La-Net

AGE 401

WATER AND LAND CONSERVATION EDUCATION

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Series 1: Foundations of Soil Conservation

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Introduction

Soil is the thin layer of weathered material covering the earth's surface that supports plant growth and serves as the foundation of all terrestrial agriculture. It represents one of humanity's most valuable and irreplaceable natural resources, yet it is subject to degradation through erosion, nutrient depletion, compaction, salinisation, and pollution at rates far exceeding its natural replenishment. In Nigeria, where agriculture supports approximately 70 percent of the rural population and contributes about 25 percent of GDP, the conservation and proper management of soil resources is an urgent national priority.

This Series establishes the foundational concepts of soil conservation by examining the importance and scope of soil and water engineering; the processes of soil formation and the physical and chemical properties of Nigerian soils; the agents and mechanisms of soil erosion and their impact on agricultural productivity; and the principles of soil fertility assessment and nutrient management. These foundations underpin the more specialised topics in subsequent series and are essential for understanding the science and practice of water and land conservation.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 1.1** define soil conservation, explain its importance, and describe the scope of soil and water engineering (Linked to Part 1.1),
- **SLO 1.2** describe the processes and factors of soil formation, classify soils by texture and structure, and explain soil drainage and water retention (Linked to Part 1.2),
- **SLO 1.3** identify the agents and types of soil erosion, explain the factors that affect erosion rate, and describe the effects of erosion on soil fertility and crop production (Linked to Part 1.3), and
- **SLO 1.4** explain how soil fertility is determined, describe methods of improving soil fertility, and identify the nutrients required for plant growth and their sources (Linked to Part 1.4).

1.1 Importance and Scope of Soil Conservation

1.1.1 Definition and importance of soil conservation

Soil conservation is the protection of soil from physical loss by erosion and from chemical deterioration through excessive leaching, acidification, salinisation, compaction, and contamination, while maintaining or improving its capacity to support plant growth. It encompasses all practices, policies, and technologies aimed at keeping soil in place, maintaining its structure and fertility, and ensuring that it continues to perform its ecological functions across generations. Soil conservation is distinct from but closely linked to water conservation: the two are addressed jointly because soil erosion is primarily driven by water and wind energy, and the loss of soil cover dramatically affects the quantity and quality of water in watersheds.

Importance of soil conservation: (1) Food security: Nigeria's population of over 220 million depends on soils for the production of all food consumed; the loss of topsoil through erosion removes the most nutrient-rich layer and directly reduces crop yields; estimates suggest that erosion costs Nigeria 3 to 5 percent of agricultural GDP annually through reduced crop productivity. (2) Water quality: eroded sediment loads increase the turbidity and nutrient content of streams and rivers (eutrophication); sedimentation of reservoirs (Kainji, Shiroro, Jebba dams) reduces their water storage capacity and hydropower output. (3) Watershed function: vegetated, well-structured soil regulates stream flow by absorbing rainfall and releasing it gradually; degraded soils generate flash floods that damage infrastructure, crops, and communities. (4) Biodiversity and carbon storage: soils store approximately three times as much carbon as the atmosphere; soil organic matter loss through erosion and tillage contributes to greenhouse gas emissions; healthy soils support diverse microbial, fungal, and invertebrate communities essential for nutrient cycling. (5) Infrastructure protection: erosion and gully formation undermine roads, bridges, buildings, and pipelines; Nigeria experiences severe annual infrastructure losses from gully erosion particularly in Anambra, Enugu, Imo, and Ebonyi states.

Fill in the blank: Soil conservation is the protection of soil from physical loss by ________ and from chemical deterioration through leaching, acidification, and compaction, while maintaining its capacity to support plant growth across generations.

1.1.2 Scope of soil and water engineering

Soil and water engineering (also called soil and water conservation engineering) is the branch of agricultural engineering that applies the principles of physics, hydrology, hydraulics, mechanics, and agronomy to the planning, design, construction, and management of structures, practices, and systems that conserve soil and water resources while supporting agricultural and other land uses. Its scope is broad and interdisciplinary, encompassing: (1) Erosion assessment and prediction: measuring and modelling the rates and patterns of soil erosion using empirical models (Universal Soil Loss Equation; Revised USLE), process-based models (WEPP; SWAT), and remote sensing data; identifying erosion hotspots and prioritising conservation interventions. (2) Conservation structure design: planning and designing terraces, contour bunds, grass waterways, check dams, gully plugs, and other physical structures that reduce erosion and manage runoff; requires knowledge of hydrology, soil mechanics, and construction materials. (3) Irrigation and drainage engineering: designing systems for delivering water to crops (gravity flow; sprinkler; drip) and removing excess water from waterlogged soils; managing salinity and waterlogging in irrigated areas.

(4) Watershed management: planning and coordinating land use, vegetation management, and conservation structures across entire catchments to optimise water yield, quality, and flood control; preparing watershed management plans that integrate engineering, biological, and agronomic measures. (5) Soil fertility and land improvement: designing and managing soil amendments, drainage works, and land levelling operations to improve the productive potential of degraded or inherently poor soils. (6) Environmental impact assessment: evaluating the potential environmental effects of agricultural development, irrigation schemes, and other land use changes on soil and water resources. In Nigeria, the Federal Ministry of Agriculture and Food Security (FMAFS), the Soil Science Society of Nigeria (SSSN), the River Basin Development Authorities (RBDAs), and the Nigerian Building and Road Research Institute (NBRRI) are among the institutions with mandates related to soil and water conservation engineering.

Fill in the blank: Soil and water conservation ________ applies principles of physics, hydrology, hydraulics, and agronomy to planning, designing, and managing structures and practices that conserve soil and water resources while supporting agricultural land use.

1.1.3 Soil conservation and crop production

The relationship between soil conservation and crop production is direct and profound. The productive capacity of agricultural land depends fundamentally on the quantity and quality of topsoil available to support crop growth. Topsoil, typically the uppermost 15 to 30 cm of the soil profile, contains the highest concentrations of organic matter, plant-available nutrients, soil microorganisms, and fine particles that retain water; it is the most valuable agricultural resource and the most vulnerable to erosion. When topsoil is lost to erosion at rates faster than it can be replaced by weathering and organic matter accumulation (which takes 200 to 1,000 years to form 1 cm of topsoil), agricultural productivity declines.

Evidence from Nigerian agricultural research: (1) Erosion impact on yields: studies on the Alfisols of south-western Nigeria show that for every centimetre of topsoil lost, maize yields decline by approximately 200 to 400 kg/ha; this decline intensifies as subsoil is exposed because subsoils have poorer physical and chemical properties. (2) Degradation cycle: unchecked erosion removes topsoil, exposing infertile subsoil or even parent material; farmers apply more fertiliser to maintain yields (increasing costs); the degraded soil retains fertiliser less well, accelerating nutrient losses; eventually the land is abandoned. (3) Positive feedback from conservation: conservation farming practices that maintain soil organic matter, residue cover, and soil structure have been shown to improve yields by 20 to 50 percent compared with conventional tillage in Nigerian conditions, while simultaneously reducing erosion rates by 60 to 90 percent; this demonstrates that conservation and productivity are complementary, not competing, objectives.

