moves towards the vegetative hedge and gets deposited against this barrier.

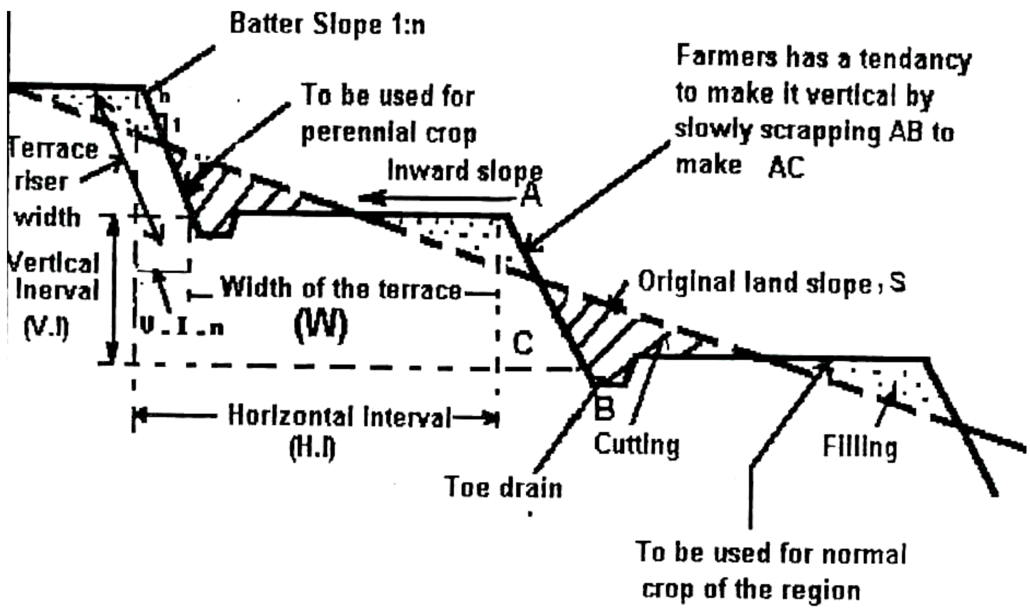

Fig. 6.3: Layout of bench terrace

Design of bench terraces

Design of bench terraces depends on rainfall, soil type and its depth and the average slope of the area. In addition the purpose for which the terraces are to be constructed should also be known.

Design parameters

It includes a) Selection of type of bench terrace, b) Terrace width, c) Terrace spacing or depth of cut and d) Terrace cross section

- Type of terrace: It is based on the rainfall, soil conditions and type of crop to be grown on the terrace
- Spacing of terrace: It is generally expressed as the vertical interval between two terraces. It is depend on depth of cut.

- Terrace width: The width of bench terrace is not fixed and depends upon the type of land use, method of construction (manual/mechanical), soil depth, slope and individual preferences.
- Terrace cross section: The design of cross section consists of (1) Batter slope (2) Dimension of the shoulder bund (3) Inward/Outward slope and dimension of the drainage channel

Land levelling /grading

Land levelling consists of reshaping the field to a desired grade. It is utmost importance for increasing the irrigation efficiency. Factors that affect land leveling / grading are topography of the area, soil type and depth, crops to be grown, source of water supply, and method of irrigation.

Table 6.4: Recommended land slopes for different soil types

Type of soil	Slope (%)
Heavy (Clay)	0.10 - 0.40
Medium (Loam)	0.20 - 0.40
Light (Sandy)	0.25 - 0.65

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Morphometric Analysis and its Relevance in Watershed Land Use Planning

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Introduction

Morphometric analysis is a quantitative assessment of the geometric characteristics of a drainage basin and its stream network. It provides numerical descriptors of basin shape, drainage texture, relief, and network organization, which are fundamental for understanding hydrological behavior, runoff generation, erosion susceptibility, and groundwater potential. In watershed land use planning, morphometric analysis serves as a scientific basis for prioritization of sub-watersheds, selection of soil and water conservation measures, and formulation of sustainable land use strategies. This chapter aims to familiarize trainees with the concepts, parameters, methods, and applications of morphometric analysis, with specific emphasis on its practical relevance to watershed-based land use planning.

Concept of morphometric analysis

The term *morphometry* originates from the Greek words *morphé* (form) and *metron* (measurement). In watershed studies, morphometric analysis focuses on:

- Drainage network characteristics
- Basin geometry and shape
- Vertical relief and slope conditions

Morphometric analysis helps in answering key planning questions such as:

- How quickly will runoff be generated?
- Which areas are more erosion-prone?
- Where water harvesting and recharge structures are most effective?

Data sources and tools for morphometric analysis

Morphometric analysis can be carried out using:

- Survey of India topo sheets
- Satellite-derived Digital Elevation Models (e.g., SRTM, ASTER)
- GIS and remote sensing software (e.g., ArcGIS, QGIS)

GIS-based analysis improves accuracy, repeatability and efficiency compared to conventional manual methods. The workflow in morphometric analysis involves a) watershed and drainage delineation

b) stream ordering c) extraction of morphometric parameters and d) statistical analysis and interpretation (Fig. 7.1).

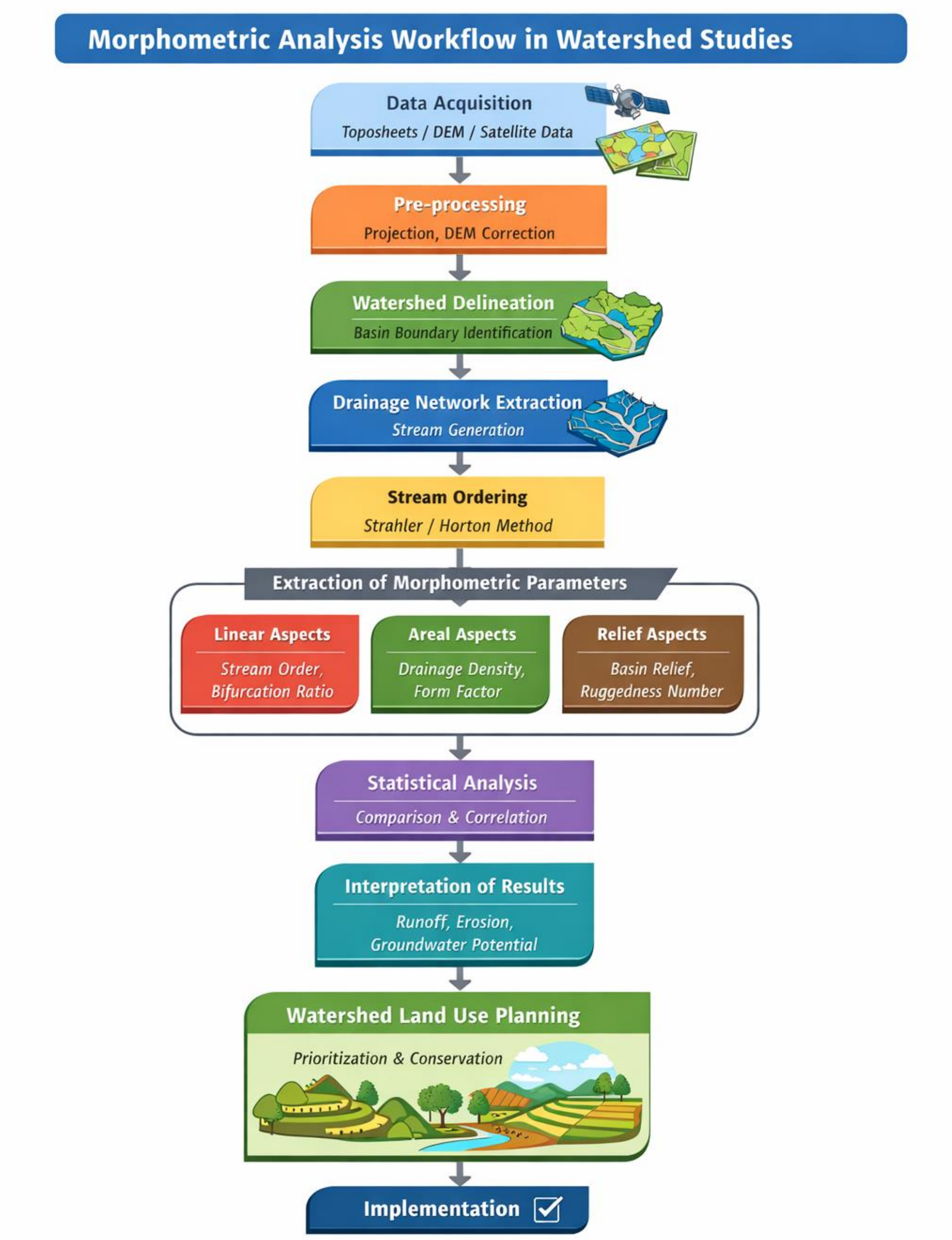

Fig. 7.1: Morphometric analysis workflow in land use planning of watershed

Classification of morphometric parameters

Morphometric parameters are broadly grouped into linear, areal, and relief aspects and presented in Table 7.1. Linear aspects describe the drainage network and its hierarchical organization. The important parameters include **s**tream order, stream number, stream length, bifurcation ratio etc. Linear parameters indicate drainage maturity, runoff concentration and degree of structural control.

Table 7.1: Morphometric parameters and its method of calculation			
Morphometric parameters		**Methods**	**References**
Linear aspect	Stream order (U)	Hierarchical order	Strahler (1964)
	Stream number (N_u)	Number of streams of each order	Strahler (1964)
	Stream length (L_u)	Length of the stream	Horton (1945)
	Bifurcation ratio (R_b)	$R_b = N_u/N_{u+1}$; Where, N_u = Total number of stream segment of order 'u'; N_{u+1} = Number of segment of next higher order	Horton (1932)
	Length of overland flow (L_f)	$L_f = 1/2D_d$ Where, D_d = Drainage density	Horton (1945)
Aerial aspect	Drainage density (D_d)	$D_d = L_u/A$ Where, L_u = Total length of streams; A = Area of watershed	Horton (1945)
	Constant channel maintenance (C)	$L_f = 1/D_d$ Where, D_d=Drainage density	Horton (1945)
	Stream frequency (Fs)	$Fs = N_u/A$ Where, N = Total number of streams; A = Area of watershed	Horton (1945)
	Drainage texture ratio (T)	$T = N_1/P$ where, N_1 = Total number of first order streams; P = Perimeter of watershed	Horton (1945)
	Form factor (R_f)	$R_f = A/(L_b)^2$; Where, A = Area of watershed, L_b = Basin length	Horton (1932)
	Circulatory ratio (R_c)	$Rc = 4\pi A/P^2$; Where, A = Area of watershed, $\pi = 3.14$, P = Perimeter of watershed	Miller (1953)
	Elongation ratio (Re)	$Re = 2\sqrt{(A/\pi)}/L_b$; Where, A = Area of watershed, $\pi = 3.14$, L_b = Basin length	Schumn (1956)
Relief aspect	Basin relief (B_h)	Vertical distance between the lowest and highest points of watershed	Schumn (1956)
	Relief ratio (R_h)	$R_h = B_h/L_b$; Where, B_h = Basin relief; L_b = Basin length	Schumn (1956)
	Ruggedness number (R_n)	$R_n = B_h \times D_d$; Where, B_h = Basin relief; D_d = Drainage density	Strahler (1957)

- **Stream order:** The term stream order, introduced by Strahler in 1964, serves as a fundamental tool in the geo-morphological analysis of drainage basin. It provides a means to assess the hierarchical branching pattern of streams within a watershed. The Strahler ordering scheme, developed by Strahler (Strahler, 1964), classifies tributaries within a stream network based on their order. In this system, all the smallest and most upstream streams, also known as first-order streams are assigned an order of 1. As these first-order streams merge together, their

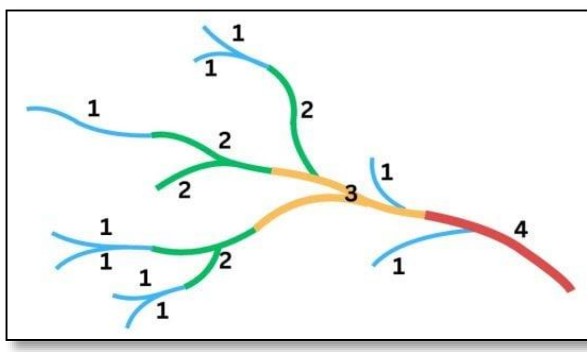

Fig. 7.2: Stream order in a watershed

orders increase accordingly. When two 1st order streams combine, they form a 2nd order stream. Similarly, the merging of two 2nd order streams results in the formation of a 3rd order stream. This process continues, and higher-order streams are generated as more tributaries combine.

- **Stream number (N_u):** It is the number of stream channels in a particular order, denoted by N_u.

  $N_u = N_{u1} + N_{u2} + N_{u3} \cdots + N_{un}$

  Where, N_{u1} is no. of 1st order stream, N_{u2} is no. of 2nd order stream and so on.

- **Stream length (L_u):** The total stream length within a watershed is determined by adding the lengths of individual stream segments in each subsequent order. This measurement provides insights into the drainage coverage and underlying bedrock hydrological characteristics of the area. In watersheds with efficient drainage systems, characterized by porous bedrock, only a few streams with relatively longer lengths are present. Conversely, in areas where the bedrock is less permeable, the watershed tends to have numerous shorter streams. This measurement is commonly denoted as L_u and serves as an indicator of the stream network characteristics within the watershed.

  $L_u = L_{u1} + L_{u2} + L_{u3} \cdots + L_{un}$

  Where, L_{u1} is length of 1st order stream, L_{u2} is length of 2nd order stream and so on.

- **Stream length ratio (R_l):** It is denoted by R_l, represents the ratio between the mean stream length of a certain order and the mean stream length of the immediately lower order. Typically, this ratio tends to increase as we move from lower stream orders to higher stream orders. A declining trend in the mean stream length ratio indicates that the terrain is undulating, characterized by numerous streams and intricate stream patterns of various orders. In such areas, higher-order streams are relatively shorter compared to lower-order streams, resulting in a higher value for this ratio at the higher stream orders. This pattern is commonly observed in regions with significant runoff, which gives rise to erosion hazards.

  $R_l = (L_u/L_{u-1})$

- **Bifurcation ratio (R_b):** It is the ratio of number of streams of a given order (N_u) to the number of segments of the higher order (N_{u+1}). It is dimensionless.

  $R_b = (N_u/N_{u+1})$

  A watershed with a lower R_b is likely to have fewer structural disturbances and a drainage pattern that has not been changed by those disturbances. The bifurcation ratio can also be used to determine how the watershed is shaped. In contrast to circular watersheds, which are more likely to have low R_b, elongated watersheds are more likely to have high R_b. When the bifurcation ratio is less than 3, it suggests an idealized theoretical watershed where the drainage network is hierarchical and minimally distorted. In the range of 3 to 5, the watershed's drainage pattern remains largely undistorted by geological features, but there is a moderate increase in branching complexity. A bifurcation ratio exceeding 5 indicates an elongated watershed where geological structures significantly control its shape, resulting in a high degree of branching complexity. These classifications help researchers understand the underlying processes shaping river networks and their interactions with the surrounding geology.

Table 7.2: Range of bifurcation ratio and its significance (Strahler, 1964)

Bifurcation ratio	Indication
<3	Theoretical basin/watershed
3 to 5	The watershed's drainage pattern is not distorted by the geological features
>5	The watershed is elongated and controlled by geological structure

Areal aspects relate to the spatial characteristics of the watershed. The important parameters include a) Drainage density b) Stream frequency c) Form factor d) Elongation ratio e) Circularity ratio. These parameters govern infiltration capacity, runoff potential, flood peaks, and basin response time.

- **Drainage density (D_d):** It is the total length of streams per unit area (Horton, 1945). It represents channels development and their arrangement in a basin. It also reflects vulnerability of watershed towards hydrological hazards, especially in areas where hydro-meteorological data are scarce or absent (Obeidat et al., 2021). Generally, drainage density is categorized into five classes i.e., very fine > 4.97 km/km^2, fine 3.73-4.97 km/km^2, moderate 2.49-3.73 km/km^2, coarse 1.24-3.73 km/km^2 and very coarse <1.24 km/km^2 (Sekhar and Mathew, 2024). The watershed with very high $D_d$values reflects closeness of streams in the basin and forms an intricate network within the landscape. Such watersheds are typically associated with areas of high elevation, where water flow is efficiently captured and transported through numerous channels. Low D_d value implies an area having coarse drainage texture, low relief, permeable sub-soil, compact vegetation cover, high infiltration capacity, less surface runoff, and higher potential of groundwater.

  $F_s = (L_u/A)$

  Where L_u is total length of streams in a watershed, and A is area of watershed.

Table 7.3: Drainage density based watershed texture

Drainage density	Texture
<1.24	Very coarse
1.24 to 2.49	Coarse
2.49 to 3.73	Moderate
3.73 to 4.97	Fine
>4.97	Very fine

- **Stream frequency (F_s):** It is determined by the number of streams per unit area (Horton, 1945) and denoted by F_s. Stream frequency is primarily influenced by the lithology of the catchment and the drainage network's texture. A higher stream frequency value corresponds to more surface runoff, resistive subsurface material, and sparse vegetation. Low relief and surface watershed material are indicated by lower stream frequency values (Obi et al., 2002).

  $F_s = (N_u/A)$

  Where N_u is total stream numbers in a watershed, and A is area of watershed. Understanding the stream frequency distribution provides essential information for various purposes, such as land management, ecological assessments and water resource planning.

Table 7.4: Stream frequency distribution

Stream frequency	Number of streams per km^2
Low	0-5
Moderate	5-10
Moderately high	10-15
Moderate	15-20
High	20-25

- **Form factor (R_f):** It is the ratio of watershed area to the square of watershed length, and indicates the flow intensity of a basin on a defined scale (Sreedevi et al., 2013). The R_f also depicts the runoff characteristics of a basin. Smaller the value of R_f, more the elongated watershed (Strahler, 1964). Hence, watershed with smaller form factor value will generate low runoff having high time of concentration, in contrary watersheds with higher form factor value with circular or nearly circular watershed, will produce high runoff due to less time of concentration (Adhikary and Dash, 2018).
- **Elongation ratio (R_e):** It is the ratio between the diameter of a circle having same area as the watershed and the maximum length of the watershed (Schumm, 1956). Though, the value of elongation ratio theoretically ranges between zero to one, however over a wide variety of climatic and geologic condition, it varies from 0.5 to 1.0. Any watershed can be classified with the help of this index 'R_e', i.e., circular (0.9-0.10), oval (0.8-0.9), less elongated (0.7-0.8), elongated (0.5-0.7), and more elongated (< 0.5). A circular watershed is more vulnerable to soil erosion due to high peak discharge and short time of concentration than an elongated watershed. R_e values close to in the range 0.6 to 0.8 are usually associated with high relief and steep ground slope (Strahler, 1964).

Table 7.5: Stream frequency distribution (Pareta and Pareta, 2011)	
Elongation ratio	**Watershed shape**
More elongated	< 0.5
Elongated	0.5 to 0.7
Less elongated	0.7 to 0.8
Oval	0.8 to 0.9
Circular	0.9 to 1.0

- **Circulatory ratio (R_c):** It is expressed as the ratio of watershed area to the area of a circle having the same perimeter as the watershed (Miller, 1953; Strahler, 1964). It is mainly influenced by geology and structure, relief, slope, climatic condition, stream frequency and its length and LULC within the watershed. Its value ranges from zero to one. High, medium and low, values of the circularity ratio represent the older, mature and younger stages of basin development respectively.

  $R_c = 4\pi A/P^2$

  Where, A = Area of watershed, $\pi = 3.14$, P = Perimeter of watershed.

Relief parameters describe the vertical dimension of a watershed. The important parameters include a) Basin relief (B_h) b) Relief ratio (R_h) c) Ruggedness number (R_n). Relief parameters indicate erosion intensity, sediment yield, and slope instability. High relief watersheds require intensive soil and water conservation interventions.

- **Basin relief (B_h):** The basin relief or total relief is the vertical distance from the highest elevation point of watershed to the point of mouth or outlet of that particular watershed.

  $B_h = H_{max} - H_{min}$

- **Relief ratio (R_h):** It is the ratio of the basin relief and basin length.

  Rh = Bh / Lb

  It expresses the overall steepness of a watershed. Relief ratio indicates the average slope gradient and controls the velocity of surface runoff and erosional processes within a watershed. A high relief ratio signifies steep terrain, rapid runoff, low infiltration, and high soil erosion potential, whereas a low relief ratio indicates gentle slopes, slower runoff, greater infiltration, and relatively stable land surfaces. In watershed land use planning, areas with high relief ratio require intensive soil and water conservation measures such as terracing, contour bunding, and afforestation, while areas with low relief ratio are more suitable for agriculture and groundwater recharge structures.

- **Ruggedness number (R_n):** It is the product of basin relief and drainage density.

  $R_n = B_h \times D_d$

Table 7.6: Watershed indication based on ruggedness number	
Ruggedness number	**Indication**
Low (< 0.5)	Smooth terrain, low erosion risk
Moderate (0.5-1.0)	Moderately rugged, moderate erosion
High (> 1.0)	Highly rugged terrain, severe erosion risk

The ruggedness number is a composite morphometric index that combines basin relief and drainage density to represent the overall ruggedness of terrain. It reflects the structural complexity, degree of dissection, and erosion susceptibility of a watershed. Higher ruggedness number values indicate highly dissected and uneven terrain with high runoff intensity, severe soil erosion, and greater sediment yield, particularly in hilly and mountainous regions. Conversely, lower ruggedness number values suggest smoother terrain with lower erosion risk and better suitability for cultivation and water harvesting.

Relevance in watershed land use planning

Morphometric analysis plays a critical role in the following planning components:

- **Watershed prioritization:** Sub-watersheds with unfavorable morphometric characteristics (high relief, high drainage density, high runoff potential) are prioritized for treatment.
- **Soil and water conservation planning**:
  - Steep and high-relief areas: Terracing, contour bunding, vegetative barriers.
  - High drainage density zones: Check dams, gully plugs, nala bunds.
  - Gentle slopes with low drainage density: In-situ moisture conservation and recharge structures.
- **Land capability and land use allocation:** Morphometric indicators guide allocation of land uses such as:
  - Forest and agroforestry in high-relief and erosion-prone areas
  - Rain-fed agriculture in moderate slope zones
  - Horticulture and irrigation-based land use in low-relief areas with recharge potential

Fig. 7.3: Relevance of morphometric analysis in watershed land use planning

- **Flood and drought management:** Understanding basin response helps in:
  - Flood mitigation through appropriate drainage and storage structures
  - Drought resilience planning by identifying recharge-friendly zones

Example 1:

A 4^{th} order watershed has an area of 50 km^2, with a basin length of 12 km. Maximum and minimum elevation in the watershed is 920 and 420 m respectively. The number of 1^{st}, 2^{nd}, and 3^{rd} order streams are 64, 16, and 4 respectively. Total stream length is 120 km. Calculate mean bifurcation ratio, drainage density, stream frequency, form factor, basin relief, relief ratio and Ruggedness number.

Answer:

Bifurcation ratio = $R_b = N_u / N_{u+1}$

$R_{b_{12}}$ = 64 / 16 = 4.0

$R_{b_{23}}$ = 16 / 4 = 4.0

$R_{b_{34}}$ = 4 / 1 = 4.0

Mean bifurcation ratio (R_{bm}) = (4.0 + 4.0 + 4.0) / 3 = 4.0

Drainage Density = $D_d = \sum Lu / A$ = 120 / 50 = 2.4 km/km^2

Stream Frequency (F_s) =Fs = $\sum Nu / A$ = 85 / 50 = 1.7 streams/km^2

Form factor= $R_f = A / Lb^2$=50 / (12^2) = 50 / 144 = 0.35

Basin relief =$B_h = H_{max} - H_{min}$ = 920 - 420 = 500 m

Relief ratio =$R_h = B_h / L_b$= 500 / 12,000 = 0.042

Ruggedness number= (R_n) = $B_h \times D_d$= 0.5 × 2.4 = 1.2

A mean bifurcation ratio of about 4 indicates normal drainage conditions with minimal structural disturbance and moderate runoff response. Moderate drainage density suggests balanced runoff and infiltration. Low form factor (0.35) indicates an elongated basin with lower flood peak and longer runoff duration. A ruggedness number of 1.2 indicates moderate to high erosion susceptibility, warranting soil and water conservation measures.