Fill in the blank: The topsoil (uppermost ________ to 30 cm) contains the highest concentrations of organic matter, nutrients, and microorganisms; for every centimetre of topsoil lost to erosion, maize yields in south-western Nigeria decline by approximately 200 to 400 kg/ha.

Pilot questions 1.1

1. Define soil conservation and state four reasons why it is important in Nigeria.

2. Describe the scope of soil and water engineering and name three Nigerian institutions with mandates in this area.
3. Explain how erosion affects crop production using evidence from Nigerian agricultural research.
4. Distinguish between soil conservation and soil fertility management.
5. State three ways in which soil erosion affects water quality and watershed function in Nigeria.

1.2 Soil Types, Formation, and Properties

1.2.1 Soil formation processes and factors

Soil formation (pedogenesis) is the process by which parent material (rock, sediment, or organic matter) is transformed into soil through the combined action of physical, chemical, and biological weathering processes over time. The five classic factors of soil formation, identified by Hans Jenny (1941), are: (1) Parent material: the mineral substrate from which soil develops; parent material determines the soil's initial mineralogy, texture, and chemical composition; soils derived from granite differ fundamentally from those derived from limestone, basalt, or alluvial sediments; in Nigeria, the parent materials range from Precambrian basement complex rocks (granite, gneiss, schist) in the north and south-west, to Cretaceous sedimentary formations (sandstone, shale, limestone) in the south-east and north-east, to alluvial and lacustrine sediments in river valleys and the Chad Basin. (2) Climate: temperature and rainfall control weathering rates and the type of soil-forming processes; high temperatures and high rainfall accelerate chemical weathering and leaching; Nigeria's humid south (above 1,500 mm/year) produces deeply weathered, leached Ferralsols and Nitisols; the semi-arid north (below 600 mm/year) produces shallower Lixisols and Cambisols with less leaching.

(3) Organisms: plants, animals, fungi, bacteria, and human activities are active agents of soil formation; plant roots penetrate and fragment rock; root exudates solubilise minerals; dead organic matter (litter, roots) contributes to soil organic matter; earthworms, termites, and other soil fauna mix and aerate the soil; microorganisms decompose organic matter and release plant-available nutrients. (4) Topography (relief): slope affects water movement, erosion, and deposition; deep, well-developed soils form on flat, stable upland surfaces; thin, poorly

developed soils form on steep slopes where erosion removes material as fast as it forms; valley bottoms receive eroded material and tend to have deeper, more fertile soils. (5) Time: soil formation is slow; a century of weathering produces millimetres of soil; thousands of years are required to develop a deep, well-differentiated soil profile with distinct horizons; young soils (Entisols; Inceptisols) have weakly differentiated profiles while old soils (Oxisols; Ultisols) are deeply weathered with highly differentiated horizons. The interaction of these five factors produces Nigeria's diverse soils.

Fill in the blank: The five factors of soil formation identified by Jenny (1941) are parent material, climate, ________, topography, and time; the interaction of these five factors determines the type, depth, and properties of soils formed in any location.

1.2.2 Soil texture, structure, and classification

Soil texture refers to the relative proportions of the three primary soil particle size fractions: sand (2.0 to 0.05 mm diameter); silt (0.05 to 0.002 mm); and clay (less than 0.002 mm). Texture is determined in the laboratory by hydrometer or pipette methods (particle size analysis) or in the field by the ribbon and feel method (experienced pedologists can estimate texture by the way a moistened soil ribbon between the fingers). The USDA textural triangle classifies soils into 12 textural classes (sandy, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, clay) based on the percentage of sand, silt, and clay. In Nigeria, most smallholder agricultural soils are sandy loams to clay loams; the extreme clay soils (Vertisols) of the Benue Valley and cotton-growing areas of the north-east are notable exceptions.

Soil structure refers to the arrangement of individual soil particles into aggregates (peds) and the pore spaces between them. Structure types: granular (spherical; characteristic of topsoil rich in organic matter; excellent for root penetration and water movement); blocky (angular or subangular blocks; common in subsoil; moderate permeability); platy (thin horizontal plates; impedes water movement; common in compacted or sodium-affected soils); prismatic or columnar (vertical prisms; common in subsoil of semi-arid soils; restricts lateral water movement). A well-structured soil with abundant, stable aggregates is said to have good tilth: it is easy to till, allows rapid root penetration, has good water infiltration, retains adequate moisture, and is resistant to crusting and erosion. Organic matter is the most important factor maintaining good soil structure in Nigerian agricultural soils; its decline under continuous cultivation without organic amendments leads to aggregate breakdown, surface crusting, increased runoff, and accelerated erosion. Soil classification systems (FAO/UNESCO World Reference Base; USDA Soil Taxonomy) organise soils into hierarchical groups based on diagnostic properties (colour, texture, structure, chemistry, horizon sequence).

Fill in the blank: Soil ________ refers to the arrangement of individual soil particles into aggregates (peds); good structure with stable, granular aggregates promotes water infiltration, root penetration, and erosion resistance, and is maintained primarily by soil organic matter.

1.2.3 Soil drainage, aeration, and water retention

Soil drainage refers to the rate at which water moves through and out of the soil profile, and is determined by the soil's texture, structure, porosity, and the permeability of underlying layers. Well-drained soils allow excess water to percolate downward within 24 to 48 hours after rain; poorly drained soils remain waterlogged for days, weeks, or seasonally. Drainage classes (USDA): excessively drained (very coarse sandy soils; droughts stress plants); well-drained (good for most crops); moderately well-drained; somewhat poorly drained; poorly drained; very poorly drained (seasonally or permanently waterlogged; requires drainage for crop production). The hydraulic conductivity (K_s; saturated) of a soil quantifies its ability to transmit water under saturated conditions; sandy soils have K_s values of 10 to 100 mm/hour while clay soils have K_s values of 0.1 to 5 mm/hour.

Soil aeration refers to the exchange of gases (primarily oxygen in, carbon dioxide out) between the soil pore space and the atmosphere; adequate aeration is essential for root respiration and aerobic microbial activity; waterlogged soils become anaerobic, producing toxic compounds (ethanol, methane, hydrogen sulphide) that damage roots and inhibit nutrient uptake. Soil water retention describes the soil's capacity to hold water against gravity for plant use. Key water content values: field capacity (FC; the water content retained 24 to 48 hours after saturation; approximately -33 kPa matric potential); permanent wilting point (PWP; the water content at which plants wilt permanently; approximately -1,500 kPa); plant-available water capacity (AWC = FC - PWP); expressed in mm of water per metre of soil depth. Loam soils have AWC of approximately 150 to 200 mm/m; sandy soils 60 to 100 mm/m; clay soils 100 to 160 mm/m. Drainage modification: installation of surface drains, subsurface tile drains, or mole drains improves drainage in poorly drained soils; raised beds reduce waterlogging for vegetable production; ridging and furrowing manage seasonal waterlogging in the humid south.

Fill in the blank: Plant-available water capacity (AWC) equals field capacity (FC) minus the permanent wilting point (________); it represents the soil water available for plant uptake and ranges from approximately 60 mm/m in sandy soils to 200 mm/m in loam soils.

Pilot questions 1.2

1. Name the five factors of soil formation and briefly explain how each influences the soils of Nigeria.
2. Explain the difference between soil texture and soil structure and state why each is important for agricultural production.
3. Define hydraulic conductivity and explain how soil texture affects it.
4. Define field capacity, permanent wilting point, and plant-available water capacity and explain their significance for irrigation scheduling.
5. Describe two methods of improving drainage in poorly drained Nigerian agricultural soils.

1.3 Soil Erosion: Processes and Agents

1.3.1 Agents and types of soil erosion

Soil erosion is the detachment, transport, and deposition of soil particles from their original position by natural agents (water, wind, gravity) or human activity. It is the primary form of soil degradation in Nigeria and in tropical agriculture globally. Types of erosion by agent: (1) Water erosion: the dominant form of erosion in most of Nigeria, driven by rainfall energy and surface runoff. Sub-types: splash erosion (raindrop impact detaches soil particles and flings them 1 to 2 m; breaks down surface aggregates and seals soil pores, reducing infiltration); sheet erosion (thin, uniform removal of surface soil by overland flow; difficult to see but collectively the most damaging; described as ‘slow death’ of soil productivity); rill erosion (concentrated flow forms small channels 1 to 30 cm deep that can be erased by tillage; intermediate stage between sheet and gully erosion); gully erosion (large permanent channels formed by concentrated runoff; cannot be crossed by farm machinery; destroys agricultural land; extremely common in south-eastern Nigeria, particularly in the soft sedimentary soils of Anambra, Enugu, Imo, and Cross River states; some Nigerian gullies exceed 50 m depth and 100 m width); streambank erosion (lateral erosion of river and stream banks by flowing water; particularly active during floods).

(2) Wind erosion: significant in the semi-arid and arid zones of northern Nigeria (Sokoto, Kebbi, Zamfara, Katsina, Kano, Jigawa, Borno, Yobe states) where vegetation cover is sparse and soils are dry and exposed during the harmattan season (November to March); wind erosion types: saltation (soil particles bounced along the surface; 50 to 75 percent of total wind erosion); suspension (fine clay and silt particles lifted and carried long distances by strong winds; harmattan dust deposited across Nigeria and even the South Atlantic Ocean); creep (slow rolling of large particles along the surface). (3) Gravity erosion (mass movement): includes slumping, slippage, and landslides on steep slopes; particularly relevant in the Jos Plateau, Mambilla Plateau, eastern highlands, and slopes near deeply incised rivers; triggered by saturation of slope materials during heavy rainfall. (4) Human-induced erosion: deforestation (removal of tree cover exposes soil to rainfall impact and reduces root binding); overgrazing (trampling destroys soil structure; removal of grass cover exposes soil to both water and wind erosion); poor tillage (deep tillage breaks up soil aggregates and leaves soil loose and vulnerable; tillage on slopes in the direction of steepest descent accelerates erosion).

Fill in the blank: The four sub-types of water erosion in order of increasing severity are: ________ erosion (raindrop impact), sheet erosion (uniform thin removal), rill erosion (small channels), and gully erosion (large permanent channels); gully erosion is the most visible and destructive form in south-eastern Nigeria.

1.3.2 Factors affecting soil erosion

The Universal Soil Loss Equation (USLE) and its revised version (RUSLE) express the average annual soil loss A as the product of six factors: A = R x K x L x S x C x P, where: R = rainfall erosivity (the energy and intensity of rainfall; the driving force of water erosion; higher in humid south Nigeria than in semi-arid north); K = soil erodibility (the susceptibility of a soil to erosion given a standard set of slope, cover, and rainfall conditions; sandy loams and silt loams are more erodible than clays or soils with high organic matter content); L = slope length factor (longer slopes accumulate more runoff and erode more); S = slope steepness factor (steeper slopes generate faster runoff and higher shear stress on the soil surface); C = cover management factor (ranges from near 0.001 for permanent forest to 1.0 for bare, freshly tilled soil; reflects the protection provided by crop canopy, crop residues, and surface mulch); P = support practice factor (reflects erosion control practices such as contouring, terracing, and strip cropping; ranges from near 0 to 1.0 where 1.0 means no erosion control practice is applied).

Practical implications of the USLE factors for Nigerian conditions: (1) R is highest at the onset of the rainy season in southern Nigeria when intense convective storms arrive before crops have established canopy cover; this is the most critical period for erosion control. (2) K is particularly high for the sandy soils of the south-east and the exposed basement complex regolith soils of the north; K is reduced by organic matter additions and stable soil aggregation. (3) L and S are high in the dissected terrain of the Jos Plateau, eastern highlands, and hills of south-west Nigeria; terracing and contour farming reduce the effective slope length and steepness. (4) C is the most manageable factor: maintaining mulch cover, using minimum tillage, intercropping, and maintaining ground cover throughout the year can reduce the C factor by 90 percent or more. (5) P measures the added benefit of specific conservation structures and practices: contouring reduces erosion by 40 to 60 percent; terracing by 75 to 95 percent relative to straight-row farming on the same slope.

Fill in the blank: In the USLE formula A = R x K x L x S x C x P, the C factor (cover management) is the most ________ factor; maintaining mulch cover, minimum tillage, and year-round ground cover can reduce C by 90 percent or more compared with bare, tilled soil.

1.3.3 Effects of erosion on soil fertility and crop production

Soil erosion selectively removes the finest and most fertile components of the soil: clay particles (which carry most of the soil's cation exchange capacity and nutrient-holding ability), organic matter (the primary store of nitrogen, phosphorus, and sulphur in most Nigerian soils), and the finest silt particles (which have the greatest surface area for nutrient adsorption). The enrichment ratio (the ratio of nutrient concentration in eroded sediment to nutrient concentration in the source soil) typically ranges from 2 to 5, meaning eroded material is 2 to 5 times more nutrient-rich per unit weight than the soil left behind; this makes erosion especially damaging even when the volume of soil lost appears modest. Effects on physical properties: loss of topsoil exposes subsoil or parent material with lower organic matter, coarser texture, poorer structure, lower water retention, and greater compactibility; surface crusting increases on eroded soils (less organic matter, more exposed silt and fine sand); water infiltration declines sharply; runoff and re-erosion accelerate (positive feedback loop).

Effects on nutrient status: topsoil loss depletes nitrogen (primarily in organic forms), phosphorus (adsorbed to organic matter and clay), potassium (exchangeable), calcium, magnesium, and micronutrients in proportion to their concentration in the topsoil; studies in south-western Nigeria show that complete removal of the top 10 cm of an Alfisol reduces available phosphorus by 40 to 60 percent, exchangeable cations by 30 to 50 percent, and organic carbon by 60 to 80 percent. Effects on crop yields in Nigeria: measured yield losses from erosion in Nigerian conditions range from 5 to 50 percent depending on the depth of topsoil lost, the crop, and whether and how fertiliser is applied to compensate; long-term on-site productivity costs of erosion are severe and include the compounding effect of each season's further loss on an already depleted base; off-site costs include sedimentation of waterways, flooding, and reservoir capacity loss.