Integration with socio-economic and climatic factors

Effective watershed land use planning requires integration of morphometric insights with socio-economic and climatic considerations such as land tenure, cropping systems, livelihood dependence, and rainfall variability. While morphometric analysis provides a physical basis, effective watershed planning requires integration with:

- Land ownership and socio-economic conditions
- Cropping patterns and livelihood dependence
- Rainfall variability and climate change projections

Such integration ensures that land use plans are technically sound and socially acceptable.

Limitations of morphometric analysis

- Does not directly account for soil properties and land cover dynamics
- Static representation of watershed characteristics
- Requires careful interpretation when used alone

Therefore, morphometric analysis should be complemented with field surveys, soil studies, and hydrological data.

Conclusions

Morphometric analysis provides a quantitative foundation for understanding watershed behavior. When integrated with GIS and field knowledge, it becomes a powerful tool for sustainable watershed land use planning, especially in diverse Indian physiographic settings.

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Design and Evaluation of Micro-irrigation System

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Introduction

Water is the most critical input in agriculture, accounting for nearly 80% of India's total freshwater use, and its efficient management is vital for improving productivity and ensuring sustainability (UNESCO, 2022; India Water Portal, 2023). Conventional irrigation systems are often inefficient, leading to waterlogging, salinity and reduced crop yields, which highlights the need for improved methods like drip and sprinkler irrigation. Micro-irrigation (MI) technologies, which deliver water directly to the plant root zone through low-pressure systems such as drippers, bubblers, and sprinklers, can save 40-80% of water and significantly enhance water use efficiency (Narayanamoorthy, 2017; FAO, 2020). Although drip irrigation has historical roots in Europe, the U.S. and Israel, India has also practiced indigenous forms using bamboo pipes and earthen pitchers, with modern adoption gaining momentum since the 1970s, particularly in water-scarce regions and high-value crops (INCID, 1994; Postel, 2014). Today, MI systems are widely used across arid, semi-arid, and even humid regions, not only conserving water but also preventing problems like salinization and declining water tables. To maximize benefits, MI should be promoted as part of a holistic approach that integrates water conservation, watershed management, improved agronomic practices, and post-harvest systems, ensuring both resource sustainability and agricultural growth.

Micro-irrigation is a modern irrigation method that delivers water directly to the plant root zone through pipes, tubes, and emitters, ensuring minimal wastage compared to conventional systems. Evolving from ancient practices like clay pots and pipes to today's perforated plastic tubing and advanced emitters, it has become highly efficient for water-scarce regions. Variants such as bubblers and micro-sprinklers cater to different crop and environmental needs, including greenhouse cultivation. By burying tubes near the soil surface and using pressurized pumps, micro-irrigation reduces evaporation, prevents leaf diseases, and allows fertigation by mixing fertilizers with water. It is particularly advantageous on sloping land where it prevents runoff and erosion, and for closely spaced or high-value crops like strawberries. Automation further enhances its efficiency, making it less labour-intensive and highly effective in conserving water while improving crop yields.

India's micro-irrigation (MI) potential is estimated at about 42 million hectares (Mha) - approximately 30 Mha for sprinkler systems (cereals, pulses, oilseeds, fodder) and 12 Mha for drip irrigation (cotton, sugarcane, fruits, vegetables, spices, certain pulses) (Raman, 2010; Palanisami et al., 2011). Actual adoption in 2011 was about 3.87 Mha (≈ 1.42 Mha under drip and 2.44 Mha under sprinkler), representing only 9.16% of potential, with highly uneven state-wise coverage (Palanisami et al., 2011).By March 2024, total MI coverage had increased to ≈ 16.7 Mha (≈ 9.05 Mha sprinkler, 7.69 Mha drip), or ~40% of potential, reflecting significant government and farmer-led initiatives (ZEF, 2024). This represents an approximate compound annual growth rate (CAGR) of ~10.5% over 13 years (2011–2024). If this growth continues, India could potentially achieve ~80% of its MI potential (≈33.6 Mha) by the early 2030s, emphasizing the critical role of policy support, financial incentives, and farmer awareness in bridging the remaining adoption gap.

Types of micro-irrigation system

Micro-irrigation can be broadly categorized into drip, spray, subsurface and bubbler systems, each designed to deliver water efficiently to plants. Drip irrigation involves the slow, frequent application of water through emitters positioned along delivery lines, either on the soil surface or buried near the root zone. The wetted soil area depends on soil properties and one or more emitters may be required per plant (Howell et al., 1980). Spray irrigation, also known as sprinkler irrigation, distributes water over crops by spraying it into the air through micro-sprayers, jets or rotating micro-sprinklers, with flow rates typically between 20-300 lph. Systems can be fixed, portable, or large-scale setups such as center-pivot irrigation that cover circular fields. Modern low-pressure sprinklers are preferred over high-pressure water guns because they reduce water loss from evaporation and wind drift. Spray irrigation can draw water from wells, reservoirs, rivers or treated wastewater sources, with the latter offering an eco-friendly option for ornamental and non-food crops while helping conserve freshwater resources.

Table 8.1: Classification of micro-irrigation systems

Type of system	Method of application	Key features	Flow rate	Placement/use	Advantages
Drip irrigation	Slow, frequent water application through emitters	Emitters on soil surface or buried; wetted area depends on soil	Low (drop by drop)	At root zone, one or more emitters per plant	High water-use efficiency, less evaporation, precise watering
Spray irrigation (Sprinkler)	Pressurized water sprayed/misted over crops	Micro-sprayers, micro-sprinklers (rotating/non-rotating	20-300 lph	Fixed, movable, or center-pivot systems	Covers larger areas, suitable for different farm sizes, can use treated wastewater

Components of micro-irrigation system

The components of a micro-irrigation system can be grouped into four main parts: the control head, chemical injection system, distribution system and emission devices. The control head includes pumps or overhead tanks to provide pressure, fertilizer applicators for adding nutrients, filters to remove impurities and valves for pressure and flow regulation. The chemical injection system uses solution tanks and injectors for fertigation and chemigation, typically through venturi, pumps or differential systems. The distribution system consists of mainlines, sub mains and laterals made of Polyvinyl Chloride (PVC), High-Density Polyethylene (HDPE) and Low-Density Polyethylene

(LDPE) pipes that transport water across the field. Finally, emission devices such as drippers, line-source emitters, bubblers and micro-sprinklers directly deliver water to the plants, with flow rates ranging from 2 lph in drippers to 180 lph in micro-sprinklers, depending on crop and soil requirements.

Table 8.2: Components of a micro-irrigation system

Component	Sub-component	Function	Key features
Control Head	Pump/Overhead tank	Provides pressure	Electric or centrifugal pumps; overhead tanks for small systems
	Fertilizer applicator	Adds fertilizers/chemicals	Venturi, injection pumps, or differential tanks
	Filters	Removes suspended impurities	Media, screen, centrifugal, disk filters
Chemical Injection	Valves	Pressure and flow control	Pressure relief, check valves, bypass systems
Chemical Injection	Solution tank and injectors	Fertigation/chemigation	Poly/fiberglass tanks, venturi/pump/differential systems
Distribution System	Mainline, sub main, laterals	Water transport	PVC/HDPE/LDPE pipes (12-150 mm dia.)
Emission Devices	Drippers (PC and non-PC), Line source emitters, Bubblers, Micro-sprinklers	Direct water application to plants	Flow rates: Drippers (2-8 lph), Bubblers (8-75 lph), Micro-sprinklers (16-180 lph)

Design of micro-irrigation system

- **Irrigation water requirement**

The irrigation water requirement for crop production is the amount of water, in addition to rainfall, that must be applied to meet a crop's evapotranspiration needs without significant reduction in yield. The amount of irrigation water requirement was estimated using the crop evapotranspiration (ET_c) which was calculated by the FAO Penman-Monteith method (Allen et al., 1998) based on the climatic data. The FAO Penman-Monteith equation is as follows:

$$ET_c = K_c \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T_{mean}} + 273\right)u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

Where, ET_c = Crop evapotranspiration under standard condition (mm day^{-1}), R_n = Net radiation at the crop surface (MJ m^{-2} day^{-1}), G = Soil heat flux density (MJ m^{-2} day^{-1}), which is relatively small and ignored for day period;, T_{mean} = Mean daily air temperature at 2 m height (°C), u_2 = Wind speed at 2 m height (m s^{-1}), ($e_s - e_a$) = Vapor pressure deficit (kPa), Δ = Slope of vapor pressure curve (kPa °C^{-1}), γ = Psychrometric constant (kPa °C^{-1}), and K_c = Crop coefficient (varies between 0.45 and 1.05), which is affected by several factors such as crop type, crop height, albedo (reflectance) of the crop-soil surface, aerodynamic properties, leaf and stomata properties and crop stages (Allen et al. 1998).

- **Net depth per irrigation**

Normally, drip irrigation wets only part of the soil area. Therefore, the equation for determining the desirable depth or volume of application per irrigation cycle and the maximum irrigation interval must be adjusted accordingly. The maximum net depth per irrigation, d_x, is the depth of water that will replace the soil moisture deficit when it is equal to MAD. The d_x is computed as a depth over the whole crop area not just the wetted area; however, the % age area wetted, P_w must be taken into account.

$$d_x = \frac{MAD}{100}\frac{P_w}{100} W_a Z \qquad (2)$$

Where, d_x = Maximum net depth of water to be applied per irrigation (mm), MAD = Management allowed deficit (%), W_a= Available water holding capacity of the soil (mm/m), Z = Plant root depth (m).

The net depth to be applied per irrigation, d_n, to meet consumptive use requirements can be computed by,

$$d_n = T_d f' \text{ and } f_x = \frac{d_x}{T_d} \qquad (3)$$

Where, d_n= Net depth of water to be applied per irrigation to meet consumptive use requirements (mm), f' = Irrigation interval or frequency (days), f_x = Average daily transpiration during peak-use period (mm), T_d = Average daily transpiration during peak-use period (mm). For the design purposes, the T_d for the mature crop should be used for sizing the pipe network. Furthermore, assuming irrigation interval as one day, so that $d_n = T_d$, simplifies design process (Keller and Bliesner, 1990).

- **Gross irrigation requirement**

Gross irrigation depth and volume requirements for drip systems are based on net requirements and efficiencies. The gross depth per irrigation, d, should include sufficient water to allow for unavoidable deep percolation. To minimize avoidable losses, systems should be well designed, accurately scheduled, and carefully maintained. Where $LR_i \leq 0.1$ or the unavoidable deep percolation is greater than the adjusted leaching water required $T_r \geq 0.9/(1.0 - LR_i)$ (Keller and Bliesner, 1990).

$$d = \frac{d_n T_r}{EU/100} \quad \text{or} \quad d' = \frac{T_d T_r}{EU/100} \qquad (4)$$

Where, d = Gross depth of application per irrigation (mm), d_n = Net depth of water to be applied per irrigation to meet consumptive use requirements (mm), d' = Maximum gross daily irrigation requirement (mm), T_r = Peak use period transmission ratio, T_d = Average daily transpiration during peak-use period (mm), E_u = Emission uniformity (%), and LR_i = Leaching requirement under drip irrigation.

The gross volume of water required per plant per day, G is a useful design parameter for selecting emitter discharge rates:

$$G = K\ d'\ S_p\ S_r \tag{5}$$

Where, G = Gross volume of water required per plant or unit length of row per day (lpd), K = Conversion constant having a value of 1.0, d' = Maximum gross daily irrigation requirement (mm), S_p = Spacing between plants (m), and S_r = Spacing between row (m).

- **Capacity of drip irrigation system**

The capacity of the drip irrigation system, Q_s is the maximum number of emitters operating at any given time multiplied by average emitter discharge, q_a. According to Keller and Bliesner (1990) for uniformly spaced laterals that supply water uniformly spaced emitters.

$$Q_s = K \frac{A}{N_s} \frac{q_a}{S_e S_l} \tag{6}$$

Where, Q_s = Total system capacity (lps), q_a= Average emitter discharge (lph), K= Conversion constant having a value of 2.778, S_e = Emitter spacing (m), A= Field area (ha), S_l = Lateral spacing (m), and N_s = Number of operating stations.

Some systems require extra capacity because of anticipated slow changes in q_a can result from such things as slow clogging due to sedimentation in long path emitters or compression of resilient parts in compensating emitters. Both decrease and increase in q_a necessitates periodic cleaning or replacement of emitters. To prevent the need for frequent cleaning or replenishment of emitters, where decreasing discharge rates are a potential problem, the system should be designed with 10-20% extra capacity.

- **Emitter flow theory**

Hydraulically, most emitters can be classified as long-path, orifice, vortex, pressure compensating and porous pipe emitters. The hydraulic characteristic of each emitter is directly related to the mode of fluid motion inside the emitter, which is characterized by Reynolds number (R_e).

$$R_e = \frac{Vd}{v} \tag{7}$$

Where, V = emitter flow velocity ($m\ s^{-1}$), d = emitter diameter (m), v = kinematic viscosity ($m^2\ s^{-1}$). These flow regimes are characterized as (1) laminar, $R_e < 2000$; (2) unstable, $2000 \leq R_e \leq 4000$; (3) partially turbulent, $4000 \leq R_e \leq 10{,}000$; and (4) fully turbulent, $10{,}000 \leq R_e$.

- **Emitter spacing**

Emitter spacing is a system design characteristic and should be selected taking into account the soil water properties of the site, the specific rooting system of the crop and the climatic characteristics as it affects the extent to which the crop depends on irrigation. Drip emitters of 2 lph are selected when planting is done in clay soils and spacing tends to be further apart. Drip emitters of 4-8 lph discharge are chosen for planting in sandy soils. Drip emitters of 2-4 lph are selected for planting in loamy soils.

- **Crops and planting geometry**

For wide spacing crops like Mango, Citrus, Litchi, Sapota, one or more than one drip emitters of higher discharge ranging from 4-8 lph are used to apply water to meet crop water requirement. For close spacing crops like Spinach, Coriander, Methi etc. micro sprinklers are suitable for irrigation.

- **Emitter capacity**

The capacity of drip irrigation emission device may be computed by using Eq. 8:

$$Q = \frac{A \times d}{H \times E_a} \tag{8}$$

Where, Q = Emission device capacity (lph), d = Depth of water application (mm), A = Area irrigated by the emission device (m^2), H = Irrigation time (h), and E_a = Application efficiency (%).

- **Area wetted by emitter**

The area wetted by an emission device (A) is computed by following equation:

$$A = \frac{LSW_p}{100N_e} \tag{9}$$

Where, A = Area irrigated (m^2), L = Spacing between adjacent plant rows (m), S = Spacing between emission points (m), W_p = % of cropped area being irrigated, N_e = Number of emission devices at each emission point. The value of W_p varies with crop and growth stage. W_p for wide spacing crops vary between 40-60% and for close spacing crops it varies from 70-90%.

- **Number of emission devices**

The number of emission devices needed for the desired wetting pattern requires information describing the horizontal and vertical movement of water through soil. For single laterals with equally spaced emission points, the following Eq.10 estimates the number of emission devices per plant (N_e).

$$N_e = \frac{100LSW_p}{D_w S_e} \tag{10}$$

$$S_e \le 0.8D_w$$

Where, D_w = Maximum diameter of wetted circle formed by a single point source emission device (cm), S_e = Spacing between the emission devices of an emission point (cm), W_P = % of S times L irrigated; L = Spacing between adjacent plant rows (m); S = Spacing between emission points (m).In drip systems with double laterals or zig-zag, pigtail, or multi exit layouts, N_e is computed with following Equation.

$$N_e = \frac{2 \times 100 W_p SL}{S_e \left(S_e + D_w \right)} \quad (11)$$

$$N_e = \frac{W_p SL}{100 \left(A_s + \frac{D_w P_s}{200} \right)} \quad (12)$$

$$S_e = D_T + \frac{D_w}{200} \quad (13)$$

Where, A_S = Area wetted by a single micro sprinkler (m^2), P_S = Perimeter of area wetted by micro sprinkler (m), D_T = Distance of throw (m).

- **Emission uniformity**

Emission uniformity (Eu) is a key measure of how evenly water is delivered by a drip irrigation system. It depends on hydraulic factors such as elevation changes and friction losses along the pipelines, as well as emitter-specific factors like manufacturing variability, clogging, temperature fluctuations, and aging. First defined by Keller and Karmeli (1975), Eu quantifies the uniformity of water discharge across all emitters within a unit or subunit, providing a standard for evaluating the efficiency and effectiveness of drip irrigation systems.

$$E_u = 100 \left[1 - 1.27 \left(C_{vm} \right) N_e^{-\frac{1}{2}} \right] \left(\frac{q_n}{\overline{q}} \right) \quad (14)$$

Where, C_{vm} = Manufacturer’s coefficient of variation for point source or line source emitters, Ne = Number of point source emitters per emission point (spacing between plants divided by the unit length of lateral line used to calculate or 1, whichever is greater, for line source emitter), q_n = Minimum emitter discharge rate in the system (lph), $\overline{q}$ = Mean emitter discharge rate (lph). The emission uniformity increases as more emitters are added to each plant. Nakayama et al. (1979) developed a coefficient of design uniformity (C_{ud}) based on statistical analysis.

$$C_{ud} = 100 \left[1 - 0.789 \left(C_{vm} \right) N_e^{-\frac{1}{2}} \right] \quad (15)$$

- **Pressure head-discharge relationship of emitter**

The relationship between pressure head and emitter discharge is a crucial characteristic in drip irrigation. Pressure-compensating emitters, which adjust to pressure changes, typically have a low exponent but may show high manufacturing variability and can be affected by temperature or material fatigue, requiring careful consideration for long-term performance. On uneven terrain, emitter placement and sizing along laterals help manage pressure variations. In laminar flow emitters, discharge changes linearly with pressure, so system pressures are usually maintained within ±5% of the average. In contrast, turbulent flow emitters follow a square-root relationship with pressure, allowing ±10% variation, meaning pressure must increase fourfold to double the flow (US Soil Conservation Service, 1984). The pressure discharge relationship for emitter is given by.

$$Q = C_d H^x \tag{16}$$

Where, Q = Flow rate, H = Operating pressure head, C_d = Coefficient of discharge, x = Exponent. Depending upon the experimental values of x, flow regimes can be obtained.

- **Pressure variation in irrigation pipe line**

Uniform water application is the primary requirement for effective irrigation, and the performance of a drip system depends largely on maintaining the desired operating pressure. Each emitter requires an optimal pressure to deliver water evenly, but friction losses in pipes and fittings, as well as elevation changes across the field, can cause pressure variations. Friction reduces pressure downstream, while elevation changes can either increase or decrease pressure depending on whether the pipe runs uphill or downhill. The pressure difference along the pipeline can be estimated using standard hydraulic formulas.

$$P_d = P_u - 9.81\left(h_l \pm \Delta z\right) \tag{17}$$

Where, P_d and P_u= Pressure at down and upstream positions, respectively (kPa), h_l = Energy loss in pipe between the up and downstream positions (m); ΔZ = Elevation difference (m) (+ve for uphill and -ve for downhill.

The energy loss (h_l) includes head loss due to friction and minor loss, which can be estimated as:

$$h_l = FH_f + M_l \tag{18}$$

Where, F = Constant, f (number of outlets and method used to estimate, H_f), H_f = Friction loss in pipe between up and downstream locations (m), M_l = Minor losses through fittings (m).

Major and minor losses are two types of losses that occur in pipe flow. Major losses occur while water flow along straight pipes. The universal equation used to calculate friction losses of water flow along a pipe is known as the Hazen-Williams equation given by,

$$H_f\left(100\right) = K\left(\frac{Q}{C}\right)^{1.852} \times D^{-4.871} \times F \tag{19}$$

Where H_f (100) = Head loss due to friction per 100 m of pipe length (m/100 m), K = A constant having a value of 1.22×10^{12} in metric units, D = Inner pipe diameter (mm), C = Friction coefficient (indicates inner pipe wall smoothness, the higher the C coefficient, the lower the head loss), Q = Flow rate (lps).

As the length of the pipe increases, the discharge in the pipe decreases due to emission outlets and hence the total energy drop is less than as estimated by the above Eq. 18. For this reason, a reduction factor F is introduced.

The Hazen-Williams Eq. is valid in a limited range of temperature and flow pattern. In small diameter laterals, the Darcy-Weisbach Eq. gives better results in calculating head loss due to friction in small diameter lateral pipes. It is given by,

$$H_f = f\left(\frac{LV^2}{2gD}\right) \tag{20}$$

Where, H_f = Head loss (m), L = Pipe length (m), f = Darcy-Weisbach friction factor, V = Flow velocity (m s^{-1}), g = Gravitation acceleration (9.81m s^{-2}), D = Inner pipe diameter (m). Both the Hazen-Williams and Darcy-Weisbach Equations include a parameter for the smoothness of the internal surface of the pipe wall. In Hazen-Williams, it is the dimensionless C coefficient and with Darcy-Weisbach the roughness factor f, as the C coefficient is higher, head loss will be lower. On the opposite, in the Darcy-Weisbach Eq., higher values of indicate higher head losses.

The minor losses through fittings can be estimated or obtained from standard tables available in text books and hydraulics manuals/ hand books. Minor losses are created by the flow at bends and transitions. If the flow velocities are high through many bends and transitions in the system, minor losses can build up and become substantial losses. Minor head losses are expressed as an equivalent length factor that adds a virtual length of straight pipe of the accessory diameter to the length of the pipe under calculation. The Darcy-Weisbach, Hazen Williams or Scobey Eq. can be used to compute head loss due to friction, H_f. The general form of these Equations can be written as:

$$H_f = \frac{KcLQ^m}{D^{2m+n}} \tag{21}$$

Where, K = Friction factor that depends on pipe material, L = Length of pipe (m), Q = Flow rate (lpm), D = Diameter of pipe (mm), c, m, n = Constants can be obtained from Table 8.3.

Table 8.3: Constants of friction loss equations

Equations for computing H_f	c	m	n
Darcy-Weisbach	277778	2	1
Hazen-Williams	591722	1.85	1.17
Scobey	610042	1.9	1.1

For the Darcy-Weisbach Equation, K is estimated by the following equation:

$$K = 0.811\left(\frac{f}{g}\right) \tag{22}$$

Where, f = Friction factor can be obtained from the Moody diagram, g = Acceleration due to gravity (9.81 m s^{-2}), and K for Hazen-William Eq. is computed by,

$$K = \left(0.285C\right)^{-1.852} \tag{23}$$

Where, C = Friction coefficient depends on pipe material and diameter; K for Scobey Eq. is given by,

$$K = \frac{K_s}{348} \tag{24}$$

Where, Ks = Friction factor values depend on pipe diameter and pipe material.

The term F in Eq. 19 equals 1 when there are no outlets between the up and downstream locations along a pipe (i.e. discharge along the pipe is constant). Eqs. 25 and 26 can be used to estimate F when there is more than one equally spaced outlet. Eq. 25 is used when the distance from the pipe line to the first outlet is equal to the outlet spacing.

$$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{\sqrt{m-1}}{6N^2} \tag{25}$$

Eq. 26 is used when the distance to first outlet is half of the outlet spacing.

$$F = \frac{1}{2N-1} + \frac{2}{(2N-1)N^m} \sum_{i=1}^{N-1} (N-1)^m \tag{26}$$

Where, m = Exponent (m) (can be obtained from Table 8.3) depending on type of Eq. involved in estimating H_f, N = Number of emitters. When the discharge varies widely from outlet to outlet, the Eq. 17 is applied between successive outlets working from the known pressure to unknown pressure.