Fill in the blank: The enrichment ratio of eroded sediment (2 to 5) means that eroded material is 2 to 5 times more ________ per unit weight than the remaining soil, making erosion especially damaging to soil fertility even when the volume of soil lost appears relatively modest.

Pilot questions 1.3

1. Name and describe four types of water erosion and state which is most destructive in south-eastern Nigeria.
2. Name the six factors in the USLE and explain which factor is most easily managed by Nigerian farmers.
3. Explain why erosion selectively removes the most fertile components of the soil.
4. State three physical and three chemical effects of topsoil loss on agricultural soils.
5. Explain why gully erosion is particularly severe in south-eastern Nigeria.

1.4 Soil Fertility and Nutrient Management

1.4.1 Determining soil fertility

Soil fertility refers to the capacity of a soil to supply plant-available nutrients in adequate amounts and in the right balance to support crop growth without toxic accumulation of any element. It is a dynamic property that changes with cropping, organic matter management, weathering, and amendment inputs. Soil fertility is not the same as soil productivity, which also depends on physical properties (drainage, texture, depth), climate, and management; a soil may be chemically fertile but physically limited (waterlogged, compacted) and therefore unproductive. Methods of determining soil fertility: (1) Soil chemical analysis (soil testing): extraction of soil samples (typically 0 to 15 cm depth for annual crops; 0 to 30 cm for tree crops) using standardised sampling procedures (20 to 30 sub-samples per field composited into one representative sample); laboratory analysis for pH, organic carbon (Walkley-Black wet oxidation or loss-on-ignition methods), available phosphorus (Bray-1 or Olsen method), exchangeable cations (K, Ca, Mg, Na; ammonium acetate extraction), total nitrogen (Kjeldahl digestion), micronutrients (DTPA or EDTA extraction); results interpreted against critical threshold levels specific to the target crop.

(2) Nutrient deficiency symptoms: visual diagnosis of deficiency symptoms provides a rapid, low-cost indication of fertility problems; characteristic symptoms: nitrogen deficiency (yellowing starting from older leaves; uniform chlorosis; stunted growth); phosphorus deficiency (purple discolouration of leaves, particularly on undersides; delayed maturity); potassium deficiency (scorching and browning of leaf margins, starting from older leaves); iron deficiency (interveinal chlorosis on young leaves in alkaline soils; common on calcareous soils in northern Nigeria); zinc deficiency (small leaves; shortened internodes; leaf striping in maize; widespread on Nigerian soils due to low inherent zinc levels and high pH); boron deficiency (growing tip death; distorted young leaves; affecting many crops on light sandy soils). (3) Biological indicators: soil microbial biomass and activity, earthworm populations, and soil fauna diversity serve as indicators of biological fertility; active earthworm populations indicate good soil health; low microbial biomass indicates organic matter depletion. (4) Plant tissue analysis: analysing the nutrient concentration in plant tissue (leaves, petioles, or whole shoots) at a standard growth

stage provides information on actual nutrient uptake and can diagnose sub-clinical deficiencies not visible in plant symptoms.

Fill in the blank: Soil fertility is determined by soil chemical analysis (soil testing), visual ________ deficiency symptoms, biological indicators (microbial biomass, earthworm populations), and plant tissue analysis; soil testing provides the most precise basis for fertiliser recommendations.

1.4.2 Methods of improving soil fertility

Soil fertility improvement encompasses all management practices that increase the supply of plant-available nutrients, improve the physical environment for root growth, and enhance the biological activity that drives nutrient cycling. Organic matter management: (1) Green manuring: incorporating fast-growing leguminous plants (Mucuna pruriens/velvet bean; Calopogonium mucunoides; Tithonia diversifolia/Mexican sunflower; Centrosema pubescens) into the soil before planting; these add nitrogen (from atmospheric fixation by associated Rhizobium bacteria), organic carbon, and other nutrients; green manure crops have been widely tested in the forest-savanna transition zone of Nigeria with nitrogen contributions of 80 to 200 kg N/ha equivalent. (2) Composting: decomposition of organic wastes (crop residues, animal manure, kitchen waste, market waste) under controlled conditions to produce a stable, nutrient-rich organic amendment; compost improves soil structure, water retention, and nutrient supply; compost quality depends on the C:N ratio of the feedstock (optimal 25:1 to 30:1 for rapid decomposition), moisture content, and aeration.

(3) Manure application: animal manure (poultry, cattle, swine, and small ruminants) is the most widely available organic amendment for Nigerian smallholders; poultry manure contains 3 to 4 percent nitrogen (dry weight basis); cattle manure 1.5 to 2 percent nitrogen; fresh manure must be composted or allowed to age before incorporation to prevent ammonia burn and pathogen transfer; recommended application rates of 5 to 10 t/ha significantly improve soil organic matter and crop yields in Nigerian conditions. (4) Crop residue retention: leaving crop residues (maize stover, sorghum stalks, cowpea haulms) on the soil surface as mulch or incorporating them into the soil; residues feed soil organisms, improve structure, reduce erosion, and contribute nutrients upon decomposition; burning residues (common practice among Nigerian farmers) destroys

organic matter and nutrients. (5) Agroforestry: integrating leguminous multipurpose trees (Gliricidia sepium; Leucaena leucocephala; Acacia species; Faidherbia albida) into farming systems to provide nitrogen through leaf litter, improve soil structure, and reduce erosion; widely promoted in Nigerian farming systems research.

Fill in the blank: Green manuring involves incorporating fast-growing ________ plants into the soil before planting; they add nitrogen through atmospheric fixation by Rhizobium bacteria and contribute organic carbon, with Nigerian studies showing nitrogen contributions of 80 to 200 kg N/ha equivalent.

1.4.3 Adding nutrients for plant growth

Crops remove nutrients from the soil with each harvest; these must be replaced to maintain soil fertility and sustain crop yields. Plant nutrition fundamentals: plants require 17 essential elements, classified as macronutrients (required in large amounts) and micronutrients (required in small amounts but equally essential). Macronutrients: (1) Primary macronutrients: nitrogen (N; component of amino acids, proteins, chlorophyll, nucleic acids; most frequently deficient in Nigerian soils; applied as urea $CO(NH_2)_2$; ammonium sulphate $(NH_4)_2SO_4$; calcium ammonium nitrate CAN; diammonium phosphate DAP); phosphorus (P; essential for root development, energy transfer (ATP), and seed formation; highly fixed in acid tropical soils; applied as single superphosphate SSP; triple superphosphate TSP; DAP); potassium (K; essential for stomatal regulation, enzyme activation, and stress tolerance; applied as muriate of potash KCl; sulphate of potash K_2SO_4). (2) Secondary macronutrients: calcium (Ca; cell wall structure; applied as lime $CaCO_3$ or gypsum $CaSO_4$); magnesium (Mg; chlorophyll core; applied as dolomite or magnesium sulphate); sulphur (S; protein synthesis; supplied as sulphate fertilisers or elemental sulphur).