Design of lateral, sub main and main pipes

- **Lateral pipe design**

Drip irrigation lateral lines serve as the hydraulic link between the supply lines (main or submain) and the emitters, which can be connected directly to the lateral (inline/online), mounted on risers for micro-sprinklers or jets, or attached via tree loops. Laterals, typically made of 12-16 mm Linear Low-Density Polyethylene (LLDPE) tubing, include fittings like tees and unions to connect to submains or mains. Designing laterals involves determining flow rate, inlet pressure, manifold spacing, and pressure variations along the line, with the goal of achieving uniform emitter discharge. On gently sloping fields (<3%), laterals are usually connected on both sides of manifolds to balance pressure, while manifold spacing balances field layout and hydraulic requirements. Because flow in laterals may be laminar, turbulent, or fully turbulent, head loss due to friction is calculated using the Darcy-Weisbach equation, with the friction factor related to the Reynolds number of the tubing.

$$R_e = \frac{\rho D V}{K \mu} \tag{27}$$

Where, R_e= Reynolds number (dimensionless), D = diameter of pipe (cm), ρ = Density of water (g cm^{-3}), V = Average velocity (cm s^{-1}), μ = Viscosity of the fluid (N s m^{-2}), K = Unit constant, 10 with these units.

The Eq. used to compute friction factor (f) depends on the magnitude of N_R. For R_e less than 2000 (laminar flow), the friction factor,

$$f = \frac{64}{R_e} \tag{28}$$

For R_e between 2000 and 10, 0000 (turbulent flow)

$$f = 0.32 R_e^{-0.25} \tag{29}$$

For R_e greater than 10, 0000 (fully turbulent flow)

$$f = 0.8 + 2\log\left(\frac{R_e}{\sqrt{f}}\right) \tag{30}$$

The Hazen-Williams Eq. with C =150 can also be used to estimate head loss due to pipe friction R_e> 1, 00, 000.

Sub main design

Sub main line hydraulics in drip irrigation are similar to lateral hydraulics but are designed to manage multiple laterals while maintaining overall system uniformity. Keller and Karmeli (1975) suggested that lateral lines should account for 55% of the total allowable energy loss, with sub mains taking 45%. Sub main design depends on flow or pressure regulation, and energy loss is primarily influenced by sub main length; exceeding allowable losses can reduce emitter uniformity. On steep slopes, individual lateral regulation may be needed, making uniformity independent of sub main losses as long as flow is not hindered. Inlets are positioned according to field slope uphill runs shorter than downhill on sloping land, and near the centre on level areas. Sub mains and mains should have flushing valves, and secondary screens at lateral connections prevent clogging. Hydraulic characteristics are computed assuming laterals act as emitters, with PVC pipes treated as hydraulically smooth (Hazen-William’s coefficient C = 140-150). Total sub main energy loss includes friction, minor fittings, and losses through filters and valves.

Mainline design

Normally, flow or pressure control or adjustment values are provided at the sub main inlet. Therefore, energy losses in the mainline should not affect system uniformity. The mainline pipe size is based on economic comparisons of power costs and pipe costs. The mainline pipe size should be selected to minimize the sum of power costs and capital costs over the life time of the pipeline.

Example 1:

Design a drip irrigation system for a citrus orchard of 1 ha area with length and breadth of 100 m each. Citrus has been planted at a spacing of 5 m × 5.5 m. The maximum pan evaporation during summer is 8 mm day^{-1}. The other relevant data are given below:

Land slope = 0.40% upward from S- N direction

Water source	=	A well located at the S-W corner of the field
Soil texture	=	Sandy loam
Clay content	=	18.4%
Silt	=	22.6%
Sand	=	59.0%
Field capacity	=	14.9%
Wilting point	=	8%
Bulk density	=	1.44 g cc^{-1}
Effective root zone depth	=	120 cm
Wetting fraction	=	0.4
Pan coefficient	=	0.7
Crop coefficient	=	0.8

Solution

Step I

Estimation of water requirement:

Crop evapotranspiration (ET_c) = Open pan evaporation $\times$ Pan coefficient $\times$ Crop coefficient

$= 8 \times 0.7 \times 0.8$

$= 4.48$ mm day^{-1}

Volume of water to be applied = Area covered by each plant $\times$ Wetting fraction $\times ET_c$

$= (5 \times 5.5)\ m^2 \times 0.40 \times 4.48$ mm day^{-1}

= 49.28 l/day ~ 50 l/day

Step II

Emitter selection and irrigation time

Emitters are selected based on the soil texture and crop root zone system. Assuming three emitters of 4 lph, placed on each plant root zone in a triangular pattern. These are sufficient to wet the effective root zone of the crop.

Total discharge delivered in one hour = $4 \times 3 = 12$ lph

Irrigation time = 50 / 12 = 4 h 10 minutes

Step III

Discharge through each lateral

A well is located at one corner of the field. Sub mains will be laid from the centre of field (Fig. 8.1). Therefore, the length of main, sub mains, and lateral will be 50, 97.25 and 47.5 m each, respectively. The laterals will extend on both the sides of the sub main.

Each lateral will supply water to 10 citrus plants. (Lateral length / Plant to plant spacing = 47.5/5)

Total number of laterals = Length of sub main / row to row spacing

= (100/5.5) × 2 = 36.36 (Considering 36)

Discharge carried by each lateral, $Q_{lateral}$ = No. of plants on each lateral × No. of emitters for each plant × each emitter discharge,

= 10 × 3 × 4 = 120 lph

Total discharge carried by 36 laterals = 120 × 36 = 4320 lph

Each plant is provided with three emitters; therefore, total number of emitters will be 36 × 10 × 3 =1080

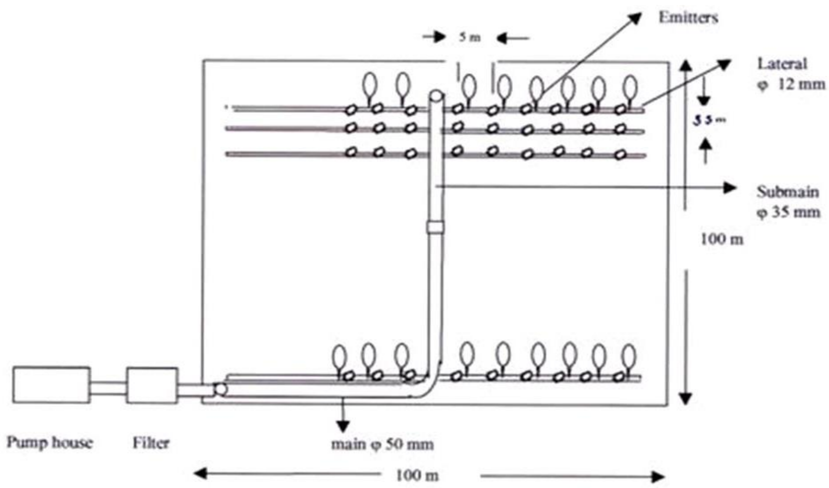

Fig. 8.1: Layout of designed drip irrigation system

Step IV

Size of lateral

Once the discharge carried by each lateral is known, then size of the lateral can be determined by using the Hazen- Williams Eq.

The reduction factor (F) can be estimated by Eq.

$$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{\sqrt{m-1}}{6N^2}$$

$$F = \frac{1}{1.852+1} + \frac{1}{2\times 36} + \frac{\sqrt{1.852-1}}{6\times 36^2} = 0.367$$

The head loss due to friction in lateral pipe can be estimated using Eq.

$$H_f(100) = K\left(\frac{Q}{C}\right)^{1.852} \times D^{-4.871} \times F$$

K= a constant which is 1.22×10^{12} in metric units

Q = flow rate, ls^{-1}

C = friction coefficient =130

D = Take 12 mm diameter pipe

$$= 1.22 \times 10^{12} \frac{\left(\frac{0.033}{130}\right)^{1.852}}{12^{4.871}} \times 0.367 = 0.54 \text{ m}$$

$$H_f = 0.54 \times \left(\frac{47.5}{100}\right) = 0.26\ m$$

The permissible head loss due to friction (H_f) is 10% of head of 10 m (head required to operate emitters of 4 lph discharge), which is 1 m. Therefore, lateral of 12 mm size is adequate and can be chosen.

Step V

Determination of number of sub mains

Assuming the pump discharge = 2.5 lps = 9000 lph

Discharge carried by each lateral = 120 lph

Number of laterals that can be operated by each submain = 9000/120 = 75

Therefore, one manifold or sub mains can supply water to all the laterals at a time.

Step VI

Size of sub main

Total discharge through the sub mains = $Q_{lateral} \times$ Number of laterals

= 120 × 36

= 4320 lph = 1.2 lps

Assuming the diameter of the sub mains as 50 mm. The values of parameter of the Hazen- Williams Eq. are

C = 150

Q = 1.2 lps

D = 50 mm

K = 1.22×10^{12}

F = 0.364

$$H_f\left(100\right) = 1.22 \times 10^{12} \frac{\left(\frac{1.2}{150}\right)^{1.852}}{50^{4.871}} \times 0.364 = 0.31 \text{ m}$$

H_f for 97.25 m of pipe length = 0.31 × (97.25/100) = 0.30 m

Therefore, frictional head loss in the sub mains = 0.30 m

Pressure head required at the inlet of the sub mains = $H_{emitter} + H_{f\ lateral} + H_{f\ sub\ main} + H_{slope}$

= 10 + 0.26 + 0.30 + 0.40

= 10.96 m

Pressure head variation = $\frac{10.96-10.26}{10.96}\times 100$

= 6.38%

Estimated head loss due to friction in the sub main is much less than the recommended 20% variation, hence reducing the pipe size from 50 to 35 mm will probably be a good option.

$$H_f(100)=1.22\times 10^{12}\frac{\left(\frac{1.2}{150}\right)^{1.852}}{35^{4.871}}\times 0.364 = 1.75 \text{ m}$$

H_f for 97.25 m pipe = 1.75× (97.25/100) = 1.70 m

Pressure head required at the inlet of the sub main = $H_{emitter} + H_{f\ lateral} + H_{f\ sub\ main} + H_{slope}$

= 10 + 0.26 + 1.70 + 0.40

= 12.36 m

Pressure head variation = $\frac{12.36-10.26}{12.36}\times 100$ = 17%

Pressure head variation lies within the acceptable limit; hence submain pipe of 35 mm is accepted for design.

Step VII

Size of the main line

Assuming the diameter of main as 50 mm

Discharge of main, Q_{main} = Discharge of sub main, $Q_{sub\ main}$

The values of parameter of the Hazen- Williams Eq. are,

C = 150

Q = 1.2 lps

D = 50 mm

K = 1.22×10^{12}

$$H_f(100)=1.22\times 10^{12}\frac{\left(\frac{1.2}{150}\right)^{1.852}}{50^{4.871}} = 0.84 \text{ m}$$

H_f for 50 mm main pipe = 0.84 × (50/100) = 0.42 m

Step VIII

Determining the horse power of pump

Assuming static head as 10 m, head variation due to uneven field and the losses due to pump fittings, etc. is taken as 10% of all other losses.

H_{local} = 10% of all other loss,

Total dynamic head = $(H_{emitter} + H_{f\ lateral} + H_{f\ sub\ main} + H_{slope}) + H_{f\ main} + H_{static} + H_{local}$

= 12.36 + 0.42 +10 +1.28

= 24.06 m

Pump Horse power (hp) = $\dfrac{QH}{75 \times \eta_p}$

Where, H = Total dynamic head, m, Q = Total discharge through main line, lps, and η_p = Efficiency of pump (60%).

hp= $\dfrac{1.2 \times 24.06}{75 \times 0.6}$ = 0.64 = 1.0

Hence 1 hp pump is adequate for operating the drip irrigation system to irrigate for 1 ha area of citrus crop.

The design details of components micro irrigation system are estimated as:

Length of each lateral = 47.5 m;
Total number of laterals = 36;
Diameter of lateral = 12 mm;

Length of sub main = 97.25 m;
Number of sub main = 1;
Diameter of sub main = 35 mm;

Length of main = 50 m;
Number of main = 1;
Diameter of main = 50 mm,

Pump horse power required = 1 hp.

Example 2

Estimate the emission uniformity (EU) of emitters for a drip irrigation sub-main unit with the following field data. Given time (sec) required to fill a 100 ml container from 24 individual emitters are 64, 79, 67, 71,75, 81,68,85,75,69,85, 77,89,68,81,90,65,61, 72,78,80,70,74 and 68.

Solution:

Individual emitter discharges (ml/s):

1.56,1.27,1.49,1.41,1.33,1.23,1.47,1.18,1.33,1.45,1.18,1.30,1.12,1.47,1.23, 1.11, 1.54, 1.64, 1.39, 1.28, 1.25, 1.43, 1.35 and 1.47

Average of lowest ¼th of emitter flow rate (ml/s):

= (1.11+1.12+1.18+1.18+1.23+1.23)/6 = 1.176

Average emitter flow rate (ml/s) = 1.35

Emission uniformity = (1.176/1.35) × 100 = 86.87%

Example 3

Design a sprinkler irrigation system to irrigate 5 ha wheat crop.

Assume

Soil type	=	Silt loam
Infiltration rate at field capacity	=	1.25 cm/h
Water holding capacity	=	15 cm/m
Root zone depth	=	1.5 m
Daily consumptive use rate	=	6 mm/ day
Sprinkler type	=	Rotating head

Solution:

Step I

Maximum water application rate = 1.25 cm/h

Step II

Total water holding capacity of the soil =15 $\times$ 1.5 = 22.5 cm

Let the water be applied at 50% depletion, hence the depth of water to be applied = 0.50 $\times$ 22.5 = 11.25 cm.

Let the water application efficiency be 90%

Depth of water to be supplied = 11.25 / 0.9 = 12.5 cm

Step III

For daily consumptive use rate of 0.60 cm

Irrigation interval = 11.25 / 0.6 = 19 days

In period of 19 days, 12.5 cm of water is to be applied on an area of 5 ha. Hence, assuming 10 hrs of pumping per day, the sprinkler system capacity would be,

$$= \frac{5\times10^{4}\times12.5\times10^{-2}}{19\times10\times3600} = 0.009\text{m}^{3}\text{s}^{-1}$$

Step IV

Spacing of lateral (S_m) = 18 m

Spacing of Sprinklers in lateral (S_l) = 12 m

This selection is based on after the following consideration:

Operating pressure of nozzle = 2.5 kg/cm^2

Maximum application rate = 1.25 cm/h

Referring sprinkler manufacturer’s chart, the nozzle specifications with this operating pressure and application rate is:

Nozzle size: 5.5563 $\times$ 3.175 mm

Operating pressure: 2.47 kg/cm^2 and

Application rate: 1.10 cm/hr (which is less than the maximum allowable application rate)

Diameter of coverage: 29.99 ≈ 30.0 m

Discharge of the nozzle: 0.637 lps = 0.637 × 10^{-3} m^3/sec

Step V

Total no. of sprinkler required = $= \frac{0.009}{0.637\times10^{-3}} = 14.12 = 14$ Sprinklers

Therefore, 7 number of sprinklers on each lateral.

Step VI

The sprinklers will be spaced at 12 m intervals on each of two lateral lines spaced 18 m apart.

Step VII

Total length of each lateral = 12 × 7 = 84

Operating pressure = 2.47 kg/cm^2

Total allowable pressure variation in the pressure head is 20%, hence maximum allowable pressure variation in pressure = 0.2 × 2.47 = 0.494 kg/cm^2 = 4.94 m

Variation of pressure due to elevation = 2 m

Permissible head loss due to friction = 4.94 – 2 = 2.94 m

Total flow through the lateral = 7 × 0.637 × 10^{-3} = 4.459 × 10^{-3} m^3/sec

$$\text{Reduction factor (F)} = \frac{1}{3} + \frac{1}{2\times7} + \frac{1}{6\times7^2} = 0.407$$

$$\text{Head loss due to friction } (\mathrm{H}_f) = \frac{0.811\times0.04\times277778\times84\times(4.459\times60)^2}{9.81\times D^5}\times0.407$$

$$2.94 = \frac{0.811\times0.04\times277778\times84\times(4.459\times60)^2}{9.81\times D^5}\times0.407$$

Diameter of lateral, $D = 59.79 \approx 63$ mm

The head required to operate the lateral lines (H_m) = 24.7 + 2.94 + 2 + 1 = 30.6 m

Frictional head loss in main pipe line (H_f) = 30.6 × 0.2 = 6.12 m

Calculating in the same way as done in case of lateral,

$$6.12 = \frac{0.811\times0.04\times277778\times36\times(0.009\times1000\times60)^2}{9.81\times D^5}$$

Or, D = 69.10 ≈ 75 mm

Total design head (H) = $H_m + H_f + H_j + H_s$

Where, H_j = difference in highest junction point of the lateral and main from pump level = 0.5 m (assume); H_s = suction lift (20 m, assume); H = 30.6 + 6.12 + 0.5 + 20 = 57.22 m

The pump has to deliver 0.009 m^3/sec of water against a required head of 57.22 m.

Hence, the horse power of a pump with 60% efficiency.

$$= \frac{0.009 \times 57.22 \times 10^3}{0.6 \times 75} = 11.44\ hp$$

Example 4

Determine the uniformity coefficient from the following data obtained from a field test on a square plot bounded by four sprinklers:

Sprinkler : 4.365 × 2.381 mm nozzles at 2.8 kg/cm^2

Spacing : 24 m × 24 m

Wind : 3.5 km/ hr from south- west

Humidity : 42%

Time of test: 1.0 hour

Table 8.4: depth of water collected in cans			
S	8.9	7.6	6.6
8.1	7.6	9.9	10.2
8.9	9.1	9.1	9.4
9.4	7.9	9.1	8.6
S	7.9	6.6	6.8

S indicates the location of sprinklers.

Solution: The computations are shown in the below Table:

$$\text{Mean} = \frac{178.0}{21} = 8.48$$

$$C_u = \left\{1 - \frac{\sum \|x\|}{m.n}\right\} \times 100$$

$$= \left(1 - \frac{17.4}{178.0}\right) \times 100$$

= (1- 0.0977)

= 90.23%

Uniformity computation				
Observation	**Frequency**	**Application rate × frequency**	**Numerical deviations**	**Frequency × deviations**
10.2	1	10.2	1.6	1.6
9.9	1	9.9	1.3	1.3
9.4	2	18.8	0.8	1.6
9.1	4	36.4	0.5	2.0
8.9	3	25.7	0.3	0.9
8.6	1	8.6	0.0	0.0
8.3	1	8.3	0.3	0.3
8.1	1	8.1	0.5	0.5
7.9	2	15.8	0.7	1.4
7.6	2	15.2	1.0	2.0
6.8	1	6.8	1.8	1.8
6.6	2	13.2	2.0	4.0
	21	**Mn = 178.0**		**∑X = 17.4**

The uniformity co-efficient is 90.23%.

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Land Resource Inventory Based Crop Planning to Mitigate Abiotic Stresses

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Introduction

Land is a vital natural resource, both for the survival and prosperity of humanity and maintenance of all terrestrial ecosystems. The limits of land resources are finite whereas human demands on them are ever increasing. Fertile land in rural areas becomes scarcer due to population growth, pollution, erosion and desertification, effects of climate change, urbanization, etc. Climate change has been recognized as the single most challenge that humans and the mother Earth is facing today. The problems would further aggravate in the years to come if no corrective measures are taken. This change has happened due to years of over exploitation of natural resources, faulty practices in agriculture and industries. On the other hand, plants are constantly subjected to various biotic and abiotic stresses, from their planting time up to the harvesting, transport, till storage, exerting deleterious harmful effects on crop health as well as cause huge losses to their production worldwide. To combat these stress factors, researchers all around the globe are involved in procuring management practices ranging from traditional genetics and breeding techniques to present day available novel biotechnological tools. Use of micro-organisms is one such method by which both abiotic and biotic stress can be tackled in an economical, eco-friendly and successful manner.

For the purpose, information on natural resources is one of the most important requirements for resource planning of vulnerability assessment. It is well known that the most important link between farming practices and sustainable agriculture is health of soils that needs regular monitoring. A soil information system can provide a platform for monitoring the changes in soil properties induced by dynamic land use changes. On the other hand, Abiotic stress factors are recognized as major environmental threats to productivity and quality of crop plants. A number of prevalent abiotic stresses reported to occur around the world include drought, salinity, extreme temperatures, flooding, and nutrient deficiencies.

Under these circumstances, the Land Resource Inventory (LRI) is very helpful in monitoring the area highly susceptible to adverse environmental changes, caused by climate change and providing the basis for planning for mitigating strategies. For the purpose, it provides two sets of data i.e. inventory of five physical factors (rock, soil, slope, erosion type severity and vegetation) which is the basis of assessing land resources bio-physical information and evaluation of the potential with particular emphasis on farm planning for sustained agriculture production (land use) in the long term. Land use capability (LUC) is a system of arranging different kinds of land according to its capacity to support long-term sustained production after taking into account the physical limitations of the land. This helps in delineating the areas under particular stress and the crop planning accordingly. Green revolution witnessed a substantial increase in food production and to turn these agricultural achievements towards evergreen revolution, the role of frontier technologies like land resource inventory using Remote sensing, Geographic Information System (GIS) and Global Positioning System (GPS) becomes important. India is blessed with a wide range of soils, geology, topography, physiography, climate, water resources and considered as a museum of many crops and soil resources as 9 out of 12 soil orders. For instance, Landsat thematic map FCC image on 1:250,000 scale was used for mapping salt affected soils of Haryana. From that it could inferred that total of 1.64 lakh ha area is affected by soil salinity and alkalinity. Using remote sensing technology characterization and classification of salt affected soils could be achieved with considerably lesser amount of ground truth which will enable better planning and efficient management of these soils (Sharma and Bhargava, 1993). Similarly, Information on the existing land use land cover pattern and its distribution is a pre-requisite for better understanding of land aspects and also plays a vital role in developmental planning (Thilagam and Sivasamy, 2013). Land resource inventory is a major tool in identifying the major issues of abiotic stresses and problem areas where proper mitigation strategies may be drafted for better crop planning for upgrading the socio-economic condition of the farmers.

The growing demand associated by the growing population is a big challenge and increasing pressure on land resources. It becomes necessary for land use planning to look into the planning systems and identify the issues.

Key challenges

The land area of India is 328.73 million hectares with a population of about 1.2 billion. The land use break-up shows that the net sown area in the country has increased from 41.77% to 46.28%, the forest area has increased from 14.24% to 22.89%, and the area under non-agriculture use, which includes industrial complexes, transport network, mining, heritage sites, water bodies, and urban and rural settlements, has increased from 3.29% to 8.67% during 2010-11, as compared to 1950-51. On the other hand, during the same period (1950-51 to 2010-11), the barren and unculturable land, other uncultivated land, and fallow lands have drastically decreased by nearly half from 40.7% to 22.17%.

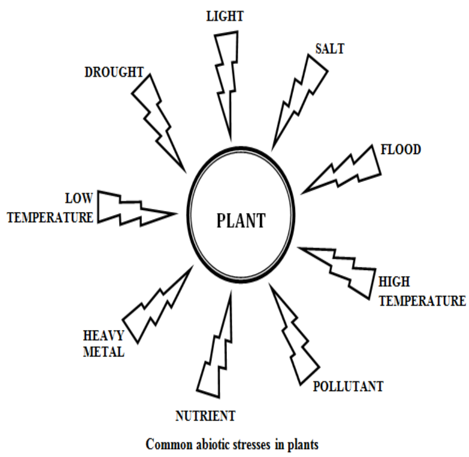


Fig. 9.1: Common abiotic stresses in plant

Universally urbanization is defining the global phenomenon of this century. For the first time in history, more than half the world’s population lives in urban areas and it is taking place at a faster rate in India. Population residing in urban areas in India, according to 1901 census, was 11.4%. This count increased to 28.53% according to 2001 census, and crossing 30% as per 2011 census, standing at 31.16%. About 34% of India's population now lives in urban areas, the U.N. World Urbanization Prospects 2018 report has said. This is an increase of about three percentage points since the 2011 Census (The Hindu, 2018). Between 2000 and 2030, in developing countries, the urban population is expected to be doubled, and entire built-up areas are projected to be tripled if current trends continue. This rapid demographic and spatial transformation may prove to be difficult for cities in developing countries, especially small and medium sized cities, where capacity is typically inadequate to cope with major urban challenges. These challenges include climate change, resource scarcity, slum growth and increased poverty, and safety and security concerns, ultimately encouraging land degradation to a significant magnitude. It is a matter of great concern that about 57 per cent of the total geographical area of the country is suffering from various forms of land degradation (NBSS Publ-106).