Micronutrients: iron (Fe; chlorophyll synthesis; deficient on alkaline soils; applied as iron sulphate $FeSO_4$ or chelated iron); zinc (Zn; enzyme activation, auxin synthesis; most widespread micronutrient deficiency in Nigerian soils; applied as zinc sulphate $ZnSO_4$); boron (B; cell wall formation, pollen germination; applied as borax $Na_2B_4O_7$); manganese (Mn; photosynthesis; deficient on alkaline or organic soils); copper (Cu); molybdenum (Mo); chlorine (Cl). Fertiliser application principles: (1) Right source: match the nutrient form to the soil and crop requirements (urea is efficient on most soils; ammonia-based fertilisers acidify soils; avoid chloride-sensitive crops with KCl). (2) Right rate: based on yield goal, soil test values, and crop response curves; over-application wastes money and causes environmental damage (nitrate leaching, phosphorus runoff). (3) Right time: apply nitrogen close to periods of maximum crop uptake (split application for maize: basal NPK at planting + urea top-dressing at 4 to 6 weeks); avoid early pre-season application that allows leaching before crop establishment. (4) Right place: banding fertiliser close to roots (5 to 10 cm beside and below seed) increases efficiency compared with broadcasting; reduces phosphorus fixation.

Fill in the blank: The four principles of efficient fertiliser application are right ________, right rate, right time, and right place; applying nitrogen in split doses (basal at planting + top-dressing at 4 to 6 weeks) maximises uptake efficiency and reduces losses.

Nutrient	Symbol	Role in Plants	Deficiency Symptom	Fertiliser Source in Nigeria
Nitrogen	N	Promotes leaf growth, chlorophyll formation	Yellowing of older leaves (chlorosis)	Urea, ammonium sulphate, NPK fertiliser
Phosphorus	P	Root development, energy transfer (ATP)	Stunted growth, purplish leaves	Single superphosphate (SSP), diammonium phosphate (DAP)
Potassium	K	Enzyme activation, water regulation	Leaf scorching, weak stems	Muriate of potash (KCl), NPK blends
Calcium	Ca	Cell wall strength, root and shoot growth	Blossom end rot, distorted leaves	Agricultural lime, gypsum
Magnesium	Mg	Central atom in chlorophyll, enzyme cofactor	Interveinal chlorosis in older leaves	Dolomitic lime, magnesium sulphate
Sulphur	S	Protein synthesis, enzyme function	Yellowing of young leaves	Ammonium sulphate, gypsum
Iron	Fe	Chlorophyll synthesis, electron transport	Interveinal chlorosis in young leaves	Ferrous sulphate, chelated iron sprays

Zinc	Zn	Hormone regulation, enzyme activation	Stunted growth, small leaves, rosetting	Zinc sulphate, foliar zinc sprays
Boron	B	Cell wall formation, reproductive growth	Poor fruit set, hollow stems	Borax, boric acid
Manganese	Mn	Photosynthesis, enzyme activation	Interveinal chlorosis with brown spots	Manganese sulphate
Copper	Cu	Enzyme activity, lignin synthesis	Dieback of shoots, pale leaves	Copper sulphate, Bordeaux mixture
Molybdenum	Mo	Nitrogen fixation, nitrate reduction	Poor nodulation in legumes, yellow leaves	Ammonium molybdate, sodium molybdate

Box 1.1: Essential plant nutrients and their management in Nigerian agricultural soils

Pilot questions 1.4

1. State four methods of determining soil fertility and explain one in detail.
2. Describe three organic methods of improving soil fertility in Nigerian farming systems.
3. Name the three primary macronutrients and state one role and one fertiliser source for each.
4. Explain the four principles of efficient fertiliser application (4Rs) with one Nigerian crop example.
5. Explain why zinc deficiency is widespread in Nigerian soils and how it can be corrected.

Series Summary

This Series examined **soil conservation as the protection of soil against erosion, nutrient loss, structural damage, and chemical deterioration**. It is essential for food security, water quality, watershed protection, biodiversity, carbon storage, and infrastructure stability. Soil and water engineering applies hydrology, hydraulics, physics, and agronomy to erosion control, irrigation, drainage, watershed management, and environmental assessment. Soil formation is influenced by parent material, climate, organisms, topography, and time. Soil texture depends on the proportions of sand, silt, and clay, while soil structure refers to how particles are arranged into aggregates such as granular, blocky, platy, and prismatic forms. Soil water availability is expressed as **AWC = Field Capacity − Permanent Wilting Point**, and good organic matter management helps maintain favourable structure and drainage.

The Series also covered **erosion, soil fertility assessment, and fertility improvement**. Major erosion forms include splash, sheet, rill, gully, streambank, wind, gravity, and human-induced erosion. The Universal Soil Loss Equation is **$A = R \times K \times L \times S \times C \times P$**, with vegetation cover being one of the most manageable factors. Erosion removes fertile topsoil, organic matter, clay, and nutrients, thereby reducing crop yield. Soil fertility may be assessed through soil testing, deficiency symptoms, tissue analysis, and biological indicators. Improvement methods include green manuring, composting, manure application, crop-residue retention, agroforestry, and balanced fertiliser use. Important nutrient sources include urea and CAN for nitrogen, SSP and DAP for phosphorus, KCl for potassium, lime and gypsum for calcium, dolomite for magnesium, and zinc sulphate for zinc. Efficient nutrient management follows the **4R principles: right source, right rate, right time, and right place**.

Glossary of Terms

- **Available water capacity (AWC):** the amount of water in the soil available for plant uptake; calculated as field capacity (FC) minus permanent wilting point (PWP); ranges from approximately 60 mm/m in sandy soils to 200 mm/m in loam soils.

- **Enrichment ratio:** the ratio of nutrient concentration in eroded sediment to nutrient concentration in the source soil; typically 2 to 5; indicates that erosion preferentially removes the most nutrient-rich fine particles.
- **Field capacity (FC):** the soil water content retained 24 to 48 hours after saturation, when free drainage has ceased; corresponds to approximately -33 kPa matric potential; the upper limit of plant-available soil water.
- **Green manure:** a fast-growing crop (usually leguminous) grown specifically to be incorporated into the soil before planting to improve fertility; provides nitrogen (80 to 200 kg N/ha equivalent in Nigerian conditions), organic carbon, and soil structure improvement.
- **Gully erosion:** the most destructive form of water erosion; large permanent channels formed by concentrated surface runoff; cannot be crossed by farm machinery and destroys agricultural land; particularly severe in south-eastern Nigeria (Anambra, Enugu, Imo, Cross River states).
- **Hydraulic conductivity (K_s):** the rate at which water moves through saturated soil; measured in mm/hour; sandy soils: 10 to 100 mm/hour; clay soils: 0.1 to 5 mm/hour; determines drainage speed and irrigation response.
- **Permanent wilting point (PWP):** the soil water content at which plants wilt permanently and cannot recover; corresponds to approximately -1,500 kPa matric potential; the lower limit of plant-available soil water.
- **Pedogenesis:** the process of soil formation through physical, chemical, and biological weathering of parent material over time; controlled by five factors: parent material, climate, organisms, topography, and time (Jenny 1941).
- **Soil conservation:** the protection of soil from physical loss by erosion and from chemical deterioration, while maintaining or improving its capacity to support plant growth; encompasses practices, policies, and technologies to keep soil productive across generations.
- **Soil erodibility (K factor):** the susceptibility of a soil to detachment and transport by rainfall and runoff under a standard set of conditions; sandy loams and silt loams are more erodible than clays; reduced by organic matter additions and stable aggregation.
- **Soil erosion:** the detachment, transport, and deposition of soil particles from their original position by water, wind, or gravity; the primary form of soil degradation in Nigeria.
- **Soil fertility:** the capacity of a soil to supply plant-available nutrients in adequate amounts and in the right balance for crop growth; determined by chemical analysis, deficiency symptoms, biological indicators, and plant tissue analysis.

- **Soil structure:** the arrangement of individual soil particles into aggregates (peds); types: granular, blocky, platy, prismatic; good granular structure promotes water infiltration, root penetration, and erosion resistance.
- **Soil texture:** the relative proportions of sand (2 to 0.05 mm), silt (0.05 to 0.002 mm), and clay (less than 0.002 mm) in a soil; classified into 12 textural classes using the USDA textural triangle.
- **USLE (Universal Soil Loss Equation):** A = R x K x L x S x C x P; predicts average annual soil loss based on rainfall erosivity (R), soil erodibility (K), slope length (L), slope steepness (S), cover management (C), and support practice (P).

Concept Check Questions [Series 1]

Objective Questions

1. Soil conservation protects soil from physical loss by ________ and from chemical deterioration through leaching, acidification, and compaction. (Linked to SLO 1.1)
2. The five factors of soil formation identified by Jenny (1941) are parent material, climate, organisms, topography, and ________. (Linked to SLO 1.2)
3. In the USDA textural classification, the three primary particle size fractions are sand (2 to 0.05 mm), silt (0.05 to 0.002 mm), and ________ (less than 0.002 mm). (Linked to SLO 1.2)
4. In the USLE formula A = R x K x L x S x C x P, the ________ factor (cover management) is the most easily managed by Nigerian farmers; maintaining year-round mulch cover can reduce it by 90 percent. (Linked to SLO 1.3)
5. The enrichment ratio of eroded sediment (typically 2 to 5) means that eroded material is 2 to 5 times more ________ per unit weight than the remaining soil. (Linked to SLO 1.3)

Short-Answer Questions

6. Define soil conservation and state three reasons why it is important in Nigeria. (Linked to SLO 1.1)
7. Explain the difference between soil texture and soil structure and state why each matters for agriculture. (Linked to SLO 1.2)
8. Name the six factors in the USLE and state which is most manageable by farmers. (Linked to SLO 1.3)
9. State three physical and two chemical effects of topsoil loss by erosion on agricultural soils. (Linked to SLO 1.3)
10. Describe three organic methods of improving soil fertility in Nigerian farming systems. (Linked to SLO 1.4)

Long-Answer Questions

11. Describe the importance and scope of soil conservation in Nigeria. Explain soil formation factors, soil texture and structure, and soil drainage and water retention. (Linked to SLOs 1.1, 1.2)
12. Describe the agents, types, and factors affecting soil erosion. Explain the effects of erosion on soil fertility. Describe methods of determining and improving soil fertility and the principles of nutrient management. (Linked to SLOs 1.3, 1.4)

Answers to Concept Check Questions [Series 1]

Objective Questions

1. Erosion.
2. Time.
3. Clay.
4. C.
5. Nutrient-rich.

Short-Answer Questions

6. Soil conservation protects soil from erosion and chemical deterioration while maintaining its capacity to support plant growth. Three reasons: food security (erosion costs Nigeria 3 to 5 percent of agricultural GDP annually in lost productivity); water quality (eroded sediment increases turbidity and causes eutrophication of streams and reservoirs); infrastructure protection (gully erosion undermines roads and buildings, causing severe annual losses in south-eastern Nigeria).
7. Texture is the relative proportions of sand, silt, and clay; it is a permanent property that determines water retention, drainage speed, and erodibility. Structure is the arrangement of particles into aggregates (peds); it is dynamic and influenced by organic matter and tillage; good granular structure improves infiltration, root penetration, and erosion resistance. Texture cannot be changed by management; structure can be improved by adding organic matter.
8. R (rainfall erosivity), K (soil erodibility), L (slope length), S (slope steepness), C (cover management), P (support practice). C factor is most manageable; maintaining mulch cover and crop residues can reduce it by up to 90 percent.
9. Physical effects: exposed subsoil has poorer structure and lower water retention; surface crusting increases and infiltration declines; runoff and re-erosion accelerate. Chemical effects: available phosphorus is reduced by 40 to 60 percent; soil organic carbon declines by 60 to 80 percent when the top 10 cm of Alfisols in south-western Nigeria is lost.
10. Green manuring (incorporating leguminous crops; contributes 80 to 200 kg N/ha equivalent in Nigerian conditions). Composting (decomposing organic wastes at optimal C:N ratio of 25:1 to 30:1; improves structure and nutrient supply). Manure application (poultry manure at 5 to 10 t/ha; supplies nitrogen, phosphorus, and organic matter; improves soil health).

Long-Answer Questions

11. Soil conservation protects soil from erosion and chemical deterioration; important for food security (erosion costs 3 to 5 percent of agricultural GDP), water quality (sedimentation, eutrophication), watershed function (flood regulation), biodiversity and carbon storage, and infrastructure protection (gully erosion in south-east Nigeria). Scope of soil and water engineering: erosion assessment (USLE, RUSLE, SWAT); conservation structure design (terraces, bunds, check dams); irrigation and drainage; watershed management; soil fertility and land improvement; environmental impact assessment; Nigerian institutions: FMAFS, SSSN, RBDAs. Soil formation factors (Jenny 1941): parent material (determines mineralogy; Nigerian soils from Precambrian basement complex, Cretaceous sedimentary formations, alluvial sediments); climate (high rainfall in south produces Ferralsols; semi-arid north produces Lixisols); organisms (roots, soil fauna, microbes add organic matter and mix soil); topography (valley bottoms accumulate deeper, more fertile soils; steep slopes thin and eroded); time (thousands of years for full profile development). Texture: sand (2 to 0.05 mm), silt (0.05 to 0.002 mm), clay (less than 0.002 mm); 12 USDA classes. Structure: granular (topsoil; best for agriculture); blocky; platy (impedes drainage; compaction); prismatic; maintained by organic matter. Drainage: hydraulic conductivity (sandy 10 to 100 mm/hr; clay 0.1 to 5 mm/hr); AWC = FC minus PWP; loam AWC 150 to 200 mm/m; drainage improvement by surface drains, subsurface tiles, raised beds.
12. Erosion agents: water (splash, sheet, rill, gully, streambank; dominant in most of Nigeria); wind (semi-arid north; saltation, suspension, creep); gravity (mass movement on steep slopes); human-induced (deforestation, overgrazing, poor tillage). USLE: A = R x K x L x S x C x P; R highest at onset of rainy season; K high on sandy south-eastern soils; C most manageable (90 percent reduction with mulch cover); contouring reduces erosion 40 to 60 percent; terracing 75 to 95 percent. Erosion effects: selective removal of clay, organic matter, and silt (enrichment ratio 2 to 5); loss of top 10 cm reduces available P by 40 to 60 percent and organic C by 60 to 80 percent; surface crusting increases; infiltration declines; yield losses 5 to 50 percent in Nigeria. Fertility determination: soil testing (pH, OC, available P, exchangeable cations, N, micronutrients); deficiency symptoms (N: yellowing old leaves; P: purpling; K: scorched leaf margins; Zn: striping in maize); biological indicators; tissue analysis. Fertility improvement: green manuring (legumes; 80 to 200 kg N/ha); composting (C:N 25:1 to 30:1); manure (poultry 3 to 4 percent N; 5 to 10 t/ha); residue retention; agroforestry (Gliricidia, Leucaena). Nutrients: N (urea, CAN, DAP); P (SSP, TSP); K (KCl); Zn ($ZnSO_4$; most widespread micronutrient deficiency). 4R