Urban land use planning, if planned judiciously and led by designed policies taking into consideration the sustainable development principles and supported by well-planned and well-managed initiatives can help addressing these challenges. Current and emerging needs in land resource planning for food security, sustainable livelihoods, integrated landscape management and restoration.

Land use planning

This is the systematic assessment of land potential and alternatives for optimal land uses and improved economic and social conditions through participatory processes that are multi-sectoral, multi-stakeholder and scale dependent. The purpose of land-use planning is to support decision makers and land users in selecting and putting into practice those land uses that will best meet the needs of people while safeguarding natural resources and ecosystem services for current and future generations (FAO, 2017). While planning, consideration on agriculture, forestry, livestock, fisheries, natural resources, etc. becomes important. Surface, ground and rainwater resources need to be managed in order to preserve and protect the productivity of soil base to enhance and achieve the sustainable crop productivity.

The food demand is growing, keeping a huge pressure on natural resources. There is a need for significant changes considering proper land use planning to attend to current issues for sustainable food production and agriculture. FAO has been a key player in land resource planning for many years and FAO (2014) identified five interconnected principles for the transition toward sustainable food and agriculture. Some of the major challenges related to land resource utilization are summarized below:

- Land is a limited resource and has pressure from social, economic and environmental needs, including urbanization, industrialization, mining, transportation, rural development, protection of environmentally sensitive zones and resource areas etc.

- There are competing land uses for the same parcel of land for their location, for example agriculture use versus industrial or commercial or residential use, mining versus other land uses.
- There are conflicting land uses, for example an eco-sensitive zone adjoining a chemical industrial park.
- There are negative impacts from improper or lack of land use planning causing social conflicts and protests against land acquisition, pollution and negative environmental impacts, over exploitation of resources, climate change and disaster risks.

Principles of land use planning

1. To encourage agricultural operations and ensure the preservation of the productivity, availability, and use of agricultural lands for continued production of agricultural products.
2. Preserve the natural, historic, recreational and scenic values, along with the healthy economy of the forested land and resource preservation districts so as to ensure that development in those areas is in conformance with their natural beauty and environmental limitations.
3. Protect natural resources, including soil, water, air, viewsheds, scenery, and fragile ecosystems.
4. Encourage residential development in designated growth areas.
5. Preserve and protect the historic character and features of the County.
6. Ensure that the provision of capital improvements including schools, parks, roads, and sewer and water service enhances the quality and character of rural and open-space environments.
7. Promote only economic growth that assists in maintaining our existing balance and is compatible with the environmental quality and rural character and does not adversely affect active farm operations, forestry operations, residential neighborhoods, the tourist industry, and the county's fiscal stability.
8. Protect the county's fiscal capabilities.
9. Encourage citizen involvement in the planning process.

Role of land use planning and management

Land use planning and other land use management programs can have a major influence on the future mosaic of natural landscapes. On private lands, land use planning and management is largely delivered through municipalities and conservation authorities, based on authority provided through provincial legislation, particularly the planning Act.

Land use planning as a solution

Land resource is put to different uses and some land uses attract other uses. For example, an industrial estate attracts other land uses such as transportation, housing areas, trade and commercial areas, waste wastewater treatment installations etc. These different uses interact and may compete or conflict with one another. For example, air pollution and disaster risks from industries can potentially pose threats to the housing areas. Therefore, all such uses are required to be planned and managed in an integrated manner.

Land management and invasive weeds

The Bureau of Land Management (BLM) has prepared this Integrated Weed Management Plan (IWMP) and draft programmatic environmental assessment (EA) to address potential environmental consequences associated with the control and/or eradication of noxious and invasive weeds, and to identify potential resource protection measures that would mitigate potential adverse impacts.

Weed management is a system approach whereby whole land use planning is done in advance to minimize the invasion of weeds in aggressive forms and give crop plants a very strong competitive advantage over the latter.

Land resources

The land resources data base contains two layers of information on physical resources which allows the creation of unique ecological land units (agro-ecological cells) within which soil, landform and climatic conditions are quantified. The climatic resource's part consists of three separate thematic layers: The thermal zones layer, the length of growing period zones layer and pattern of number of length of growing period zones layer. The soil resources layer includes information of soils, landform and geology/parent materials. Subsequent to digitizing, the soil map unit composition of each mapping unit and the associated edaphic conditions have been incorporated.

Land resource planning and sustainable land management (SLM)

SLM is "the use of land resources, including soils, water, animals and plants, for the production of goods to meet changing human needs, while simultaneously ensuring the long-term productive potential of these resources and the maintenance of their environmental functions" (United Nations, 1992). It includes a range of complementary measures adapted to the biophysical and socio-economic context for the protection, conservation and sustainable use of resources (e.g. soil, water and biodiversity) and the restoration or rehabilitation of degraded natural resources and their ecosystem functions. Promising SLM options are available to sustain various productive land uses. It also provides options for managing soil, water and plants and the ways these interact under a given set of biophysical and socio-economic conditions.

Crop plants and abiotic stresses

Crop plants encounter environmental stresses, both abiotic and biotic stresses. Abiotic stress has main impact on the crop productivity, reducing average yields for major crop plants. These abiotic stresses are interconnected as osmotic stress, resulting in the disruption of ion distribution and homeostasis in the cell. It is mainly due to changes in the expression patterns of a group of genes, leads to responses that affect growth rates, productivity.

Human activities and land use determine the sustainability of land resources (FAO, 2017b): Information on natural resources is one of the most important requirements for resource planning of any country. It is well known that the most important link between farming practices and sustainable agriculture is health of soils that needs regular monitoring. A soil information system can provide a platform for monitoring the changes in soil properties induced by dynamic land use changes. On the other hand, Abiotic stress factors are recognized as major environmental threats to productivity and quality of crop plants. A number of prevalent abiotic stresses reported to occur around the world include drought, salinity, extreme temperatures, flooding, and nutrient deficiencies.

Cold stress is one of the main abiotic stresses that limit agricultural crop productivity by affecting their quality and post-harvest life as observed in Cold Arid region of Ladakh because most temperate plants acquire chilling and freezing tolerance upon their exposure to sub-lethal cold stress, a process called cold acclimation. Soil salinity is a worldwide problem and poses a serious threat to entire world agriculture, because it reduces the crop yield in the affected areas. Nearly, one billion hectares of arid and semi-arid areas of the world are salt-affected and remain barren due to salinity or water scarcity. Nearly, one billion hectares of arid and semi-arid areas of the world are salt-affected and remain barren due to salinity or water scarcity. In India, about 6.75 Mha lands are either sodic or saline in nature and 6.41 Mha land is degraded due to waterlogging (Dagar, 2015). Under such conditions, identification of suitable salt-tolerant species for a specific situation and cataloguing of salt tolerant species describing their distribution with respect to ecoclimate, habitat, and soil salinity becomes important, making strategic possibility through land resource inventory database. Geospatial technologies (Remote sensing, GIS and GPS) have demonstrated the potential to generate faster, cheaper and reliable spatial data on natural resources (Shrivastava, 2016).

Table 9.1: State wise distribution of salt affected soils in India (000 ha)

States	Sodic	Saline	Total
Andhra Pradesh	196.6	77.6	274.2
Andaman & Nicobar Islands	0	77.0	77.0
Bihar	105.9	47.3	153.2
Gujarat	541.4	1,680.6	2,222.0
Haryana	183.4	49.2	232.6
Jammu & Kashmir	17.5	0	17.5
Karnataka	148.1	1.9	150.0
Kerala	0	20.0	20.0
Madhya Pradesh	139.7	0	139.7
Maharashtra	422.7	184.1	606.8
Odisha	0	147.1	147.1

Punjab	151.7	0	151.7
Rajasthan	179.4	195.6	375.0
Tamil Nadu	354.8	13.2	368.0
Uttar Pradesh	1,347.0	22.0	1,369.0
West Bengal	0	441.3	441.3
Total	**3,788.2**	**2,956.9**	**6745.1**

(Source: Mandal et al. (2010). (Based on NRSA data of 1996 and reconciled during 2006 jointly by NRSA, CSSRI and NBSS & LUP, Nagpur) Exact figures may slightly differ because of rounding off the data)

Increased dependency of agriculture on chemical fertilizers and sewage wastewater irrigation and rapid industrialization has added toxic metals to agricultural soils causing harmful effects on soil-plant environment system.

Global climate changes are leading to increases in temperature and atmospheric CO_2 levels as well as disturbance in rainfall patterns. Prolonged periods of in-appropriate rainfall led to drought, causing premature plant death, while intermittent drought conditions affect the plant growth and development but are not usually lethal. High temperature has become a global concern, which seriously impacting the growth and production of crops. In near future, the vulnerability of crop plants will increase with increasing high temperature variation.

The land to sea temperature gradient during the monsoon is regarded as the main driving force behind the monsoon circulation over the Indian subcontinent (Meehl, 1994). Over land regions of the Indian subcontinent, the area averaged annual mean surface temperature rise by the end of this century is projected, ranging between 3.5 and 5.5°C. During winter, the area averaged surface temperature increase over India by 2080s would be at least 4°C, while during monsoon, it might range between 2.9 and 4.6°C. The projected surface warming is more pronounced during winter than during monsoon season. The spatial distribution of annual mean surface warming over the Indian subcontinent by 2050s suggests that north India may experience an annual mean surface warming of 3°C or more, depending upon the future trajectory of anthropogenic forcing. The spatial pattern of temperature change has a large seasonal dependency. The model simulates peak warming of about 3°C over north and central India in winter (Lal, 2001).

Climate change projections for India

Table 9.2: Climate change projections for India

Year	Season	Temperature change (°C)		Rainfall change (%)	
		Lowest	Highest	Lowest	Highest
2020s	Annual	1.00	1.41	2.16	5.97
	Rabi	1.08	1.54	-1.95	4.36
	Kharif	0.B7	1.17	1.B1	5.10
2050s	Annual	2.23	2.87	5.36	9.34

	Rabi	2.54	3.18	-9.22	3.82
	Kharif	1.81	2.37	7.18	10.52
2080s	Annual	3.53	5.55	7.48	9.90
	Rabi	4.14	6.31	-24.83	-4.50
	Kharif	2.91	4.62	10.10	15.18

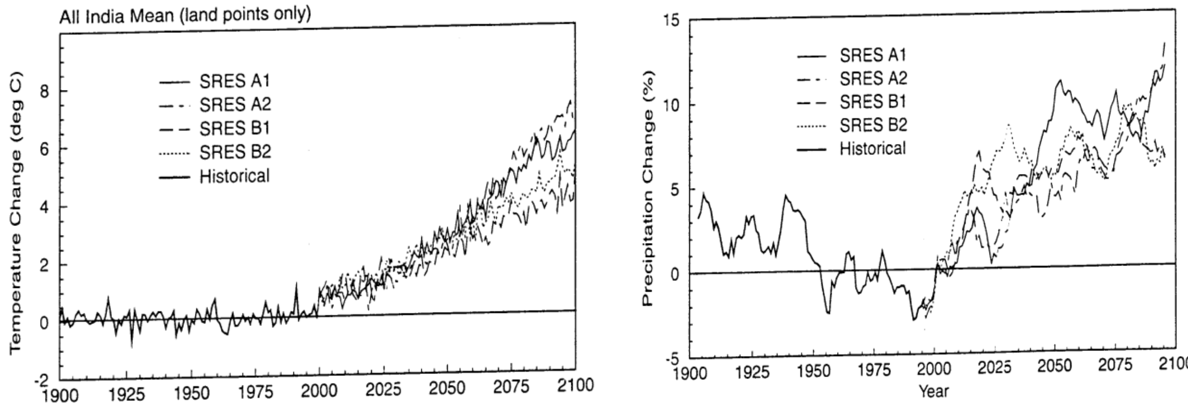


Fig. 9.2: Trends in annual mean area-averaged temperature change (with respect to 1961-90 period) and rainfall change (in%, 10-year running mean) over the land regions of Indian subcontinent as simulated by the model under the four SRES 'Marker' forcing scenarios (Source: Lal, 2001)

Farmers' challenges

Cost of inputs has increased, Soil has lost its physical, chemcial, biological characters, declined ground water, loss of traditional seeds/local biodiversity, biotic and abiotic stresses. Small and marginal farmers with less than two hectares of land account for 86.2% of all farmers in India, but own just 47.3% of the crop area.

Small Farmers: The core of Indian agriculture

- 17.6% of the world's human and 15% livestock population and counting
- 4.2% of the world's water
- 2.4% of the world's area
- 142 m ha cultivated & 63.6 m ha net irrigated
- 140% cropping intensity

Abiotic stress management - a crucial component of land-use planning

It is key to fostering sustainable and resilient landscapes in the face of climate change and environmental pressures. Abiotic stresses, which include drought, salinity, flooding, and extreme temperatures, significantly impact agricultural productivity, food security, and ecosystem health. By integrating stress management strategies into land-use planning, communities can minimize environmental degradation and proactively address future risks.

Role in shaping land-use decisions

Abiotic stress management plays a crucial role in land-use planning by providing a framework for aligning land uses with specific environmental conditions. This approach enables planners to make informed decisions that enhance sustainability, resilience, and productivity.

Key applications

- **Determining agricultural viability**

Assessing regional vulnerabilities to abiotic stresses such as drought, salinity, and temperature extremes allows planners to identify areas best suited for agricultural use. In arid regions, drought-tolerant crops can be promoted, while coastal zones may favor salt-tolerant varieties, ensuring sustainable food production under changing climatic conditions.

- **Informing urban development**

Urban planning can integrate resilient green infrastructure—such as green roofs, urban parks, and permeable landscapes to reduce the urban heat island effect and manage stormwater. Selecting plant species capable of withstanding high temperatures and poor soil quality is key to maintaining urban ecosystem health.

- **Protecting and restoring ecosystems**

Land-use plans should include strategies for conserving and rehabilitating critical ecosystems, such as wetlands, which act as natural flood buffers and enhance water retention. Preserving biodiversity also safeguards the genetic resources necessary for developing plant varieties adapted to future environmental challenges.

- **Strengthening climate adaptation**

Effective land use planning supports local climate adaptation by accounting for regional climate risks. This includes managing water resources in drought-prone areas, relocating development away from floodplains, and designing adaptive strategies for vulnerable communities.

Key strategies for integrating abiotic stress management in land use planning

Water management

- **Efficient irrigation systems:** Adopt precision technologies such as drip irrigation to conserve water and optimize agricultural productivity.
- **Water harvesting and retention:** Incorporate rainwater harvesting and urban retention basins to maintain water availability during dry seasons.
- **Flood mitigation:** Enforce zoning regulations that restrict floodplain development and promote nature-based flood management solutions.

Soil management

- **Conservation agriculture:** Practices such as no-tillage, cover cropping, and mulching enhance soil organic matter and water retention.
- **Nutrient management:** Integrated soil fertility management using biofertilizers and organic matter improves soil structure and nutrient cycling.
- **Soil restoration:** In areas affected by salinity or contamination, land-use plans can integrate soil reclamation and bioremediation using resilient plants and microbes.

Biodiversity and urban greenery

- **Selection of tolerant species:** Incorporate plant varieties with genetic tolerance to heat, drought, or salinity in agricultural and urban landscapes.
- **Agroforestry systems:** Integrate trees and shrubs into farmlands to create microclimates, reduce heat stress, and prevent soil erosion.
- **Green infrastructure:** Develop connected networks of green spaces, urban forests, and green roofs to enhance ecological resilience and support biodiversity.

Governance and technology

- **Integrated planning:** Foster coordination among sectors such as agriculture, forestry, water management, and urban development.
- **Stakeholder engagement:** Encourage inclusive participation of local communities to co-develop adaptive and context-specific strategies.
- **Precision agriculture and monitoring:** Utilize technologies like satellite sensing, AI, and remote monitoring to track abiotic stress indicators and support data-driven decision-making.

Land degradation

Soil erosion and land degradation are among the glaring environmental problems posing a big threat to the natural resources adversely affecting soil productivity (Singh 2008). "Land degradation" refers to a temporary or permanent decline in the productive capacity of the land (UNEP, 1992b). It covers various forms of soil degradation, adverse human impacts on water resources, deforestation, and lowering of the productive capacity of rangelands and is one of the most important global issues for the 21st century because of its adverse impact on agronomic productivity, environment, security and overall quality of life.

Table 9.3: Harmonized area statistics of degraded lands/ wastelands of India (Mha) (Source: ICAR & NAAS, 2010)

Sr. No.	Type of degradation	Arable land	Open forest (<40% canopy)
1.	Water erosion (>10 t ha^{-1} yr^{-1})	73.27	9.30
2.	Wind erosion (Aeolian)	12.40	-
	Sub-total	85.67	9.30
3.	Chemical degradation		

	a) Exclusively salt-affected soils	5.44	-
	b) Salt-affected and water- eroded soils	1.20	0.10
	c) Exclusively acidic soils (pH <5.5)	5.09	-
	d) Acidic (pH <5.5) and water- eroded soils	5.72	7.13
	Sub-total	17.45	7.23
4.	Physical degradation		
	a) Mining and industrial waste	0.19	-
	b) Water-logging (permanent) (water table within 2 m depth)	0.88	-
	Sub-total	1.07	-
	Total	104.19	16.53
	Grand total (arable land and open forest)	**120.72**	

Table 9.4: Extent of salt affected and water logged soils in India (ha)

States	Saline	Sodic	Total	Water logged
Andhra Pradesh	77598	196609	274207	0.43
Andaman & Nicobar Island	77000	0	77000	-
Bihar	47301	105852	153153	0.35
Gujarat	1680570	541430	2222000	0.17
Haryana	49157	183399	232556	0.23
Karnataka	1893	148136	150029	0.05
Kerala	20000	0	20000	0.08
Madhya Pradesh	0	139720	139720	0.06
Maharashtra	184089	422670	606759	0.02
Orissa	147138	0	147138	0.18
Punjab	0	151717	151717	0.30
Rajasthan	195571	179371	374942	0.18
Tamil Nadu	13231	354784	368015	0.61
Uttar Pradesh	21989	1346971	1368960	0.59
West Bengal	441272	0	441272	0.29
Total	**2956809**	**3770659**	**6727468**	**3.55**

Role of land use planning and management

Land use planning and other land use management programs can have a major influence on the future mosaic of natural landscapes. On private lands, land use planning and management is largely delivered through municipalities and conservation authorities, based on authority provided through provincial legislation, particularly the planning Act.

To understand, crop planning, it becomes important to know what is Land Use Planning (LUP) (FAO, 1993) is the systematic assessment of physical, social and economic factors in such a way as to encourage and assist land users in selecting land use options that is an interactive and continuous process of development; requires flexibility, is problem oriented, is area specific and involves all stakeholders. Or can be defined as "Systematic and iterative procedure carried out in order to create an enabling environment for sustainable development" of land resources which meets people's needs and demands.

The need and relevance of undertaking Land Resource Inventory of the country on different scale say 1:10000 scale is to generate resource base information required for situation-specific agricultural land use planning and management of land resources (Singh, 2016).

Land resource inventory

Land resource inventory and mapping play a vital role in resource planning and management to assess its potential and limitations for wide range of land use options and formulate sustainable land use plans to meet the ever increasing demand for food, fodder and fuel production. Further, land resource inventory is necessary to deal with the issues of sustainable land resource management and land use planning, food security and assess the impact of climate change on soil resources and their sustainability. The integrated remote sensing and Geographic Information System (GIS) applications have immense potential in land resources inventory, mapping and generation of spatial databases for better planning, management, monitoring and implementing the land use plans more efficiently at different levels. In India, ICAR-National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), the premier institute in soil resource inventory and mapping is being used various satellite remote sensing products in soil resource inventory and mapping at different scales ranges from 1:250,000 to 1:4,000 scale depending upon the objectives and scale of mapping. These advancements provide accurate, timely, relevant information in cost effective and time efficient manner on real time basis. The information generated through land resource inventory on climate, soils and water resources, cropping systems, land use pattern, production and productivity, vegetation, socio-economic profile of the region, etc., could be effectively used to assess land capability, land irrigability, crop suitability, delineation of land management units and evaluate the alternative land use options (Reddy et al , 2018). Land use planning is carried out at different levels viz. national or state, district or tehsil, and village (local)/ farm or watershed levels keeping in view the goals and available resources.

The Land Resource Inventory (database of physical land resources) provides two sets of data:

- Land Resource Inventory (LRI) - inventory of five physical factors (rock, soil, slope, erosion type & severity, and vegetation) which is the basis of assessing land resources.
- Land Use Capability classification (LUC) - evaluation of the potential with particular emphasis on farm planning for sustained agriculture production (land use) in the long term. LUC is a system of arranging different kinds of land according to its capacity to support long-term sustained production after taking into account the physical limitations of the land.
- The information to be collected for Land Use Planning (LUP) can be broadly categorized as:

- Bio-physical information
- Socio-economic information
- Environmental information

Spatial and spectral resolution of remote sensing data plays an important role in determining the scale of mapping. The coarse resolution data from IRS LISS-I, WiFS, AWiFs and LANDST-MSS sensors have been used by NBSS&LUP, Nagpur to prepare maps on 1:250,000 scale or smaller. To map soils on 1:50,000 scale, medium resolution remote sensing data from LANDSAT-TM, IRS LISS-II/LISS-III and POT-MLA (Prasad, 2016).