principles: right source; right rate (soil test-based); right time (split N: basal + top-dress); right place (banding improves P efficiency).

Answers to Pilot Questions [Series 1]

Part 1.1

1. Soil conservation is the protection of soil from erosion and chemical deterioration while maintaining its capacity to support plant growth. Four reasons it is important in Nigeria: food security (erosion costs 3 to 5 percent of agricultural GDP; reduces crop yields); water quality (eroded sediment causes turbidity and eutrophication of streams and reservoirs); watershed function (healthy soils regulate stream flow and reduce flooding); infrastructure protection (gully erosion undermines roads and buildings in south-eastern Nigeria).
2. Soil and water engineering applies physics, hydrology, hydraulics, and agronomy to: erosion assessment and prediction; conservation structure design (terraces, bunds, check dams); irrigation and drainage engineering; watershed management; soil fertility and land improvement; and environmental impact assessment. Three Nigerian institutions: FMAFS (Federal Ministry of Agriculture and Food Security); SSSN (Soil Science Society of Nigeria); RBDAs (River Basin Development Authorities).
3. Studies on Alfisols in south-western Nigeria show that for each centimetre of topsoil lost, maize yields decline by 200 to 400 kg/ha. Loss of topsoil exposes infertile subsoil; farmers must apply more fertiliser to maintain yields; degraded soils retain fertiliser poorly, accelerating nutrient losses. Conservation farming practices that maintain soil cover and organic matter improve yields by 20 to 50 percent while reducing erosion by 60 to 90 percent.
4. Soil conservation focuses on preventing the physical loss of soil through erosion and its chemical deterioration (preventing the problem). Soil fertility management focuses on supplying and maintaining adequate plant-available nutrients (restoring or maintaining productivity); fertility management may be needed even in the absence of erosion, and conservation alone does not restore depleted nutrients.
5. Sedimentation (eroded sediment increases turbidity and deposits in rivers, streams, and reservoirs, reducing storage capacity and hydropower output). Eutrophication (nutrient-rich eroded material enriches water bodies, stimulating algal blooms that deplete oxygen and harm aquatic life). Flash

flooding (degraded soil surfaces with low infiltration generate rapid runoff, increasing peak flood flows that damage downstream infrastructure and communities).

Part 1.2

1. Parent material (determines initial mineralogy and texture; Nigerian soils from Precambrian basement complex, Cretaceous sedimentary formations, and alluvial sediments). Climate (high rainfall in humid south produces deeply leached Ferralsols; semi-arid north produces shallower Lixisols). Organisms (plants and soil fauna add organic matter; microbes decompose litter and release nutrients). Topography (valley bottoms accumulate deeper, more fertile soils; steep slopes develop thin soils due to erosion). Time (thousands of years needed for deep, well-differentiated profiles; young soils have weakly developed horizons).
2. Texture is the relative proportions of sand, silt, and clay; it is permanent and determines water retention, drainage speed, and inherent erodibility. Structure is the arrangement of particles into aggregates; it is dynamic and influenced by organic matter, tillage, and biological activity. Texture matters because it determines AWC, drainage class, and tilling difficulty; structure matters because good granular structure improves infiltration, root penetration, and erosion resistance.
3. Hydraulic conductivity (K_s) is the rate at which water moves through saturated soil (mm/hour). Sandy soils (large pores, little tortuosity): K_s = 10 to 100 mm/hour; water drains quickly but soil dries rapidly. Clay soils (small pores, high tortuosity): K_s = 0.1 to 5 mm/hour; water moves slowly; soils remain waterlogged after rain.
4. Field capacity (FC): water content retained 24 to 48 hours after saturation when free drainage has ceased (approximately -33 kPa); upper limit of plant-available water. Permanent wilting point (PWP): water content at which plants wilt permanently (approximately -1,500 kPa); lower limit. AWC = FC minus PWP; significance for irrigation: scheduling irrigations when soil moisture approaches PWP; AWC determines how much water can be stored between irrigations.
5. Installation of subsurface tile drains (perforated pipes buried 0.6 to 1.2 m deep to intercept and remove excess subsoil water). Construction of surface drains and open ditches (channels excavated to collect and divert surface water away from the field; effective for removing ponded water from flat, clay-dominated soils such as those in the Niger Delta and Benue floodplain).

Part 1.3

1. Splash erosion (raindrop impact detaches particles; seals surface pores). Sheet erosion (uniform thin removal of surface soil by overland flow; 'slow death' of productivity). Rill erosion (concentrated flow forms small channels 1 to 30 cm deep; erasable by tillage). Gully erosion

(large permanent channels; cannot be crossed by machinery; most destructive). Most destructive in south-eastern Nigeria: gully erosion; the soft Cretaceous sedimentary soils (sandstone, shale) of Anambra, Enugu, and Imo states are highly erodible and produce some of the worst gullies in Africa.

2. R (rainfall erosivity), K (soil erodibility), L (slope length), S (slope steepness), C (cover management), P (support practice). Most manageable factor: C (cover management); maintaining mulch cover, residues, and minimum tillage can reduce C by up to 90 percent compared with bare tilled soil at minimal cost to the farmer.
3. Erosion selectively removes clay particles (carry most cation exchange capacity), organic matter (primary store of N, P, and S), and fine silt (highest surface area for nutrient adsorption); these are the most fertile components of the soil. The enrichment ratio of 2 to 5 means eroded sediment is 2 to 5 times more nutrient-rich per unit weight than the source soil; so even modest volume loss causes disproportionate nutrient depletion.
4. Physical effects: exposed subsoil has poorer structure and lower water retention; surface crusting increases, reducing infiltration; runoff and re-erosion accelerate. Chemical effects: available phosphorus declines by 40 to 60 percent; soil organic carbon declines by 60 to 80 percent; exchangeable cations (K, Ca, Mg) decline by 30 to 50 percent when the top 10 cm of south-western Nigerian Alfisols is removed.
5. South-eastern Nigeria (Anambra, Enugu, Imo, Cross River states) is underlain by soft, unconsolidated Cretaceous sedimentary formations (sandstone, sandy shale) that are highly susceptible to detachment and transport. High seasonal rainfall (1,500 to 2,500 mm) combined with deforestation and loss of protective vegetation exposes these erodible soils to intense convective storms. Once a rill forms in these materials, it rapidly enlarges into a gully because the sandy subsoil has very low cohesion and high infiltration that generates concentrated seepage erosion (piping) below the surface.