Table 9.5: High, medium and coarse resolution remote sensing based systems in land resource inventory

Satellites	Purpose	Country
High resolution images (Spatial resolution: 1 – 15 m)		
WorldView-2	Precision on agriculture	India
IRSIC/IDPAN+L	Resource management	India
Resourcesat-1+Cartosat-1	Soil fertility assessment	India
Cartosat -1	Soil Resource Inventory	India
IRS-P6-LISS IV	Watershed prioritization	India
IRS-P6, LISS III, LISS IV	Soil mapping	India
IKONOS	Soil Mapping	India
IRS-P6-LISS IV	Waste land mapping	India
IRS-P6-LISS IV	Resource inventory of Hilly terrain	India
LiDAR	Natural resource inventory	Philippines
ASTER–Level-1A	LULC mapping	Turkey
Medium resolution images (Spatial resolution: 15 – 30m)		
Landsat ETM + DEM	Physiography mapping	Egypt
Landsat ETM	Soil Mapping	Thailand
IRS-P6- LISS III	Land degradation mapping	India
IRS-P6- LISS III	LULC mapping	India
Coarse resolution images (Spatial resolution: 30 m and above)		
Landsat TM and ETM+	Climate analysis	Romania
Hyperspectral image	Soil mapping	France
SRTM + Nigersat	Terrain analysis	Nigeria
ASTER	Lithological mapping	Egypt

Table 9.6: Abiotic stresses encourage biotic stresses i.e. infiltration of invasive weeds and occupying specific locations in India

Weed species	Region/ States	Impact on
Parthenium hysterophorus	All states (Throughout the country)	Replacing native species and crop yields (more than 80%)
Eichhornia crassipes	All states	Water bodies
Phalais minor	Punjab, Haryana, Himachal Pradesh, UP, MP Bihar	*Rabi* crops and wheat particularly (20-40%)
Mikania micrantha	North East Region, Kerala, West Bengal, Orissa	Forest cover
Lantana camara	Himachal Pradesh, North East Region, Karnataka, Tamil Nadu	Hilly tracks, Railway tracks
Chromalaena odorata	Kerala, Karnataka, Tamil Nadu, North East Region	Forest cover
Cuscuta sp	Orissa, Madhya Pradesh, Chhattisgarh	Trees and shrubs
Ipomea carnea	Andhra Pradesh, North East Region, West Bengal, Orissa, Bihar	Culverts

Alternanthera philoxeroides	All water bodies	Water bodies

Steps in crop planning of a particular site using land resource inventory

- Slope
- Landform-soil relationship with Land use/ land cover
- Soil resource characterization
- Physical and chemical properties of soils
- Soil map legends- Brief description of soil, Soil map units under different soil series with area considering the profile, its depth, water holding capacity, fertility status
- Soil and water conservation measures with problems identification, erosion, irrigatability, its potential, etc.
- Land use capability, where soils are grouped into various classes with their extent and distribution excluding habitation, rivers and other landforms
- Soil suitability for major crops
- Socio-economic data collection modules and indicators used in land use planning

Table 9.7: Soil-capability evaluation

Cultivation parameters	LCC	SI	RPI	FK
Intensive soil cultivation	I	1	P1	S1
Moderate soil cultivation	II	2	P2	S2
Limited soil cultivation	III	3	P3	
Occasional soil cultivation	IV	4		S3
Grazing	V, VI	5	P4	N
Forestry	VII	6	P5	
Natural reserves	VIII			

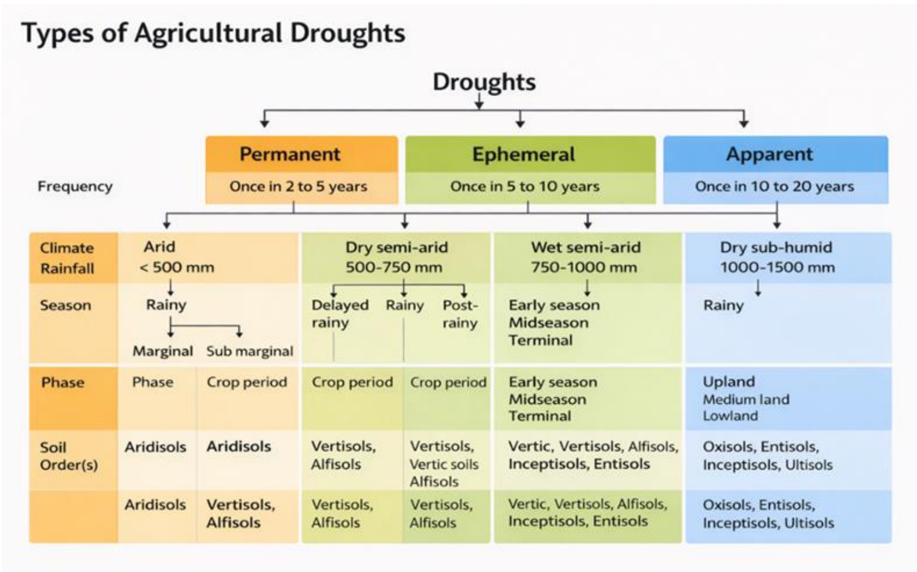
Table 9.8: USDA land use capability classes

Attributes	Symbol	Description or concern
Class (1)	I	Few Limitations
	II	Some limitations
	III	Severe limitations
	IV	Very severe limitations
	V	Require special management
	VI	Limited to pasture, range, woodland
	VII	Severe restrictions for any use
	VIII	Non-agricultural
Sub-class	e	High erosion risk
	w	Wetness limitations
	s	Soil property limitation
	c	Climate limitation
Unit	1 through 10 the most soil limiting factor	
1. concerns sustained agricultural production with minimum erosion		

Table 9.10: Data and information for land use planning	
Data	**Information**
Land resource data	• Climate • Land forms and Soils • Land Cover • Land Resources
Land use related data	• Present Land Use and Characteristics • Selected Physiological Characteristics of Crops (As Determining Ecological Requirements) • Land Utilization Types (LUTS) And Production Systems (Present And Potential) • Ecological Requirements of LUTS, Production Systems, Land Use
Socio-economic data	• Population (Including Age and Gender Distribution, Stakeholder) Living Conditions (Including Workload, Cultural Aspects, Traditions, Etc.) • Access To Markets • Costs Of Production And Product Prices Socio-Economics of Communities
Land Legal data and information	• Relevant Government Policy Documents, Laws And Regulations Related To Land • Present System of Land Allocation Land Tenure Information • Traditional Ownership And User Rights
Institutional information	• Involved Institutions And Their Mand ates, Resources And Infrastructure • Links Between Institutions • Support Services (Extension, Etc.)
General data and information	• Infrastructure, Accessibility

Possible interventions

Considering stress factors, drought and salinity are the most significant issues threatening agricultural production on a global scale. It is estimated that the total economic value of loss caused by drought and heat globally is about 1.3 billion, and due to cold is about 18.6 million. But conventional and non-conventional methods have been suggested and information on stress tolerant plant is accumulating.



Drought-tolerant crop cultivars

- Paddy - Abhishek, Anjali, Sahbhagi Dhan, Naveen, Prabhat, Turanta Dhan, Birsa Vikas Dhan
- Sorghum - Co-16
- Bottle Guard - Warad (drought coping strategy)
- Fingermillet - ML-365, GPU-48 (short duration)
- Ground nut - TARM-1, GG-5 (short duration for late sown)
- Blackgram variety - Azad-1
- Soybean variety - JS 9305, JS-95-60
- Short and medium duration fodder cultivars of several crops that can withstand up to 2-3 weeks of exposure to drought in rainfed areas (sorghum (Pusa Chari Hybrid-106 (HC-106), CSH 14, CSH 23 (SPH-1290), CSV 17); Bajra (CO 8, TNSC 1, APFB 2, Avika Bajra Chari (AVKB 19); Maize (African tall, APFM 8)
- Cultivars of rabi crops like Berseem (Wardan, UPB 110) and Lucerne (CO 1, LLC 3, RL 88) were demonstrated in NICRA villages as second crop with the available moisture during winter. Perennial fodders like APBN-1, CO-3 and CO-4 were also demonstrated under limited irrigated conditions
- Farmers in Yagnantipalle village became self-sufficient in seed of foxtail millet (SIA 3805) and successfully switched over to its cultivation instead of risky crops like cotton due to occurrence of prolonged dry spells.

Drought-tolerant crop cultivars resist crop yield losses in drought-prone areas. Thus, deep understanding of pertinent drought-tolerance-associated agronomic traits and of their interrelationships in target environments is indispensable to cultivar development. Such associations can reveal direct and/or indirect selection criteria for crucial traits of economic importance. Some physiological traits of barley, associated with low-moisture stress, are water-soluble carbohydrate concentration (WSC) and relative water content (RWC) (Li et al., 2013; Teulat et al., 2003), late leaf senescence (Guo et al., 2008; Sayed et al., 2012), osmotic adjustments (Blum, 1988; Diab et al., 2004; Teulat et al., 2001a), chlorophyll content, initial fluorescence (Fo), maximum fluorescence (Fm), variable fluorescence (Fv), and maximum quantum efficiency of PSII (Fv/Fm) (Guo et al., 2008) and yield-related traits (Von Korff et al., 2008).

Salt tolerant varieties of rice, wheat and mustard

These promising varieties have been developed which can be grown either without or with half the recommended dose of amendments.

Rice : CSR 10, CSR 13, CSR 23, CSR 27, CSR 30 and CSR 36

Wheat	:	KRL 1-4, KRL 19, KRL210 and KRL213
Mustard	:	CS 52, CS 54 and CS 56

Table 9.11: Ameliorating effects of mesquite and other tree plantations on an alkali soil

Species	Original		After 20 years	
	pH	OC (%)	pH	OC (%)
Eucalyptus	10.3	0.12	9.18	0.33
Tereticornis				
Acado nilotica	10.3	0.12	9.03	0.55
Albizia lebbek	10.3	0.12	8.67	0.47
Terminalia arjuna	10.3	0.12	8.15	0.47
Prosopis juliflora	10.3	0.12	8.03	0.58

Table 9.12: Change in soil properties (0-30 cm) under different tree-crop combinations in 5 years

Land use systems	**Organic carbon (%)**	**Available N (kg/ ha)**
Crop based system	+0.07	+10
Eucalyptus based	+ 0.12	+21
Acacia based	+0.20	+ 31
Populus based	+0.17	+ 2S

In general, it is difficult to build organic carbon in soils where summer temperature exceeds 40-45 °C. However, integration of trees with crops in a unified agroforestry system helped building appreciable quantity of organic matter in the soil certain salt-tolerant shrub and grass species have been recognized by their incorporation in pasture-improvement programmes in many salt-affected dry regions. Considerable success has been achieved in Indian Subcontinent and elsewhere in cultivating halophytic forages such as chenopads, especially *Atriplex* in areas subject to total summer drought on badly salt-affected lands.

Halophytic forage species for alkali / saline soils even drought conditions

Salicornia, *Chenopodium*, *Kochia*, *Atriplex*, Salsala, Trianthema, Portulaca, Tribulus and Alhogi along with several grasses such as Aeluropus/ agopoides, Sporobolus (S. morginatus, S. airoides, S. diander, S. he/vo/us, s. tramulus), Cynodon dactylions, Dactyloctenium sindicum, Pospalum vaginatum, Chloris gayana, Echinochloa turnerano, E. colonum, Eragrostis ton ella, Dichanthium onnulatum, Brachiaria mutica, Bathriochloa pertusa and many others are commonly found grown naturally. Salt affected grazing lands are predominant landscapes throughout the country. Major species which contribute significant biomass as fodder in Rajasthan include: Aeluropus, Atrialex, Bothriochloa, Cenchrus, Chenopodium, Chloris, Cynodon, Dactyloctenium, Dichanthium, Eragrostis, Leptochloa, Kochia, Panicum, Salsola, Suaedo, Tribulus, Salvadora, Prosopis and Ziziphus.

Important top feed shrubs and trees include *Ailanthus excelso, Acacia nilotica*, *A. catechu*, *A. eucophloea*, *A. tortilis*, *Balanites roxburghii*, *Prosopis cineraria*, *P. juliflora*, *Azadirachta indica*, *Albizia*, *Leucaena Jeucocephala, Dahlbergian sissoo*, *Melia ozadirach*, *Hordwickia binata*, *Grewia ovata*, *Ficus bengalensis*, *F. religiosa*, *Anogeissus pendula*, *Bauhinia variegata*, *B. racemosa*, *Butea monosperma*, *Cordia dichotoma*, *Flacourtia indica*, *Moringa oleifera*, *Dichrostachys nuttiness*, *Morus alba*, *Ziziphus mauritiana* and *Z. nummularia*. The leaves of most of these trees are rich in nutrients. This type of fodder becomes more relevant during drought scarcity period.

Trees species grown on inland salty lands

Species - *Acacia*, *Prosopis*, *Salvodora*, *Cordia*, *Ailanthus*, *Balanites* and *Ziziphus* are traditional fodder plants of drought prone arid regions. Many species of Acacia (*A. cyclopes*, *bivenosa*, *haloserice*a, *saligna*, *salicina, and victoria*) and Prosopis (P. *juliflora, cineraria, chilensis, giandulosa*, *pallida and tamarugo*) are among the most promising genetic resources to be utilized in developing fodder sources in drought prone areas.

Scientific land use planning is the way out for conservation of natural resources through sustainable land management practices evolved during land evaluation process and other principles of land use planning.

Conclusions

To avoid disastrous role of climatic imbalance and sustainable agriculture development, there is a need for sustainable land use planning through agricultural and associated eco-systems services to address climate change, resource scarcity, slum growth and increased poverty, and safety and security concerns and sustainable planning. In many cases, urbanization has had dramatic effects on peri-urban zones and leads to resource degradation in peri-urban zones due to increased pressure on land resources in terms of destruction of biotopes, fragmentation of ecosystems, consequently diminishing the open space. The importance of land use planning and land use management as particular tools for sustainable land use in peri-urban zones has to be a strategic issue. Land use planning, as one of the mechanisms that have impact on the reduction of pressure on land resources, is one of the key components of sustainable land management. In accordance with that, this paper will pay special attention to basic natural and production resources in peri-urban areas – agricultural land.

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Digital Soil Mapping- The Fundamentals

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Introduction

Soil plays a vital role in addressing global environmental sustainability challenges, including food and water security, climate regulation, biodiversity conservation, and ecosystem service delivery. Accurate mapping of soil properties is essential for effective soil and land management at both global and local scales. Over recent decades, Digital Soil Mapping (DSM) has emerged as a modern alternative to conventional soil surveys, producing predictive soil maps and quantifying associated uncertainties by integrating large spatial datasets with ancillary and recent environmental data. DSM has evolved significantly with advances in computing, geographic data processing and the growing availability of environmental covariates derived from digital elevation models, remote sensing and climate data. It bridges traditional pedological knowledge with modern statistical and machine learning approaches, providing spatially continuous, reproducible, and high-resolution soil information. This makes DSM an indispensable tool for supporting decision-making in natural resource management, environmental modeling and land-use planning. However, its effective implementation still relies on the expertise of skilled pedologists combined with strong modeling and data analysis capabilities. Recognizing its importance, the Food and Agriculture Organization (FAO) has promoted DSM methodologies to generate reliable soil information for sustainable land management. Conventional soil mapping, which depends heavily on ground-based surveys, often struggles to represent soil variability at fine spatial resolutions and over large extents. Such methods are also time-consuming, costly and limited in capturing the dynamics of soil properties at national or global scales. In contrast, DSM provides a scientifically robust and cost-effective solution to predict and map soil properties across diverse landscapes. In India, the ICAR-National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur has recently advanced DSM initiatives aligned with GlobalSoilMap specifications, producing digital maps of key soil properties to enhance the national soil information system and support sustainable land-use planning.

Conventional soil mapping

Conventional soil mapping is the traditional approach used to identify, classify, and delineate soils within a given landscape based on systematic field surveys, observations and expert interpretation. This method integrates direct field sampling, visual examination of landforms, and interpretation of aerial photographs to generate soil maps that represent the spatial distribution of different soil types. It has been a cornerstone of soil survey programs worldwide for over a century and remains an essential reference for land evaluation, agricultural planning and environmental management. In this approach, soil scientists conduct extensive fieldwork to describe soil profiles, noting features such as color, texture, structure, drainage, and horizon development. These data are then linked to surface features, vegetation and topographic attributes to delineate soil boundaries. Aerial photographs and topographic maps assist in extrapolating the information from sampled points to unsampled areas. The mapped units are represented as polygons, each labelled with a soil series or mapping unit that summarizes its key physical and chemical properties. While conventional soil mapping provides valuable insights into soil variability, it is often constrained by its subjectivity, coarse resolution, and limited reproducibility. The accuracy of the maps largely depends on the surveyor's experience and the density of field observations, which can be time-consuming and expensive.

Conventional representations of soil

Conventional representations of soil are fundamental concepts used in soil science to describe and classify soils at different spatial scales. These representations namely the soil profile, pedon, polypedon, and map unit form the structural basis of traditional soil survey and mapping practices (Fig. 10.1). Each represents a distinct level of soil observation and generalization, helping soil scientists understand and communicate soil variability across the landscape.

Soil profile

It is a vertical cross-section of the soil extending from the surface to the parent material. It reveals the sequence of soil horizons that have formed through pedogenic processes such as leaching, organic matter accumulation and weathering. Describing the colour, texture, structure, and horizon boundaries of a soil profile provides insight into the soil's genesis and functional properties.

Pedon

It represents the smallest, three-dimensional body of soil that can be considered a complete unit for classification. Typically, a pedon covers an area of about one to ten square meters and extends vertically through all soil horizons. It captures the full range of soil characteristics at a point and serves as the fundamental unit in soil taxonomy and field description.

Poly-pedon

It is a group of similar pedons that occur together in a landscape and share consistent morphological and chemical properties. It represents a natural soil individual that can be recognized and delineated in the field. Polypedons form the basis for defining soil series, which are the named categories used in mapping and classification.

Map unit

It is the cartographic representation of soil variability on a map. It encompasses one or more poly-pedons with similar characteristics or associations of different soils that occur in a predictable pattern. Map units are the practical outcome of soil surveys and serve as the link between detailed field observations and broader land-use planning applications.

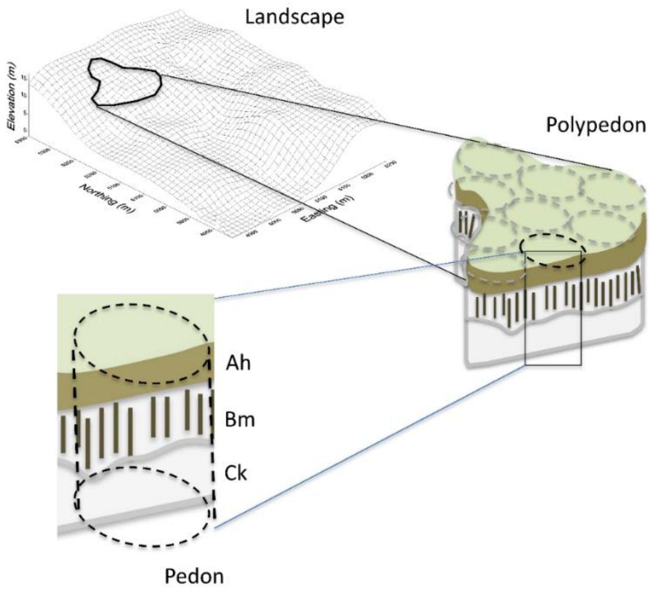

Fig. 10.1: Illustration of the concept of the soil pedon and soil poly-pedon

Limitations of conventional soil mapping

- **Time-consuming and labor-intensive**: Requires extensive field surveys, profile descriptions and manual interpretation of aerial photographs.
- **High cost**: Fieldwork, laboratory analysis, and manual cartography demand significant financial and human resources.
- **Subjectivity**: Strongly depends on the expertise and judgment of individual surveyors, leading to inconsistencies between mappers.
- **Low spatial resolution**: Maps are often produced at coarse scales, limiting their usefulness for site-specific or precision agriculture applications.
- **Limited reproducibility**: Results are difficult to replicate due to qualitative assessments and expert-based delineation of soil boundaries.
- **Static nature**: Conventional maps are not easily updated or modified to reflect land-use changes, erosion, or new data.
- **Limited data integration**: Traditional methods do not effectively incorporate modern geospatial data such as remote sensing or digital elevation models.

- **Generalized boundaries**: Soil map unit delineations are approximate and may not accurately capture fine-scale soil variability.
- **Limited accessibility**: Historical soil maps are often available only in printed form, making them less compatible with digital platforms and geographical information system (GIS) applications.
- **Reduced predictive capacity**: Lacks statistical or model-based relationships between soils and environmental variables, making extrapolation beyond sampled areas less reliable.

What is digital soil mapping (DSM)?

DSM is the generation of geographically referenced soil databases based on quantitative relationships between spatially explicit environmental data and measurements made in the field and laboratory. The digital soil map is a raster composed of two-dimensional cells (pixels) organized into a grid in which each pixel has a specific geographic location and contains soil data. Digital soil maps illustrate the spatial distribution of soil classes or properties and can document the uncertainty of the soil prediction. The scientific foundation of soil mapping is Hans Jenny's (1941) conceptual model that soils (S) on a landscape are a function of five environmental factors, namely climate (cl), organisms (o), relief (r), parent material (p), and time (t):

$$S = f(cl, o, r, p, t) \quad (1)$$

While this model, sometimes known as CLORPT, has been useful in conventional soil mapping, it is not quantitative nor spatially explicit. To represent soil and the related environmental factors in a spatial context and express these relationships quantitatively, McBratney et al. (2003)proposed the SCORPAN model, where soil (as either soil classes, Sc, or soil attributes, Sa) at a point in space and time is an empirical quantitative function of seven environmental covariates: soil (s), climate (c), organisms (o), relief (r), parent material (p), age (a), and spatial location (n):

$$Sc, a = f(s, c, o, r, p, a, n) \quad (2)$$

The important advances of the SCORPAN model for use in DSM are: (1) the recognition that the environmental factors are not necessarily independent of each other and are thus defined as environmental covariates, (2) the inclusion of soil as an environmental covariate, (3) the spatially explicit nature of the model, and (4) the quantitative nature of the functional relationships. In the SCORPAN model, soil, either as point observational data, existing soil maps, or remotely sensed spectral properties, can be used as input data. The SCORPAN model facilitates the quantification of the relationships between spatially explicit digital environmental covariates and the soil classes or attributes to be predicted in a spatial context. It also facilitates the estimation of error or uncertainty of the spatial prediction of soil classes or properties. Schematic representation of the DSM methodology used in prediction of soil properties is presented in Fig. 10.2.

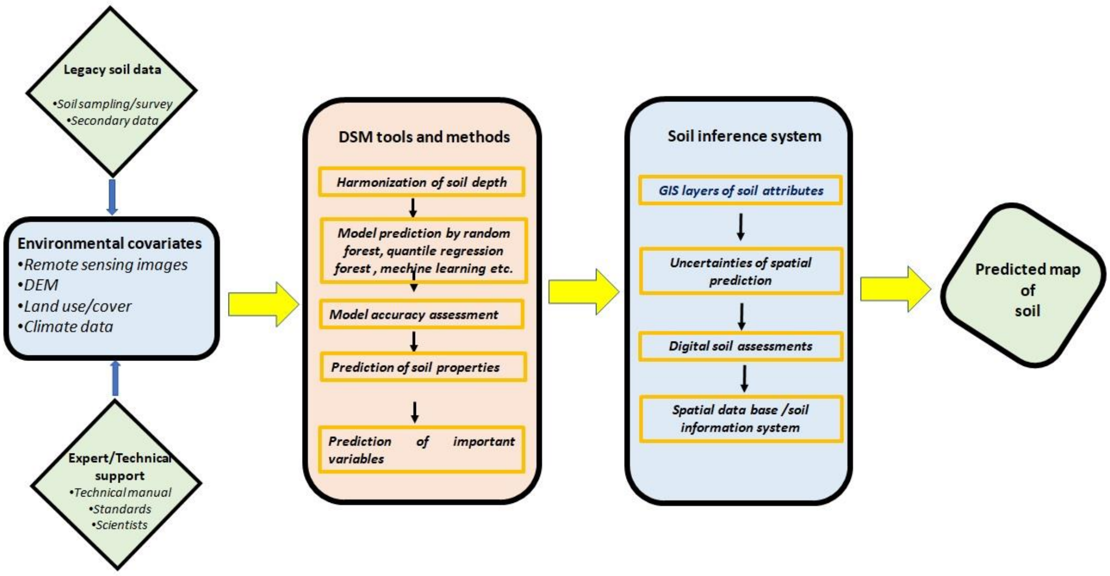

Fig. 10.2: Schematic representation of the DSM methodology used in prediction of soil properties

Difference between conventional soil mapping and digital soil mapping

Conventional soil mapping relies on field surveys, expert interpretation, and manual delineation of soil boundaries based on visible landscape features. It produces polygon-based maps that are often qualitative and limited in spatial resolution. In contrast, DSM uses quantitative models to predict soil properties and classes by linking field observations with environmental covariates derived from digital elevation models, remote sensing, and climate data. DSM employs GIS, statistics, and machine learning to generate continuous, high-resolution soil maps with uncertainty estimates. While conventional mapping is labor-intensive and subjective, DSM is data-driven, reproducible, and suitable for large-scale applications. Detailed difference between conventional soil mapping and digital soil mapping is given in Table 10.1.

Table 10.1: Difference between conventional and digital soil mapping

Aspect	Conventional Soil Mapping (CSM)	Digital Soil Mapping (DSM)
Approach	Based on expert knowledge, field observation, and manual interpretation of aerial photographs	Uses quantitative models and geospatial data to predict soil properties continuously across the landscape
Data source	Field surveys, soil profiles, and topographic or aerial maps	Remote sensing data, digital elevation models (DEMs), climate, vegetation indices, and existing soil data
Scale and resolution	Coarse-scale maps with generalized boundaries	Fine-scale maps with continuous spatial predictions at pixel level
Representation of soil	Polygons representing mapping units	Raster or gridded datasets showing spatially continuous variables
Subjectivity	Highly subjective; depends on the	Objective and data-driven, based on

	mapper's expertise	statistical or machine learning models
Update and reproducibility	Difficult to update and replicate	Easily reproducible, modifiable, and updatable with new data
Accuracy	Moderate; accuracy varies with surveyor skill and sampling density	Generally higher; accuracy assessed quantitatively through validation statistics
Time and cost	Time-consuming and expensive due to extensive fieldwork	More efficient once covariate datasets and models are established
Boundary definition	Sharp, often artificial polygon boundaries	Smooth, continuous transitions between soil types or properties
Integration with GIS	Limited compatibility with modern GIS systems	Fully integrated within GIS and spatial analysis frameworks
Output format	Printed or static digital maps	Digital raster maps compatible with online databases and decision-support tools
Usefulness in precision Agriculture	Limited due to low spatial detail	Highly suitable for precision agriculture and environmental modeling

Environmental covariate

Environmental covariates are the variables characterizing soil forming factors of climate, parent material, topography, vegetation, human activities and time. In the last decade, many efforts have been made in sifting and developing effective environmental covariates according to the targeted soil properties and landscapes. Climate and terrain factors have been widely used in DSM. Common climate variables such as air temperature and precipitation are often generated through interpolating the observations from meteorological stations. With the advance of remote sensing techniques, a recent progress is that remotely sensed surface moisture, temperature and evapotranspiration products can also be used to characterize climate conditions. The SCORPAN factors have been interpreted from aerial photography and topographic and geological maps (Table 10.2). Recent advances in remote sensing and geomorphometry have made the quantification of such ancillary information more readily accessible in formats that can be manipulated with GIS. Perhaps the most easily quantified and directly correlated state factors are relief, as digital elevation model (DEM) derivatives have been the most popular predictor (Table 10.3).

Table 10.2: Environmental covariates commonly used in DSM, classified according to the SCORPAN model

SCORPAN Factor	Type of covariate	Variables used in DSM	Typical data sources
S – Soil (existing soil data)	Legacy soil information	Soil texture, pH, organic carbon, bulk density, electrical conductivity	Soil survey databases, previous maps, national soil grids
C – Climate	Climatic conditions influencing soil processes	Mean annual temperature, rainfall, evapotranspiration, aridity index, seasonal precipitation	Weather stations, WorldClim, CHELSA, or interpolated climate surfaces
O – Organisms (biological and anthropogenic	Vegetation and land use	NDVI, EVI, land cover type, crop type, biomass productivity, management practices	Remote sensing imagery (MODIS, Landsat, Sentinel), land use maps

factors)			
R – Relief (topography)	Terrain attributes derived from DEMs	Elevation, slope, aspect, curvature, topographic wetness index (TWI), stream power index (SPI), terrain ruggedness index (TRI)	Digital Elevation Models (SRTM, ASTER, LiDAR)
P – Parent material	Geological and geomorphological characteristics	Lithology, surface geology, mineral composition, geomorphic units	Geological maps, satellite imagery, geomorphological databases
A – Age (time factor)	Soil or landscape development over time	Chrono sequence data, landform age, sediment deposition rate	Geochronological data, geomorphological studies, historical maps
N – Spatial neighborhood	Spatial position and proximity effects	Latitude, longitude, spatial coordinates, distance from rivers or roads, spatial autocorrelation indices	GIS spatial layers, geostatistical models, spatial databases

Table 10.3: Summary of important DEM-derived terrain attributes

Terrain attributes	Definition	Pedologic significance
Slope gradient (°) (SG)	Maximum rate of change (°)	Flow velocity
Slope aspect (SA)	Direction of slope gradient (°)	Flow velocity
Profile curvature (PC)	Curvature of slope gradient (radians)	Flow acceleration
Tangential curvature (radians) (TC)	Curvature perpendicular to slope gradient (radians)	Flow convergence
Multi-resolution valley bottom Flatness index (MVBFI)	Measure of flatness and lowness	Depositional environments
Multi-resolution ridge top flatness index (MRTFI)	Measure of flatness and upness	Stable uplands settings
Contributing area (CA)	Upslope area (m^2)	Effective precipitation
Specific contributing area (SCA)	CA/grid size (m)	Effective precipitation
Topographic wetness index (TWI)	ln (SCA/SG)	Water accumulation or soil saturation
Catchment height	Average upslope height	Potential energy
Catchment slope	Average upslope gradient	Flow velocity
Overland flow distance to stream	Relative topographic position (m)	Potential energy
Vertical distance to channels	Relative topographic position (m)	Cold air drainage
Solar radiation or insolation	Amount of incoming solar energy (kWh/mA^2)	Soil temperature and evapotranspiration

Global soil map project

GlobalSoilMap project is an initiative of the Digital Soil Mapping Working Group of the International Union of Soil Sciences (IUSS) and is led by academic and research centres in all continents (*GlobalSoilMap.net*). This project aims to make a new digital soil map of the world using state-of-the-art and emerging technologies for soil mapping and predicting soil properties at fine resolution. It will be supplemented by interpretation and functionality options, and could assist better decisions in a range of global issues, such as food production and hunger eradication, climate change, and environmental degradation. Coordinated by FAO, several universities and institutes integrated the regional soil maps to a new comprehensive Harmonized World Soil Database (HWSD) which have been widely used. As per recent *GloabalSoilMap* specifications, there are 12 parameters to be predicted along with uncertainty over six depth intervals e.g., 0-5 cm, 5-15 cm, 15-30 cm, 30-60 cm, 60-100 cm and 100-200 cm. Soil property values and uncertainty to be predicted

- Total profile depth (cm)
- Plant exploitable (effective) soil depth (cm)
- Organic carbon (g/kg)
- pH (×10)
- Sand (g/kg)
- Silt (g/kg)
- Clay (g/kg)
- Gravel (m^3 m^{-3})
- Effective cation exchange capacity (ECEC) (cmol (c^+)/kg)
- Bulk density of the fine earth fraction (excludes gravel) (Mg/m^3)
- Bulk density of the whole soil in situ (includes gravel) (Mg/m^3)
- Available water capacity (mm)

Soil sampling strategy for DSM

Soil sampling is an important part of DSM. It largely determines the accuracy of DSM, and directly influences the cost of the mapping. In the last decade, significant progresses have been made in developing soil sampling methods, with the purpose of obtaining the highest soil mapping performance with the least soil samples. Design-based sampling (simple random sampling, stratified random sampling, systematic random sampling, etc.) and model-based sampling (geostatistical sampling and centered grid sampling, *etc*.) are used in soil mapping strategy. Besides, the conditioned Latin hypercube sampling method has been popular for soil mapping in recent years. This method is a type of stratified random sampling that accurately represents the variability of environmental covariates in feature space. Lots of potential access constraints may prevent sampling at our desired locations. The constraints can be some kinds of land use, land cover, high-relief terrain, and unexpected road blocking, *etc*. Several scientists proposed a flexible Latin hypercube sampling strategy to deal with operational sampling problems in a large and remote region. It can be expected that more flexible and efficient soil sampling methods would be developed for DSM.

Predictive models

Numerous techniques were applied in the field of soil mapping to deal with the regression/classification of soil properties or soil classes, including statistical, geostatistical, hybrid and machine learning methods (Table 10.4). A lot of case studies have been conducted to compare the performance of different predictive techniques, such as geostatistics and machine learning. The geostatistics approaches often generated similar or better performance than regression models. Some geostatistical techniques, such as kriging with an external drift, regression kriging could incorporate environmental variables and achieved better performance than ordinary/simple kriging. Classification and regression tree (CART) recursively produces a tree-based structure storing predictors and soil data. This technique has been widely adopted in the soil mapping case study due to the robust prediction. Random forest (RF) is an up-to-date ensemble approach using the recursive partitioning for the exploring of the relationships between predictors and the variable of interest. RF has the same model building process with CART, sharing similar model advantages (*i.e.*, flexible with different types of datasets, and insensitive to missing data). Many trees can be built in RF, in which variables are randomly selected and only a subset of the variables will be adopted to identify splits in each tree. Therefore, compared with CART, RF can provide a better error measurement and is less susceptible to over-fitting, which has been validated in the mapping of regional soil type. Some hybrid approaches, such as random forest plus residuals kriging, were proposed in an effort to generate a reliable prediction.

Table 10.4: Predictive models commonly used in digital soil mapping

Model Type	Model name / approach	Description / principle	Typical application in DSM
Statistical	Multiple linear regression (MLR)	Establishes linear relationships between soil properties and environmental covariates.	Predicting continuous soil properties like organic carbon, pH and texture.
	Generalized linear models (GLM)	Extends linear regression to handle non-normal data distributions using link functions.	Modeling categorical or non-linear soil attributes (e.g., soil class probabilities).
	Regression kriging (RK)	Combines regression of soil properties on covariates with spatial interpolation of residuals.	Mapping soil variables that exhibit both deterministic and spatially auto-correlated patterns.
	Geostatistical models (Ordinary kriging, Co-kriging)	Use spatial autocorrelation structures to predict values at unsampled locations.	Interpolating soil properties when spatial correlation is strong.
Machine Learning	Random forest (RF)	Ensemble learning method that builds multiple decision trees and averages predictions.	Widely used for soil property prediction due to robustness and high accuracy.
	Gradient boosting machines (GBM, XGBoost, LightGBM)	Sequentially builds decision trees to minimize prediction error through boosting.	High-performance prediction of continuous and categorical soil data.
	Support vector machines (SVM)	Constructs optimal hyperplanes to classify or predict soil attributes.	Soil classification and texture prediction using complex, non-linear relationships.
	Artificial neural networks (ANN)	Mimics human brain processing by modeling complex non-linear relationships between inputs and outputs.	Predicting soil fertility, moisture, or chemical properties.
	k-Nearest neighbors (kNN)	Predicts soil values based on the similarity (distance) to neighboring samples.	Local-scale prediction and spatial interpolation where dense sampling exists.
Hybrid and Advanced Models	Random forest kriging (RFK)	Integrates Random Forest predictions with kriging of residuals for spatial refinement.	Enhances prediction accuracy by combining machine learning and geostatistics.

	Bayesian networks	Probabilistic models capturing uncertainty in soil-environment relationships.	Mapping soil classes and assessing prediction uncertainty.
	Deep learning models (CNN, DNN)	Use multiple hidden layers to learn spatial patterns and feature hierarchies from large datasets.	High-resolution soil mapping using imagery and terrain data.

Legacy soil database

Legacy soil data mainly include polygon-based soil maps and soil profile databases. They both can serve as the input of digital soil mapping procedures. Different types of soil surveys at different scales and intensities have been carried out in the country by the ICAR-NBSS&LUP in collaboration with the various state soil survey and land use organizations. NBSS&LUP have been completed a soil survey of the entire country at a scale of 1: 250,000 as a part of the mission project on Soil Resource Mapping. Reconnaissance soil survey was conducted at 1:50,000 scale using toposheets and Landsat/IRS (Indian Remote Sensing) imagery by the ICAR-NBSS&LUP and State Land Use Survey of India (SLUSI) under which many districts were surveyed in different states of the country. Generally, the reconnaissance maps show an association of two or three soils in one map unit or delineation. Detailed soil survey was carried out by SLUSI and other state soil survey organizations at different scales (1:4000 to 1:10,000) to survey many catchment and command areas. ICAR-NBSS&LUP have also surveyed many research farms, watersheds across the country and recently > 50 blocks were covered in different agro-ecological regions of the country at 1:10000 scales under a Land Resource Inventory programme. Detailed legacy database is given in Table 10.5.

Table 10.5: Legacy soil databases in India and the World

Region	Database name	Maintaining organization	Coverage/scale	Key features
India	Soil and Land Use Survey of India (SLUSI)	Department of Agriculture and Farmers Welfare, Government of India	National (1:250,000 to 1:10,000)	Provides soil resource maps, land capability, and land irrigability classifications for agricultural planning.
	National Bureau of Soil Survey and Land Use Planning (NBSS&LUP) Database	ICAR-NBSS&LUP, Nagpur	National (1:1,000,000 and 1:250,000)	Contains detailed soil profile data, soil series information, and land evaluation datasets used in soil correlation and mapping.
	Indian Council of Agricultural Research (ICAR) Soil Data Repository	ICAR Institutes and Agricultural Universities	Regional to national	Integrates soil fertility, texture, and organic matter data from various research projects and experiments.
	Soil Health Card Scheme Database	Department of Agriculture &	Farm-level, nationwide	Contains laboratory-analyzed soil test data

		Cooperation, Government of India		for macro- and micronutrients for millions of farmers.
	National Soil Information System (NASIS-India)	NBSS&LUP (in collaboration with ICAR and FAO)	National	A digital framework integrating legacy soil survey data for use in digital soil mapping and land resource inventories.
Global	SoilGrids	ISRIC-World Soil Information	Global (250 m and 1 km resolution)	Provides global predictions of standard soil properties (e.g., organic carbon, pH, clay, sand) using machine learning models.
	Harmonized World Soil Database (HWSD)	FAO & IIASA	Global (1 km resolution)	Integrates regional and national soil databases with standardized classification for global modeling.
	GlobalSoilMap Project	Global consortium led by ISRIC and regional partners	Global (100 m resolution)	Aims to produce fine-resolution, gridded soil property maps based on the SCORPAN framework.
	WISE (World Inventory of Soil Emission Potentials)	ISRIC-World Soil Information	Global (coarse resolution)	Contains soil property data relevant for greenhouse gas emission modeling and soil carbon studies.
	European Soil Database (ESDB)	European Soil Data Centre (ESDAC), European Commission	Continental (1:1,000,000)	Comprehensive dataset on soil typology, texture, and land cover across Europe.
	Africa Soil Information Service (AfSIS)	Alliance of Bioversity International and CIAT	Africa-wide (250 m to 1 km)	Provides high-resolution soil property maps and field data using advanced DSM and spectroscopy.
	Soil Data Mart (USA)	USDA-NRCS	United States (1:24,000)	Provides access to SSURGO, STATSGO, and NASIS databases with detailed soil survey data for the US.

Major progresses in India and abroad

DSM has moved from research phase to operational phase across the countries but no fully fledged research has been carried out in India. In India, DSM approach was used in predicting soil organic carbon and inorganic carbon stocks at 250 m resolution using limited observations. Quantitative soil information is also more important to identify the vulnerable areas of land degradation/desertification. This type of information helps in modelling soil losses and highlights the areas with the greatest degradation susceptibility. Recently, land degradation/desertification was mapped using Global gridded soil information such as coarse fragments, organic carbon, pH and clay content. DSM has moved towards an operational activity from research phase which has been concretized by the *GlobalSoilMap* project. It aims to map over the world several key soil properties onto a three-dimensional grid at fine spatial resolution with local uncertainty estimates. First versions of GlobalSoilMap products have been already produced in various countries. Detailed work progresses in DSM in India and the World is given in Table 10.5.

Software tools and R packages

DSM relies on a combination of GIS, statistical software, and machine learning tools to process spatial data, model soil-environment relationships, and generate predictive soil maps (Table 10.6). Among GIS platforms, ArcGIS and QGIS are widely used for spatial analysis, map creation, and environmental covariate generation. SAGA GIS and GRASS GIS provide advanced terrain analysis functions and are commonly integrated with R or Python for automated workflows. Cloud-based tools such as Google Earth Engine (GEE) allow large-scale processing of remote sensing data for soil prediction and monitoring. Statistical and machine learning software such as R and Python are central to DSM modeling. R provides a comprehensive set of packages for data handling, geostatistics and predictive modeling. Key packages include gstat and automap for variogram analysis and kriging, raster, terra and sf for spatial data management and random forest, ranger, xgboost and caret for machine learning-based soil predictions. The GSIF package developed by ISRIC implements the SCORPAN framework for DSM. Additionally, visualization packages like plot KML enable 3D soil data representation in Google Earth. These tools collectively enable the efficient integration of field data, environmental covariates and computational models to produce high-resolution, reproducible soil maps that support decision-making in agriculture and environmental management.

Table 10.6: Software and R packages used in digital soil mapping

Category	Software / R Package	Developer / Source	Primary Function	Key Applications in DSM
Geospatial & GIS software	ArcGIS/ ArcGIS Pro	Esri	GIS-based spatial analysis, interpolation, and cartographic visualization	Processing covariates, generating environmental layers, spatial analysis, and map production.
	QGIS	Open-source geospatial foundation (OSGeo)	Open-source GIS software for raster/vector analysis	Pre-processing of DEMs, extraction of terrain attributes, spatial overlay, and visualization.
	SAGA GIS	University of Hamburg	Terrain analysis and raster processing	Derivation of terrain attributes (slope, curvature, TWI), hydrological

				modeling, and spatial prediction.
	GRASS GIS	GRASS development team	Advanced raster and vector data management	Spatial modeling, environmental covariate extraction, and integration with R for DSM workflows.
	ILWIS (Integrated land and water information system)	ITC, Netherlands	Raster analysis and land resource mapping	Land evaluation, soil and terrain analysis, and map algebra in DSM.
	Google earth engine (GEE)	Google	Cloud-based geospatial computation platform	Handling large-scale remote sensing data and environmental covariates for DSM applications.
Statistical & machine learning software	R (Statistical Software)	R core team	Open-source statistical computing platform	Widely used for soil property prediction, modeling, and validation using various R packages.
	Python (scikit-learn, TensorFlow, PyTorch)	Python software foundation	Data science and machine learning framework	Machine learning-based DSM modeling and spatial prediction workflows.
	GS+	Gamma design software	Geostatistical analysis software	Variogram modeling and kriging for spatial interpolation of soil properties.
	Surfer	Golden software	Surface modeling and contour mapping	Visualization and interpolation of soil data using kriging and gridding methods.
R Packages for DSM	raster, terra, sf, sp	R community	Spatial data handling and analysis	Managing raster and vector datasets for DSM and environmental covariate extraction.
	gstat	Pebesma (2004)	Geostatistical modeling	Variogram fitting, kriging, and spatial prediction of soil attributes.
	automap	R community	Automated variogram modeling and kriging	Simplifies geostatistical interpolation workflows.
	caret, randomForest, ranger, xgboost	R machine learning community	Supervised machine learning algorithms	Predicting soil properties using ensemble models (RF, GBM, XGBoost).
	nnet, keras, neuralnet	R community	Neural network modeling	Modeling nonlinear soil–environment relationships for DSM.
	mlr3, tidymodels	R community	Machine learning framework	Streamlined model training, validation, and hyper parameter

			tuning for DSM.
Soiltexture	R soil science community	Soil texture classification	Classifies soils based on particle size distribution using texture triangle.
PlotKML	Tomislav Hengl et al.	KML and 3D visualization	Exports DSM results to Google Earth for visualization.
spdep, spatialEco, geoR	R spatial analysis community	Spatial autocorrelation and spatial statistics	Spatial analysis of soil variability and covariate relationships.
GSIF (Global Soil Information Facility)	ISRIC- World Soil Information	DSM data modeling and soil prediction	Implements SCORPAN modeling and integration with SoilGrids workflows.

Application of DSM

DSM originally focused on the soil-landscape modelling, which quantified the relationships between soil properties and environmental variables. The emphasis of soil mapping is gradually shifting from the soil variation and predictive techniques design to the application in various fields like agricultural management, ecosystem services assessment, land evaluation etc. (Table 10.8). The up-to-date multi-scale soil maps have been new global imperative and have attracted much attribution. Like conventional soil mapping, the major stakeholders of digital soil maps are farmers, land use planners, researchers and policy makers. Carbon sequestration studies, land degradation assessment, water resource management and climate change analysis are some of the major fields in India where quantitative soil information is needed. For instance, soil carbon studies have become increasingly important for environmental reasons to know not just the carbon storage at particular time also the changes or trend with time. The widespread availability of digital elevation data and other DEM attributes, mapping of soil organic carbon mapping is possible at higher resolution. DSM can be useful in regular monitoring soil health Card data launched by Government of India to help the farmers to access the status of soil, to identify the crop suitability, nutrient availability and providing further recommendation for improving the soil quality. Availability of digital soil maps helps in preparing soil health cards by providing site specific quantitative information and also in identifying the suitability of land resources for different crops. DSM can be used to create initial soil survey maps, refine or update existing soil surveys, generate specific soil interpretations, and assess risk. It can facilitate the rapid inventory, re-inventory and project-based management of lands in a changing environment

Table 10.7: Applications of digital soil mapping

Application Area	Description	Examples
Soil resource inventory and mapping	DSM provides detailed and consistent spatial information on soil properties such as texture, organic carbon, pH, and nutrient	National and regional soil information systems (e.g., GlobalSoilMap, SoilGrids, NBSSLUP DSM outputs).

	content at various depths.	
Precision agriculture	DSM supports variable-rate input applications by mapping within-field variability of soil properties to optimize fertilizer, irrigation, and pesticide use.	Precision nutrient management in IARI and ICAR experiments; site-specific soil fertility maps.
Land use planning and land evaluation	High-resolution DSM maps assist in identifying suitable areas for different crops or land uses based on soil characteristics and environmental covariates.	AHP-based and FAO framework suitability analysis for crops such as rice, wheat, and maize.
Climate change and carbon modeling	DSM contributes to estimating SOC stocks and changes under different land management and climate scenarios.	Soil carbon stock assessment in national GHG inventories and IPCC reporting.
Environmental monitoring and soil degradation assessment	DSM helps in detecting soil erosion, salinity, and compaction patterns over time using repeated mapping and remote sensing data.	Soil degradation monitoring under watershed and desertification control programs.
Hydrological and ecosystem modeling	Soil maps from DSM are essential inputs for hydrological, ecological, and biogeochemical models to simulate water and nutrient flows.	Integration with SWAT, InVEST, and other ecosystem modeling tools.
Urban and infrastructure planning	DSM provides information on soil stability, bearing capacity, and drainage properties critical for engineering and urban development.	Site suitability mapping for construction and wastewater disposal planning.
Policy support and land management	DSM-derived datasets support evidence-based policy decisions for land resource management, soil conservation, and sustainable agriculture.	National soil health and land degradation neutrality programs.
Pedometric research and soil process understanding	DSM facilitates the exploration of soil-landscape relationships using statistical and machine learning approaches.	Modeling pedogenic trends and spatial prediction of soil horizons and properties.
Integration with RS and big data platforms	DSM benefits from satellite imagery and machine learning to produce near-real-time soil updates.	Integration with Google Earth Engine (GEE) and cloud-based soil data services.

Conclusions

DSM represents a transformative shift from traditional soil survey methods toward data-driven, model-based prediction of soil properties and classes. By integrating GIS, remote sensing, environmental covariates and advanced statistical or machine learning algorithms, DSM provides a quantitative and reproducible framework for soil information generation. Unlike conventional mapping, which relies heavily on expert interpretation and manual delineation, DSM applies the SCORPAN model to establish explicit relationships between soils and their environmental drivers, leading to high-resolution, spatially continuous soil information. The fundamentals of DSM lie in its capacity to combine soil observations (from field samples and legacy data) with environmental predictors derived from topography, climate, vegetation and parent material. These relationships are then modelled using regression, geostatistical, or ensemble machine learning techniques to generate maps of soil properties such as texture, organic carbon, pH and nutrient availability. The resulting products are not only more consistent and scalable but also provide quantitative uncertainty estimates that enhance their scientific reliability and usability. DSM contributes significantly to agricultural management, environmental monitoring, and land-use planning by providing precise and accessible soil information at various scales. It supports initiatives like precision farming, carbon accounting and land degradation assessment, which require spatially detailed soil data. Moreover, the integration of cloud computing platforms and open-access soil databases such as SoilGrids and GlobalSoilMap has democratized soil information, enabling collaboration and innovation across disciplines. Overall, DSM stands as a cornerstone of modern soil science, bridging field-based expertise with computational advancements. Its fundamentals rooted in spatial modelling, data integration, and predictive analytics are driving a new era of soil information systems, ensuring that soil knowledge remains accurate, up-to-date and applicable for sustainable land and resource management in a changing global environment.

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Soil Nutrient and Crop Water Requirement Information System under Changing Climate Scenario

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Introduction

Soil fertility management remains a persistent challenge for researchers striving for sustainable development in agricultural production systems, as the harvest of arable crops continually depletes the soil's nutrient reserves. In the traditional system of agriculture, soil was regularly supplied with organic manures to make up for nutrients that are mined by the crops. However, quest for higher yields to meet the rising need of food for the exploding population with unsustainable practices such as mismanagement of inputs and imbalanced fertilizer application make the soil nutrient reserve more depleted (Surendran et al., 2016). In urgency for higher production, no serious attention has been given to long-term soil health. This fanatic policy of attaining higher production without giving due emphasize on sustainability and soil health can be clearly visualized from the decline in annual compound yield growth rate (CGR) of 1.31 during 2021 from 2.56 during 1991 for all principal crops that are grown in India. The compound growth rate in yield in major crops is either declining or negative. It is the experience of the researchers that with newer crop varieties these yield barriers cannot be broken. The logical conclusion is that the soil resource base is degraded below a critical level that newer crop varieties or hybrids are not able to yield beyond a level, which is primarily determined by the level of native soil fertility.

Kerala experiences a humid tropical climate, characterized by heavy and intense rainfall, high relative humidity, alternate wet and dry periods, abundant sunshine and high ambient temperature. It is a leading producer of commercial agricultural commodities in the country. Major crops grown are coconut, arecanut, oil palm, rubber, coffee, tea, cardamom, paddy, tapioca, cashew etc. The agricultural scenario of the Kerala state is unique, characterized by diversity of crops and multiplicity of cropping situations. In general, the soils of Kerala are acidic, kaolintic and gravelly with low cation exchange capacity (CEC), low water holding capacity and high phosphate fixing capacity. The climate is conducive for intensive weathering and hence major area is covered with laterite soils. Laterite soils cover about 65 per cent of the total area of the State, occupying a major portion of the midland and upland regions and are the most extensive of the soil groups found in Kerala. Laterites are in general poor in plant nutrients especially available nitrogen, phosphorus and potassium and are low in the bases. They have poor water-holding capacity and low CEC, exhibit high phosphorus-fixing capacity, contain low organic matter, and often show toxicity due to elevated levels of Al, Fe, and Mn. Lateritic soils are more prone to erosion due to the porous nature and coarse texture of soil with medium to low cohesiveness.

The large-scale erosion of fine-textured top soil and organic matter from majority of the areas due to high rainfall and undulating topography has given rise to soils consisting of large particles and gravels with low water holding capacity. The first predominant cause of soil degradation in these high rainfall zone regions undoubtedly is water erosion. The process of erosion sweeps away the topsoil along with organic matter and exposes the subsurface horizons.

The erosion status of soils in Kerala indicates that, out of the total geographical area, 83,500 ha is severely eroded, 973,245 ha is moderately eroded, 1,064,879 ha experiences moderate to slight erosion, and 307,708 ha is slightly eroded, while only 620,965 ha under permanent vegetation remains well protected. Besides, on an average 15-18 t ha^{-1} of top fertile soil is eroded in Kerala ultimately resulting in low fertility status besides having other implications like low crop productivity, limited groundwater recharge etc. The second major indirect cause of degradation is loss of organic matter by virtue of temperature mediated rapid decomposition of organic matter and leading to loss of rapid soil fertility. Consequences of depletion of organic matter are poor soil physical health, loss of favourable biology and occurrence of multiple nutrient deficiencies.

Another important reason is that Kerala has the lowest average size of operational holdings of 0.24 ha in the country as against the national average of 1.33 ha. Out of the 66.57 lakhs operational holdings in the State, 95% of the holdings are marginal in size (<1 ha), 3.4% are small (1 to 2 ha), and the rest 1.6% of the total number of the holdings only belong to other above-small categories (DoES, 2022). About, 40% of the cropped area in the State is occupied by coconut, which is cultivated mainly in small homesteads. Organic matter recycling in these coconut gardens is very poor as besides coconut kernel, most of the crop residues like dry leaf fronds, dry spathes, coconut husks, coconut shells etc. are taken out of the plantation for various purposes like thatching, burning, coir retting etc. This poor organic matter recycling is one of the reasons for the declining soil health and low yield in coconut based cropping systems. It was stated that in humid tracts, next to poor rain water management, depletion of nutrients caused by organic matter deficiency is an important cause of soil degradation.

Productivity of almost all the crops except rubber is lower in Kerala compared to other Indian states. Low fertile lateritic soils, nature of topography with undulating terrain, coupled with high intensity rainfall, leads to top fertile soil loss through severe erosion and nutrient lost through leaching might have been one of the contributing factors for low productivity. There are several possible reasons for this low productivity, however at this juncture the low yield of crops associated with high cost of production is a great concern in Kerala's agriculture.

Improper fertilizer schedules adopted over the years under intensive cultivation of the crop further deteriorated the soil fertility and simultaneously might cause surface and groundwater pollution. Decline in soil fertility does not get the same public attention as that of floods, droughts, pest infestation *etc.*, since it is a gradual process and not associated with catastrophes and mass starvation and therefore largely invisible.

This necessitates a regular monitoring of changes in soil fertility that occurs in the soil**.** For understanding the role of different process, a budgetary approach offers good tool through analyzing the turnover of nutrients in the soil-plant system at different spatial scales. The productivity level of almost all crops is low except rubber in Kerala when compared to many other states of India. For instance, the coconut productivity is even lower than the national average (8303 nuts per ha). In Kerala, the productivity of coconut is only 7365 nuts per ha, while it is 13771, 9327 and 8338 nuts per ha in Tamil Nadu, Andhra Pradesh and Maharashtra respectively (www.coconutboard.nic.in).

Water and nutrients are the two most critical inputs for crop production. However, the desired economic benefits of drip irrigation are possible in the field crops only when proper precision farming strategies for nutrient application (4 Rs - Right Source, Right Rate, Right Time and Right Place) are adopted. These are seldom practiced and hence profitability gets reduced for high capital investments. This may be one of the reasons for less adoption of drip irrigation. The important problems associated with the lateritic soils of Kerala are P fixation, heavy rainfall during monsoon season resulting in nutrient losses through run off, leaching of basic cations and very poor nutrient retention capacity due to low CEC (3 -15 cmol kg^1). Deficiency of N and K was reported in laterite soils of this region. Due to these problems, fertilizers should be applied in synchrony with crop demand at the root zone in smaller quantities

Changes in soil fertility level should be monitored to provide early caveat on adverse trends and to identify the problem areas. Scientists in the recent past have reported that there is mining of N, P and K from soil reserves in almost all the agro-climatic zones across India without taking into account of the soil processes such as leaching, denitrification losses. This necessitates a regular monitoring of changes in soil fertility that occurs in the soil. For understanding the role of different process a budgetary approach offers good tool through analyzing the turnover of nutrients in the soil-plant system at different spatial scales.

DSS in nutrient budgeting

Recently many computerized decision support models for working out the nutrient balance were developed, *viz*., NUTrient MONitoring (NUTMON), NUtrient MAnagement Support System (NUMASS), MINeral Accounting system (MINAS), N CYCLE, OVERSEER, Ythan Nutrient budgeting tool *etc*., of which NUTMON-Toolbox is a user friendly computerized software for monitoring nutrient flows and stock especially in tropical soils (Vlaming et al., 2001)."NUTMON-Toolbox" enables the assessment of trends based on the local knowledge on soil fertility management and the calculation of nutrient balances. Utilizing these results one can easily identify the factors limiting crop production in the farm or region and propose possible solutions for adoption and testing. Farm-NUTMON is a tool encompassing a structured questionnaire, a database, and two simple static models (NUTCAL for calculation of nutrient flows and the ECCAL for calculation of economic parameters). Finally, a user-interface facilitates data entry and extraction of data from the database to produce input for both models (Surendran and Murugappan, 2006). The tool calculates flows and balances of the macro-nutrients such as N, P, and K through independent assessment of major inputs using the following equation.

$$\text{Net soil nutrient balance} = \Sigma\,(\textit{Nutrient INPUTS}) - \Sigma\,(\textit{Nutrient OUTPUTS}) \qquad (1)$$

This is based on a set of five inflows (IN 1-5 mineral fertilizer, organic inputs, atmospheric deposition, biological nitrogen fixation and sedimentation), five outflows (OUT 1-5 farm products, other organic outputs, leaching, gaseous losses, erosion and human excreta), and six internal flows (consumption of external feeds, household waste, crop residues, grazing, animal manure, and home consumption of farm products).

Components of NUTMON-toolbox

The NUTMON-toolbox includes four modules and two databases that together facilitate nutrient monitoring at the level of individual farmers' fields and farms as a whole.

Modules

- A set of questionnaires to collect the required farm-specific information on inventory and monitoring. They are a structured guide used to gather and record information during an interview with one or more members of the farm regarding farm environment, farm management, farm household, soils and climate.
- A data entry module that facilitates entry of the data from the questionnaires into the computer.
- A background data module, storing non-farm-specific information on crops, crop residues, animals, inputs and outputs.
- A data processing module that calculates nutrient flows, nutrient balances and economic indicators, based on the farm-specific data from the questionnaires and general data from the background database, using calculation rules and assumptions.

Databases

- A background database containing non-farm-specific information on, for instance, nutrient contents of crop and animal products, crop and livestock parameters, as well as calibration factors of local units of measurement.
- A farm database in which information about a particular farm are stored.

The diagnostic phase is being carried out at farm level where, soil and crop management decisions are usually made through farmer participatory analysis of the current situation in the farm regarding nutrient flows into and out of the farm and their economic performance. This can be done using farm inventory and farm monitoring. Farm inventory is to identify the important features of the farm to be studied. Basically, the inventory entails a simplification of the real farm in order to make it fit into the conceptual framework and is done by means of a one-off inventory of the farm. Monitoring identifies the material flows within and outside the farm over a period of time.

Additional information that is needed for the calculations but that cannot be given by the farmer, for instance, nutrient contents of crop products and fertilizers, soil parameters and calibration factors for local units of measurement needs to be gathered from literature reviews that provide data, valid for the study area.

Similarly, for some of the crops and other livestock products, input parameters like nutrient contents, which are not stored in the background database, have to be analyzed and entered. Soil sampling and their analysis provide information on the current nutrient status of soils. Complete database for crops that are not included in the toolbox but are grown in the study area has to be generated afresh.

Farm conceptualization

Farms are conceptualized as a set of dynamic units, which depending on management, form the source and/or destination of nutrient flows and economic flows.

- Farm Section Unit (FSU) - Areas within the farm with relatively homogeneous properties.
- Primary Production Unit (PPU) / crop activities - Piece of land with different possible activities such as one or more crops (annual or perennial), a pasture, a fallow and located in one or more FSUs.
- Secondary Production Unit (SPU) / livestock activities- Group of animals within the farm that are treated by the farm household as a single group in terms of feeding, herding and confinement.
- Redistribution Unit (RU) - Nutrient storage activities. Location within the farm where nutrients gather and from which they are redistributed, such as manure heaps and compost pits.
- House Hold (HH) - Group of people who usually live in the same house or group of houses and who share food regularly.

- Stock - The amount of staple crops, crop residues and chemical fertilizers temporarily stored for later use.
- Outside (EXT) - The external (nutrient) pool consisting of markets, other families and neighbours, being a source and destination at the same time which itself is not monitored.

Quantification of nutrient balance at farm level

In Farm-NUTMON, nutrient flows are quantified in three different ways *viz*., by using primary data, estimates and assumptions. Flows directly related to farm management were quantified by asking the farmers on inputs to and outputs from the different compartments. Flows quantified this way are the use of chemical fertilizer (IN 1), organic inputs (IN 2), farm products (OUT 1) and other organic products (OUT 2), redistribution of household waste, crop residues and farmyard manure (FYM). The resulting data fall in the category of primary data. These flows are quantified using the following equation,

$$Flows = \Sigma_x\ wd\ Prod_{x.t} \times fr\ Prod_x \qquad (2)$$

Where, $wdProd_{x,t}$ is amount of product x in month t (kg), $frProd_x$ is nutrient content in product x (kg kg^{-1}).

Atmospheric deposition (IN 3), biological N fixation (BNF, IN 4), leaching (OUT 3) and gaseous losses (OUT 4) are quantified fully on the basis of off-site knowledge using *transfer functions*, and the resulting data are estimates. Inflow through atmospheric deposition (IN 3) in kg is calculated using the in-built regression equations of NUTMON-toolbox, linking nutrient input with rainfall, which are given in equations 3 to 5

For N:

$$(Area/10000) \times (SQRT(PrecAnnual)) \times (PrecMonth_t \times Annual) \times 0.14 \qquad (3)$$

For P:

$$(Area/10000) \times (SQRT(PrecAnnual)) \times (PrecMonth_t \times Annual) \times 0.023 \qquad (4)$$

For K:

$$(Area/10000) \times (SQRT(PrecAnnual)) \times (PrecMonth_t \times Annual) \times 0.092 \qquad (5)$$

Where, Area is area of PPU (ha), PrecAnnual is precipitation (mm), and $PrecMonth_t$ is monthly precipitation (mm)

Non-symbiotic N fixation (IN 4b) is calculated using a function relating N fixation with mean annual precipitation. It is assumed that symbiotic N fixation (IN 4a) can take place within all primary production units. For primary production units with leguminous (annual or perennial) species, a crop-specific percentage of the total N uptake is assumed to be the result of symbiotic N fixation. The total N uptake is defined as the sum of the amounts of N in the crop product and the crop residues. N input through biological fixation (IN 4) is given as,

$$IN4Non\text{-}Symb\ t\ p + IN4Symb\ t\ p \tag{6}$$

Non-symbiotic N-fixation by crops in PPU (kg) is given in Eq. 7.

$$Non\text{-}Symb\ t\ p = (Area/10000)\times (1/12) \times 2+ (PrecAnnual - 1350)\times 0.005) \tag{7}$$

Symbiotic N-fixation by crops in PPU (kg) is given in Eq. 8.

$$Symb\ t\ p = Uptake_{cp\ t\ ,\ p\ c} \times frFixation_{cp} \tag{8}$$

Where, $Uptake_{cp\ t\ pc}$ is nutrient uptake by crops in PPU in month t (kg), $FrFixation_{cp}$ is fraction of N obtained from biological N-Fixation for crop taken. The percentages of leaching for N and K are calculated as a function of the clay percentage of the soil and the mean annual precipitation using transfer functions based on in built model “Smaling 1993” (Smaling *et al*., 1993).

For N

$$(Mineralised\ N_p/12)+ IN\ 1\ MinFert\ N_{p\,t}+ IN\ 1\ MinOrg\ N_{p\,t})\times(2.1\times 10^{-2}\times PrecAnnual-3.9) \tag{9}$$

For K

$$frLeachK_p \times((ExchK_p \times 1/12) + IN\ 1\ MinFert\ K_{p\,t}+ IN\ 1\ MinOrg\ K_{p\,t}) \tag{10}$$

Where, $IN\ 1\ MinFert\ N_{p\,t}$ *is* inflow from fertilizers on PPU in month t, $IN\ 1\ MinOrg\ N_{p\,t}$ is inflow from organic manures on PPU in month t, $FrLeach\ K_P$ *is* fraction of potassium leached from PPU, and $ExchK_p$ is exchangeable K in soil PPU.

The percentage of gaseous loss (OUT 4) of N is assumed to be the same for each primary production compartment and is calculated as a function of the clay percentage of the soil and the mean annual precipitation using a transfer function (Smaling *et al*., 1993). Gaseous losses (OUT 4) are calculated by multiplying the loss percentage by fertilizer N, mineralized soil N and given in Eq. 11.

$$(Soil\ N + Fertilizer\ N) \times (-9.4)+ 0.13 \times frclay_p \times 100 + 0.01 \times PrecAnnual \tag{11}$$

Erosion (OUT 5), can occur in any of the primary production compartments. Soil loss (kg ha^{-1} yr^{-1}), is estimated using the universal soil loss equation (USLE) (Wischmeier and Smith, 1965). The estimated soil loss is converted to nutrient loss (kg ha^{-1} yr^{-1}), using the total N, P and K content (%) of the soil and an enrichment factor.

$$USLE = R\times K\times L\times S\times C\times P \tag{12}$$

$$(Soil\ loss_f \times 1000 \times frSoil_p \times EnrichFact \times SoilFormFact \times (Area_p/Area_f) \times Cusle_p \tag{13}$$

Where, soil $loss_f$ is soil loss from FSU, $FrSoil_P$ is nutrient content in soil on PPU, EnrichFact is enrichment factor, and $Cusle_p$ is USLE crop cover factor for PPU.

The calculations for feed consumption, manure excretion, feed conversion factors for different livestock types and farmers' information on average stocking rates are based on a combination of literature data, assumptions, in-built values and farm specific data on farm management using the Livestock Model- Energy Model and Dry Matter model (Vlaming *et al*., 2001).

To make a clear distinction between primary data on the one hand and estimates and assumptions on the other, two different balances were worked out. The partial balance at farm level [(Σ IN1-2) -Σ OUT1-2)] is made up solely of primary data. The full balance, (ΣIN - ΣOUT), is a combination of the partial balance and the emissions (atmospheric deposition and nitrogen fixation) and emissions (leaching, gaseous losses, erosion losses and human excreta) from and to the environment.

Case studies

- **Crop water requirement for Kozhikode district**

The selected district for the current study is Kozhikode, which lies between North latitudes 11° 08' and 11º 50' and East longitudes 75 º 30' and 76 º 8'. The agro-ecological zones and units of Kozhikode district delineated by National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), Bengaluru based on slope, rainfall, temperature, soil depth, length of growing period (LPG) etc. was used for this study (Nair et al. 2012). NBSS&LUP has classified Kozhikode district into 3 agro-ecological zone (AEZ) and 4 agro-ecological units (AEU). They are:

Agro-ecological zone	Zone name	Agro-ecological unit	Description
AEZ-1	Coastal plains	AEU 1.2	Northern coastal plain
		AEU 1.7	Kaipad lands
AEZ-2	Midland laterites	AEU 2.4	Northern laterite
AEZ-4	High hills	AEU 4.2	Northern high hills

A decision support software CROPWAT 8.0 developed by FAO, based on FAO Irrigation and Drainage Paper 56 was utilized for the calculation of ET_0 of individual AEUs (FAO, 2009). ET_0 was estimated using the FAO Penman-Monteith method. Details about the secondary data used for the calculation of crop water requirement are explained in the subsequent sections.

Data used

The details of meteorological data of different AEUs used in the calculations and the climatic characteristics of different AEUs are shown in Table 11.1. The parameters used for calculation of ET_o are latitude, longitude and altitude of the station, maximum and minimum temperature (ºC), maximum and minimum relative humidity (%), wind speed (km day^{-1}) and sunshine hours. Effective rainfall calculated based on rainfall data available from various stations within these AEUs using the inbuilt formula of

USDA Soil Conservation Service (SCS) in CROPWAT model. There are four major soil types encountered in the district. Soil characteristics considered for estimation of crop water requirement is available water content (mm m^{-1}) and depth of soil (cm) (Table 11.2). The major cultivated crops in Kozhikode district are rice, coconut, rubber, pepper, banana, brinjal, tomato, gourds, pumpkin, tapioca, cardamom, tea, etc. The salient details of crops considered for the study are given in Table 11.3. Crop coefficient values (K_c) for initial, mid and late growth stages of annual and seasonal crops are used from the available literature. In the case of perennial crops, same K_c value is used for the whole year.

Table 11.1: Climatic characteristics of different AEUs in Kozhikode district

AEUs	Location of meteorological stations	Annual rainfall range (mm)	Temperature (°C)		Data source
			Maximum (°C)	Minimum (°C)	
2	Vadakara	1639 - 4276	34.6 (Apr)	18.9 (Dec)	IMD
7	Koilandi	2390 - 5016			IMD
11	CWRDM	2431 - 4645			CWRDM
15	Peruvannamuzhy	3773 - 5788	35.1 (Mar)	19 (Jan)	IMD

IMD - Indian Meteorological Department, DAF - Department of Agriculture Farm

Table 11.2: Soil characteristics used for different agro-ecological units

AEUs	Available water content (mm m^{-1})	Soil depth (cm)
2	70	105
7	70	105
11	110	129
15	102	93

Table 11.3: Details of crops considered for the study

Cropping season*	Duration (days)*	Planting season (Irrigated crop)*	Spacing*	Depth of active root zone (cm)	Canopy coverage (% of spacing)	Management Allowable Deficit **
Rice						N.A.
- ***Viruppu***	85-110	Apr-May to Sep-Oct	15 cm x 10 cm	30	100	
- ***Mundakan***	110-125	Sep-Oct to Dec-Jan	15 cm x 10 cm	30		
- ***Puncha***	85-110	Dec-Jan to Mar-Apr	15 cm x 10 cm	30		
Cow pea	110	Jan - Feb	30 cm x 15 cm	30	100	0.45
Tapioca	240-300	Sep - Oct & Feb - Apr	90 cm x 90 cm	40	80	0.35
Coconut	Perennial	May/Sep	7.5 m x 7.5 m	90	60	0.50
Bitter gourd	120	Dec - Jan Sep - Oct	2m x 2m	50	100	0.50
Solanaceous crops **Brinjal**	125	Sep - Oct	60 cm x 60 cm	35	100	0.45
Bhindi	90	Aug - Sep Feb - Mar	60 cm x 30 cm	35	100	0.50
Banana	365	Apr - May & Aug - Sept	2 m x 2 m	30	80	0.35

Total water requirement and net irrigation requirement

From the calculated ET_0, total water requirement / Crop evapotranspiration *(ETc)* was worked out for the specific crops according to the equation. The fraction of the crop water requirement that needs to be satisfied through irrigation contribution in order to guarantee the optimal growing conditions of the crop is termed as irrigation requirement and is usually expressed in mm and the equation is given in 11.12.

$$ETc = Kc \times ETo \qquad (12)$$

$$NIR = TWR - ER - Ge \qquad (13)$$

Where, TWR is total water requirement, ER is effective rainfall, Ge is Groundwater contribution from the water table (not considered in the calculation as this is negligible).

Water resources scenario and balance computations

Water resource information estimated on an annual as well as a seasonal basis by CWRDM in its earlier studies has been taken as a source for the present study (CWRDM, 1999). With respect to groundwater, the data has been mainly extracted from the report on Ground water resources of Kozhikode district (CGWB, 2009). Salient features/data on the irrigation projects have been extracted from the Irrigation Projects of Kerala by PWD (1974) and Farm Information Bureau (2010). Block wise cultivable command area, irrigated area has been derived from report of Economics and Statistics Department of Government of Kerala (DoES, 2022). Irrigated area under minor irrigation schemes has been taken from the report of Minor irrigation census 2010-11. The available data from different sources have been grouped as per AEZ based on the list of blocks. Based on the gross irrigated area statistics, the net irrigation demand for each of the AEUs has been worked out both for the major/medium and minor irrigation schemes. The major crop under irrigation is paddy followed by coconut. Paddy is mainly irrigated by government canals. While calculating the irrigation demand for the uplands, coconut or coconut based cropping systems are found to be the major ones and hence the irrigation demand is worked out based on the demand for coconut.

- **Reference evapotranspiration (ET_0)**

The ET_0 of different agro-ecological units ranged from 1445 to 1527 mm yr^{-1}. AEU 2 showed the lowest ET_0 and the highest was observed in AEU 15 (data not shown). This indicates the differences observed in the meteorological parameters within the study area and stress the need for having scientific water requirement (Gunter et al. 2009). The results are in accordance with Adeniran et al. 2010, which showed that ET_0 was lowest during the peak of the rainy season to highest during the peak of the dry season for the respective AEUs.

- **Total water requirement (ET_c)**

The total water requirements for different crops in various agro-ecological zones are given in Table 11.4. The total water requirement for paddy ranged from 1377 to 1668 mm. The lowest water requirement of paddy is recorded in *Viruppu* season (rainy) in all the zones. The results showed that ET_0 and ET_C were higher for crops with longer growing seasons than for those with shorter ones. Also ET_C were more during the dry season than the rainy season. This is similar to the FAO (2009) report, in that crop grown in the dry season needs more water than those grown during the rainy season. In short-term crop, the range of water requirement for low land rice was particularly high in Mundakkan season, because of very less or no rainfall. This data showed that there are differences in the case of total water requirement within the district mainly because of variation in meteorological parameters and the existing soil types. This shows that it is essential to plan a scientific water management schedule, so that higher productivity can be achieved with optimum water use.

Table 11.4: Total water requirement (mm) of crops in AEUs of Kozhikode district

Crops	AEU 2	AEU 7	AEU 11	AEU 15
Paddy[a]				
Viruppu	1401	1403	1403	1377
Mundakan	1605	1521	1522	1668
Puncha	1431	1529	1530	1489
Arecanut	1318	1344	1268	1432
Banana				
Sep - Aug[b]	1261	1184	1185	1335
May - Apr[c]	1273	1191	1193	1400
Coconut	1013	1059	1061	1066
Tapioca				
Sep to May	689	626	626	763
Feb to Oct[d]	558	632	633	579
Bitter gourd	461	434	434	514
Nutmeg	1320	1279	1281	1425
Rubber	1334	1284	1286	1447

a- In paddy, the values are inclusive of percolation losses @ 6mm day^{-1} and 300 mm towards land preparation (puddling); b – September planting; c- May planting; d- February planting

- **Net Irrigation requirement (NIR)**

The NIR of different crops in different AEUs are given in the Table 11.5. The net irrigation requirement for paddy ranged from 442 to 1483 mm. The lowest requirement is recorded during rainy *(Viruppu)* season for all the AEUs and the highest is recorded during s*ummer (Puncha)* season invariably for all the AEUs. Among the AEUs, AEU-15 recorded the lowest NIR of 442 mm for *Viruppu* season and AEU-7 recorded the highest NIR of 552 mm for the same season. This indicates the differences in water requirement even within a single district for the same period and hence it shows the significance of requirement of scientific planning for irrigation. The difference in the NIR in AEUs might be due to the combined effect of the temperature, sunshine hour, wind speed and the decrease in effective rainfall.

- **Water resources assessment**

The district is drained by six rivers, *viz.*, Chaliyar, Kuttiyadi, Mahe, Kadalundi, Kallayi and Korapuzha. Total water potential (available and utilizable) of these rivers are pooled and given in Table 6 for the district as whole. Utilizable water resources in the district are 1363 Mm^3 (CWRDM 1999). The net cultivated area of the district is 1, 55,677 ha, which is 66.3 % of the geographical area of the district. The major irrigation scheme of the district is Kuttiyadi irrigation project across the Kuttiyadi river, which caters to an area of 14556 ha. Block wise list of irrigated area under minor irrigation schemes are collected and it includes wells, bore wells and diversion structures. The gross area irrigated by both major and minor schemes in the district works out to 24,846 ha.

Table 11.5: Net irrigation requirement (mm) of different crops in various AEUs of Kozhikode

No.	Crops	AEU-2	AEU-7	AEU-11	AEU-15
1	**Paddy**[a]				
	Viruppu	526	552	521	442
	Mundakan	923	758	727	1086
	Puncha	1423	1483	1452	1431
2	**Arecanut**	514	593	487	511
3	**Banana**				
	Sep to Aug[b]	519	357	326	503
	May to Apr[c]	619	325	296	604
4	**Coconut**	396	416	391	356
5	**Tapioca**				
	Sep to May	359	147	131	333
	Feb to Oct[d]	42	170	152	39
6	**Bittergourd**	313	312	291	278
7	**Nutmeg**	513	515	489	502

a- In paddy, the values are inclusive of percolation losses @ 6 mm day^{-1} and 300 mm towards land preparation (puddling); b – September planting; c- May planting; d- February planting

- **Gross Irrigation demand**

Based on the irrigated area statistics, the net irrigation demand for each of the AEUs has been worked out both for major and minor irrigation schemes. The net irrigation requirement for Kozhikode district based on the current irrigated area is 412 $Mm^{3.}$ The gross irrigation demand for the Kozhikode district as a whole at 70% efficiency estimated to be 535 Mm^3.

Table 11.6: Total water potential of Kozhikode district				
Item	**Rainy June-Sept**	**Winter Oct-Jan**	**Summer Feb-May**	**Annual**
Available water resources				
Surface water (Mm^3)	3288.05	1080.93	135.1	4504.08
Groundwater (Mm^3)	87.76	87.79	117.15	292.7
Total	3375.8	1168.72	252.24	4796.78
Maximum utilizable water resources (for all consumptive uses)				
Utilizable surface water (Mm^3)	778.6	324.2	40.51	1143.3
Utilizable groundwater (Mm^3)	65.7	65.9	87.89	219.55
Utilizable total	844.32	390.15	128.4	1362.86

Future irrigation demands

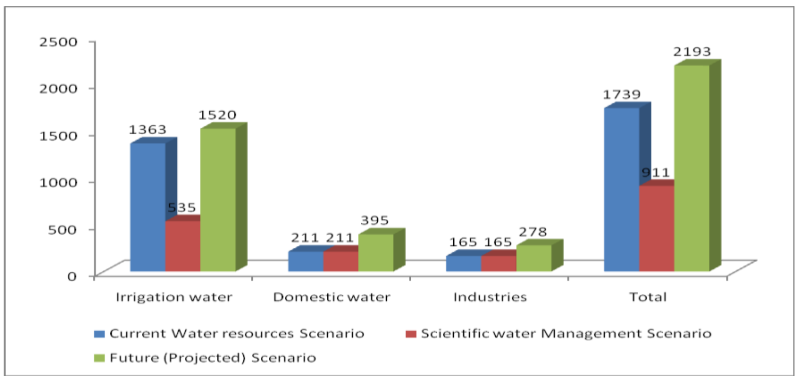

Fig. 11.1: Water demand for various sectors at current

The consumptive water demand in Kozhikode district comprises irrigation, domestic, and industrial requirements. The future net irrigation demand, assuming irrigation of the presently rain-fed cropped area, is estimated at 689 Mm³, which corresponds to a gross irrigation requirement of 985 Mm³ at 70% irrigation efficiency. Including the existing irrigated area, the total projected gross irrigation demand (excluding rubber) is 1520 Mm³ (Fig. 11.1).

Domestic water demand, estimated using IS 1172:1993, is 211 Mm³ at present and is projected to increase to 395 Mm³ by 2050 (CWRDM, 1999). Industrial water demand is currently about 165 Mm³, with a projected requirement of 278 Mm³.The utilizable yield of the six rivers in the district is 1363 Mm³. With scientifically managed irrigation based on crop water requirements, irrigation demand could be reduced to 911 Mm³, indicating potential for expansion of irrigated area. However, the projected total water demand including irrigation, domestic, and industrial sectors amounts to 2193 Mm³, resulting in a deficit of 830 Mm³. This deficit, compounded by reliability considerations, suggests that full irrigation of the entire cropped area may not be feasible during deficit years, necessitating deficit irrigation or reduction in command area.

The analysis highlights the need to enhance water-use efficiency, particularly in irrigation. Although monsoon periods generate surplus water, non-monsoon deficits can only be addressed through limited storage and improved water management. Given constraints on large-scale storage, scientific water management and conservation practices are essential.

The study suggests that complete irrigation of the cultivable area is unlikely. Therefore, policymakers and planners should promote water-saving agricultural practices, including micro-irrigation, crop diversification, drought-tolerant varieties, optimized cropping calendars, deficit irrigation, and advanced tillage and mulching techniques. Despite improvements since the 1980s, adoption of such practices remains limited. Integrated agricultural water-saving measures and optimized water allocation are critical to addressing the growing water scarcity in Kozhikode district.

Nutrient budgeting and development of DSS

This study adopts a holistic, multi-phase approach to derive fertilizer optima and enhance the sustainability of agro-production systems, aimed at breaking yield barriers in humid tropical regions. Although investigations were conducted in both Kerala and Tamil Nadu, the present discussion focuses exclusively on Kerala.

Kerala experiences a humid tropical climate with high rainfall, relative humidity, alternating wet-dry periods, and high temperatures. The state is a major producer of commercial crops such as coconut, arecanut, rubber, coffee, tea, cardamom, paddy, tapioca, and cashew. Despite crop diversity and multiple cropping systems, crop productivity remains low compared to national and global averages. Contributing factors include low fertility lateritic soils, undulating topography, high rainfall induced erosion and nutrient leaching, coupled with rising production costs. Climate variability further exacerbates constraints by affecting water availability, crop suitability, pest incidence, and yield stability. Except for rubber, most crops show comparatively low productivity, necessitating sustainable interventions. In this context, a DST-TIFAC funded project under the India-IIASA programme was implemented at CWRDM on *"Evaluation of soil nutrient budgets at field, farm and regional levels in the humid tropics of Kerala and development of a soil health management model"*. The objective was to assess soil fertility status and nutrient balances of major crops and cropping systems across plot, farm, and district scales, and to develop a Decision Support System (DSS) for sustainable soil fertility management. The approach integrated field experiments, nutrient stock-flow analysis, and regional assessments to identify fertility constraints and productivity enhancement strategies.

Field experiments indicated that 125% of the recommended NPK dose produced the highest yield (7685.9 kg ha^{-1}), significantly outperforming other treatments. Soil loss ranged from 0.0 to 14.44 t ha^{-1}, increasing with rainfall intensity. A strong positive correlation between rainfall and soil loss was observed ($r = 0.90$; $R^2 = 0.81$). Nutrient inflows and outflows were analyzed using the NUTMON model, linking rainfall with nutrient transfer functions for calibration and validation. Observed and simulated soil loss values showed good agreement in most cases; discrepancies were attributed to factors such as rainfall intensity, antecedent soil moisture, and canopy cover.

Additional experiments evaluated runoff, soil erosion, nutrient losses through runoff and leaching, and conservation measures including contour trenches (50 cm × 50 cm × 50 cm) and pineapple strip cropping across slopes. Model validation using combined experimental datasets confirmed the applicability of NUTMON under humid tropical conditions.

At the regional scale, Kozhikode district was selected, and 20 representative farms covering all agro-ecological units were assessed. Results showed universally low available soil N, medium to low K (12 farms medium, 8 low), and predominantly high P levels (15 farms). Farm-level nutrient budgeting revealed significant nutrient out flows, and Soil Health Cards with crop-specific fertilizer recommendations were issued. Regional nutrient balances computed using NUTMON indicated negative N and K balances and positive P balance, both at farm and district levels. The per hectare nutrient balance for Kozhikode district was 9.5 kg N ha^{-1} yr^{-1}, 17.2 kg K ha^{-1} yr^{-1}, and 7.4 kg P ha^{-1} yr^{-1}.

Overall, the NUTMON toolbox, applied across micro, meso and macro scales, revealed consistent depletion of soil N and K reserves and accumulation of P, underscoring the need to redefine nitrogen and potassium management strategies for long-term soil fertility and sustainable agricultural productivity in Kerala.

Construction of a decision support system (DSS)

DSSIFER (Decision Support System for Integrated Fertilizer Recommendation) is a computerized agricultural decision-support tool developed to generate site-specific, balanced fertilizer recommendations for most crops grown in Tamil Nadu. Based on validated fertilizer optima and soil test calibrations derived through a systematic research approach, DSSIFER was developed as a technology transfer tool to enhance fertilizer use efficiency, soil fertility, and sustainable crop productivity (Fig. 11.2).

The software utilizes soil test data on macro and micronutrients as inputs and first verifies the availability of site-specific fertilizer prescription equations from a database of 28 calibrated situations. When available, the user specifies a target yield, and fertilizer requirements are computed within predefined safe yield ranges. If unavailable, DSSIFER applies Mitscherlich–Bray functions stored for 24 site-specific situations to estimate N, P, and K requirements corresponding to 87.5, 93.75, and 96.875% yield sufficiency. In cases where neither database applies, recommendations are generated using blanket fertilizer doses, adjusted by ±25% based on soil nutrient status (low or high), or retained unchanged for medium fertility levels.

Micronutrient recommendations are generated using critical soil test thresholds for Zn, Cu, Mn, Fe and B. DSSIFER also provides management guidance for saline-alkali soil reclamation using soil pH and EC, and evaluates irrigation water quality, including recommendations for the safe use of marginal-quality water.

Nutrient balances were computed using the NUTMON toolbox, replacing farmers' fertilizer practices and yields with DSSIFER-generated fertilizer schedules and target yields. Results showed positive nutrient balances at both farm and district scales, with mean balances of 29.6, 14.7, and 10.4 kg ha^{-1} yr^{-1} for N, P, and K at farm level and 41.8, 55.1, and 19.9 kg ha^{-1} yr^{-1}, respectively, at district level (Table 11.7). These findings confirm that DSSIFER-based fertilizer programmes are balanced and sustainable.

Fig. 11.2: Screen capture of DSSIFER

Table 11.7: Nutrient balances at farm and district level after adopting DSSIFER generated integrated nutrient management strategy

Nutrient (kg ha^{-1})	Mean farm level nutrient balance		Mean	District level nutrient balance		Mean Coimbatore
	Coimbatore	Erode		Coimbatore	Erode	
N	25.9	33.3	29.6	63.9	19.6	41.8
P_2O_5	13.9	15.4	14.7	71.2	38.9	55.1
K_2O	10.5	10.2	10.4	37.7	2.1	19.9

Building on this work, a comprehensive DSS-CWRDM-Integrated Crop Nutrient Management Software (CWRDM-ICNMS) was developed by integrating project databases with secondary data sources. This system supports crop and site-specific nutrient recommendations for Kerala by accounting for all farm-level nutrient inflows and outflows, enabling identification of nutrient depletion and formulation of appropriate management strategies.

The study also compiled documentation on climate variability and future climate projections for Kozhikode district and evaluated the impacts of rising temperature, rainfall uncertainty, and CO_2 fertilization on soil, water and crop productivity under humid tropical conditions. In addition to DSS-based nutrient management, climate adaptation strategies to mitigate productivity losses were reviewed and discussed (Surendran et al., 2016). Overall, the outputs provide cost-effective, eco-friendly nutrient and resource management technologies that enhance input-use efficiency, productivity, and farm profitability while conserving natural resources in Kerala and Tamil Nadu.

Conclusions

The study demonstrates that site-specific, integrated nutrient management is essential for improving fertilizer use efficiency, sustaining soil fertility and enhancing crop productivity under humid tropical conditions. The development and application of DSS-based tools such as DSSIFER and CWRDM-ICNMS, supported by field experimentation and nutrient budgeting using the NUTMON toolbox, clearly indicate that conventional fertilizer practices lead to imbalanced nutrient use, particularly the depletion of nitrogen and potassium, while phosphorus tends to accumulate.

The DSS-generated fertilizer recommendations, when evaluated against farmer practices, resulted in positive nutrient balances at both farm and district levels, confirming their effectiveness in ensuring long-term sustainability of agro-production systems. By integrating soil test data, crop yield targets, water quality, soil constraints, and climate variability, these decision support systems provide a scientifically robust and user-friendly framework for rational fertilizer management.

The findings also highlight that improving agricultural productivity in Kerala and Tamil Nadu cannot rely solely on increased inputs but must emphasize efficient resource use, conservation practices, and climate-resilient management strategies. In the context of increasing climate variability, the adoption of DSS-based nutrient management combined with appropriate adaptation measures offers a cost-effective, eco-friendly pathway to sustain crop yields, profitability, and natural resource health. Wider dissemination and adoption of such decision support tools can significantly contribute to achieving sustainable and resilient agricultural systems in the humid tropics.

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Socio Economic Considerations for Land Use Planning

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Introduction

To meet the increasing demand for food and other essential necessities of the rapidly growing global population, the role of natural resources is becoming more critical. Soil, water and other natural resources are essential resources to meet the requirements of people. In the food and livestock production system, agricultural land is a very important non-renewable scarce resource used by farmers. Due to the finite and fragmented landholdings, food production is a challenge in the world and the pattern of land use can be impacted by social, economic and environmental factors. Unsuitable and irrational use of land leads to deterioration of soil quality, organic matter, soil nutrients and damages the soil structure, which reduces the production and productivity of agriculture. Changes in land use reflect different phases of socio-economic development and political climates, as well as environmental changes. To recognize the productive capacity of land, soil survey and crop yield in a given land type are the major aspects of evaluating the land areas. Keeping in view the concern, it becomes clear that there is a need to consider the socio-economic factors when land use planning is executed for the best use of available land resources and to assess the performance of used land. Socio-economic considerations for land use planning include population density, economic activities, and cultural needs, all of which are influenced by rapid urbanization, industrialization, and the country's agrarian economy. Effective planning must balance the land demand for residential, commercial and industrial uses with the need to preserve agricultural land for food security and the livelihoods of a significant portion of the population. Planning must also account for social equity, income levels and the specific cultural context of different regions to ensure sustainable development and mitigate potential conflicts and environmental degradation.

Economic considerations

Economic considerations for land use planning include assessing the economic benefits and costs of development, analyzing land and real estate market dynamics and understanding the link between land use, economic development and social equity. Planning must also incorporate factors like the economic impacts of land use changes, such as job creation and revenue and the long-term economic sustainability of land and resource preservation for future generations. Some important issues related to economic considerations discussed below:

- **Population pressure**: Increasing population and economic development lead to greater pressure on land for non-agricultural purposes.

- **Industrialization and urbanization**: Rapid industrial growth and urbanization drive demand for land, often at the expense of agricultural and rural areas.
- **Livelihoods and income**: Planning must protect agricultural land, as a large part of the population depends on it for their livelihood and income, especially given the small land parcel sizes per capita in India.
- **Economic development**: Land use planning must support economic development by allocating land for commercial, industrial and housing needs to generate wealth and employment.
- **Balancing costs and benefits**: Planners must weigh the economic costs of land use restrictions against the benefits of development, considering factors like land prices relative to wages in India.
- **Social considerations:** Social considerations for land use planning include ensuring equity and social justice, meeting community needs like affordable housing and public amenities, understanding and respecting cultural and traditional land values, and managing social impacts like displacement and livelihood changes. Planners must also consider the long-term needs of both current and future generations when making decisions. Some important issues related to social considerations discussed below:
    - **Population density**: High population density in urban areas creates a need for residential, commercial, and recreational spaces.
    - **Community needs**: Planning must address the needs of the community, including housing, education, recreation, and healthcare, ensuring equitable access across different areas.
    - **Cultural factors**: Land use decisions should be informed by the cultural preferences and social characteristics of local communities.
    - **Social equity and food security**: Planning must ensure that development does not lead to social exclusion and that food and income security are preserved for vulnerable populations.
    - **Stakeholder engagement**: Engaging with stakeholders is crucial to understand their preferred land uses and to build consensus for policies that serve the larger development vision.

Environmental and risk management considerations

Environmental and risk management in land use planning involve a risk-informed, sustainable approach to guide development, focusing on preventing harm to communities and ecosystems. Key considerations include identifying and mitigating hazards through zoning and building codes, reducing vulnerability by avoiding development in high-risk areas, protecting ecosystems and their services, managing the impacts of climate change and integrating environmental and risk assessments into all planning decisions. Some important issues related to environmental and risk management considerations discussed below:

- **Resource depletion**: Rapid land use change can lead to resource depletion and environmental degradation if not properly managed.
- **Risk assessment**: Planning should incorporate the analysis of natural and human-made risks to prevent settlement and development in hazardous areas.
- **Sustainable development**: Land use planning is essential for ensuring sustainable development and protecting biodiversity and natural resources for future generations.

Land use directly influences socio-economic conditions

- **Income and livelihoods:** Land use patterns, particularly the conversion of land, have significant impacts on the economy and local livelihoods. Urban areas often exhibit better socioeconomic indicators, such as higher incomes and lower poverty rates, than rural areas.
- **Social equity and inequality:** The location and type of land use can reinforce or alleviate social inequities. For instance, land use planning near large-scale industrial projects like railways can produce significant disparities in living conditions, with some areas experiencing greater prosperity while others face neglect.
- **Human well-being:** Planning decisions affect human well-being through access to housing, employment, and resources. For example, residential location shifts from urban centers to suburban areas, driven by desires for more land and escape from city pollution, can lead to urban sprawl and long-term ecological consequences.

Competing demands create conflicts and require trade-offs

- **Managing competing interests:** With increasing population and finite land, land use planning must resolve conflicts among various stakeholders, including residents, developers, and industries. It must balance land allocations for purposes like housing, industry, agriculture, and conservation.
- **Stakeholder engagement is essential:** Inclusive planning that involves local communities, governments, and the private sector is crucial. This engagement ensures that land use reflects the needs and preferences of the local population and helps resolve land disputes.

Sustainable land management requires integrated planning

- **Linking land use to ecosystem services:** Land use decisions directly affect the ecosystem services that communities depend on, such as food and water supply, carbon sequestration, and soil conservation. Effective planning must incorporate ecological data to protect these services.
- **Addressing environmental risks:** Land use planning is an effective tool for mitigating risks from natural hazards by restricting development in high-risk areas. For example, planning efforts can reduce coastal community exposure to tsunamis and manage floodplains more effectively.

Broader factors affect land use patterns

- **Demographic changes:** Population growth, density, and migration patterns significantly drive land-use change. Understanding these trends is crucial for anticipating demand for resources and planning for future needs.

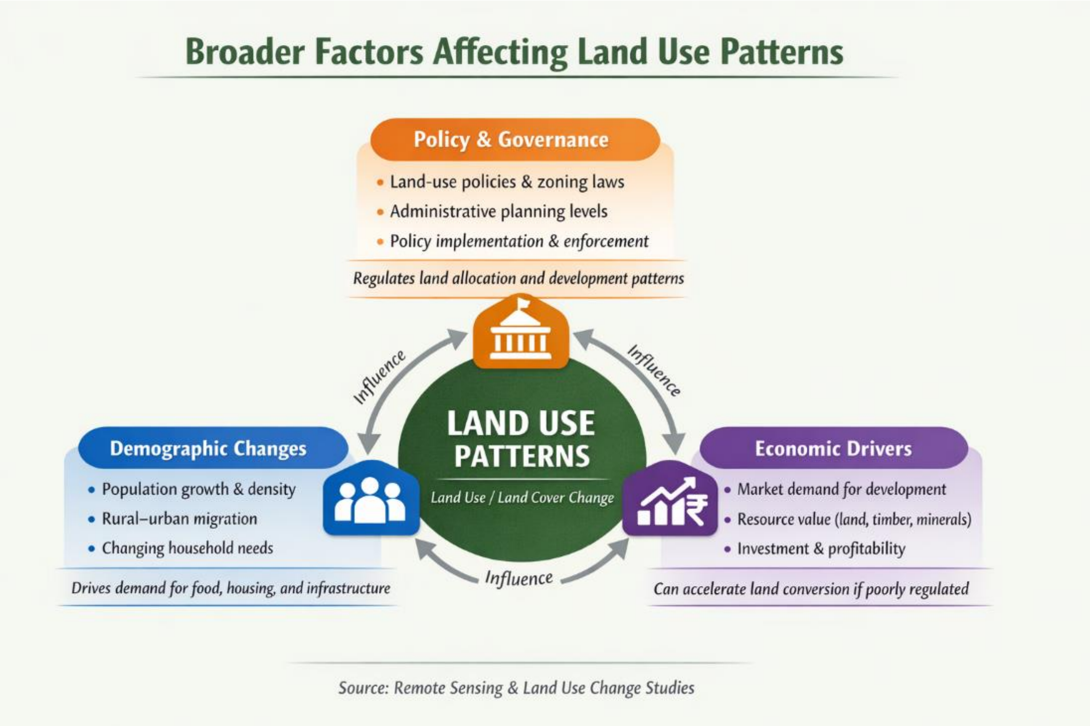

Fig. 12.1: Broader factors affecting land use pattern

- **Policy and governance:** Government policies, zoning laws, and administrative boundaries profoundly influence land use. The level of planning administration (e.g., national vs. local) and the implementation of specific policies can determine overall land use outcomes.

- **Economic drivers:** Economic incentives and market forces, such as the demand for development or the value of resources like timber and minerals, are major drivers of land use changes. However, prioritizing economic gain without considering social and environmental impacts can lead to unsustainable development.

Conclusions

In food production system, natural resources such as water, climate, land etc. are the major inputs and rational use of these resources is essential for present and future generations therefore, our key conclusions regarding socioeconomic considerations for land use planning include the critical need to balance competing demands for land, address social inequalities, and account for how land use patterns affect human well-being and economic development. Ignoring these dynamics can lead to unsustainable outcomes, such as resource depletion and increased social vulnerability.

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