Part 1.4

1. Soil testing (chemical analysis of pH, OC, available P, exchangeable cations, N, micronutrients; most precise basis for fertiliser recommendations). Visual deficiency symptoms (rapid, low-cost; N: yellowing old leaves; P: purpling; K: scorched leaf margins; Zn: leaf striping in maize). Biological indicators (earthworm populations; microbial biomass; indicate overall soil health). Plant tissue analysis (nutrient concentration in leaves or shoots at a standard growth stage; diagnoses sub-clinical deficiencies). Soil testing in detail: soil samples (20 to 30 sub-samples composited) are extracted with standardised reagents and analysed by laboratory for key

parameters; results are interpreted against crop-specific critical threshold levels to generate fertiliser recommendations.

2. Green manuring (leguminous crops incorporated before planting; contribute 80 to 200 kg N/ha equivalent through Rhizobium fixation; improve organic carbon and structure). Composting (organic wastes decomposed at C:N 25:1 to 30:1 to produce stable amendment; improves structure, water retention, and nutrient supply). Manure application (poultry manure at 5 to 10 t/ha; supplies N, P, and organic matter; most widely available organic amendment for Nigerian smallholders).
3. Nitrogen (component of proteins, chlorophyll, nucleic acids; applied as urea, CAN, or DAP). Phosphorus (essential for root development, energy transfer as ATP, and seed formation; applied as SSP, TSP, or DAP). Potassium (stomatal regulation, enzyme activation, and stress tolerance; applied as KCl or K2SO4).
4. Right source: match nutrient form to soil and crop (urea is efficient on most Nigerian soils; avoid chloride-sensitive crops with KCl). Right rate: based on soil test and yield goal (over-application wastes money and causes nitrate leaching). Right time: apply N close to maximum uptake periods (split application: basal NPK at planting + urea top-dress at 4 to 6 weeks for maize). Right place: band fertiliser 5 to 10 cm beside and below seed to improve efficiency and reduce phosphorus fixation.
5. Zinc deficiency is widespread because Nigerian soils are inherently low in plant-available zinc (low total Zn in the parent material; high pH in calcareous soils reduces Zn solubility; continuous cropping without Zn replacement further depletes supplies); it is the most common micronutrient deficiency affecting maize, sorghum, and vegetables. Correction: apply zinc sulphate (ZnSO4) at 5 to 10 kg Zn/ha as a soil application or foliar spray; ensure soil pH is not excessively high (above 7.5) where Zn becomes insoluble.

References and Attributions [Series 1]

Textual References (Books and External Sources)

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Figures, Plates, Tables, and Boxes

- Box 1.1: Essential plant nutrients and their management in Nigerian agricultural soils. Attribution: AI generated. Suggested OER search string: “essential plant nutrients deficiency symptoms fertiliser sources Nigeria soil table OER⇓.

Series 1: Foundations of Soil Conservation

- **Part 1.1: Importance and Scope of Soil Conservation**
  - Sub Part 1.1.1: Definition and importance of soil conservation
  - Sub Part 1.1.2: Scope of soil and water engineering
  - Sub Part 1.1.3: Soil conservation and crop production
- **Part 1.2: Soil Types, Formation, and Properties**
  - Sub Part 1.2.1: Soil formation processes and factors
  - Sub Part 1.2.2: Soil texture, structure, and classification
  - Sub Part 1.2.3: Soil drainage, aeration, and water retention
- **Part 1.3: Soil Erosion: Processes and Agents**
  - Sub Part 1.3.1: Agents and types of soil erosion
  - Sub Part 1.3.2: Factors affecting soil erosion
  - Sub Part 1.3.3: Effects of erosion on soil fertility and crop production
- **Part 1.4: Soil Fertility and Nutrient Management**
  - Sub Part 1.4.1: Determining soil fertility
  - Sub Part 1.4.2: Methods of improving soil fertility
  - Sub Part 1.4.3: Adding nutrients for plant growth

Introduction

Soil is the thin layer of weathered material covering the earth's surface that supports plant growth and serves as the foundation of all terrestrial agriculture. It represents one of humanity's most valuable and irreplaceable natural resources, yet it is subject to degradation through erosion, nutrient depletion, compaction, salinisation, and pollution at rates far exceeding its natural replenishment. In Nigeria, where agriculture supports approximately 70 percent of the rural population and contributes about 25 percent of GDP, the conservation and proper management of soil resources is an urgent national priority.

This Series establishes the foundational concepts of soil conservation by examining the importance and scope of soil and water engineering; the processes of soil formation and the physical and chemical properties of Nigerian soils; the agents and mechanisms of soil erosion and their impact on agricultural productivity; and the principles of soil fertility assessment and nutrient management. These foundations underpin the more specialised topics in subsequent series and are essential for understanding the science and practice of water and land conservation.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 1.1** define soil conservation, explain its importance, and describe the scope of soil and water engineering (Linked to Part 1.1),
- **SLO 1.2** describe the processes and factors of soil formation, classify soils by texture and structure, and explain soil drainage and water retention (Linked to Part 1.2),
- **SLO 1.3** identify the agents and types of soil erosion, explain the factors that affect erosion rate, and describe the effects of erosion on soil fertility and crop production (Linked to Part 1.3), and
- **SLO 1.4** explain how soil fertility is determined, describe methods of improving soil fertility, and identify the nutrients required for plant growth and their sources (Linked to Part 1.4).

1.1 Importance and Scope of Soil Conservation

1.1.1 Definition and importance of soil conservation

Soil conservation is the protection of soil from physical loss by erosion and from chemical deterioration through excessive leaching, acidification, salinisation, compaction, and contamination, while maintaining or improving its capacity to support plant growth. It encompasses all practices, policies, and technologies aimed at keeping soil in place, maintaining its structure and fertility, and ensuring that it continues to perform its ecological functions across generations. Soil conservation is distinct from but closely linked to water conservation: the two are addressed jointly because soil erosion is primarily driven by water and wind energy, and the loss of soil cover dramatically affects the quantity and quality of water in watersheds.

Importance of soil conservation: (1) Food security: Nigeria's population of over 220 million depends on soils for the production of all food consumed; the loss of topsoil through erosion removes the most nutrient-rich layer and directly reduces crop yields; estimates suggest that erosion costs Nigeria 3 to 5 percent of agricultural GDP annually through reduced crop productivity. (2) Water quality: eroded sediment loads increase the turbidity and nutrient content of streams and rivers (eutrophication); sedimentation of reservoirs (Kainji, Shiroro, Jebba dams) reduces their water storage capacity and hydropower output. (3) Watershed function: vegetated, well-structured soil regulates stream flow by absorbing rainfall and releasing it gradually; degraded soils generate flash floods that damage infrastructure, crops, and communities. (4) Biodiversity and carbon storage: soils store approximately three times as much carbon as the atmosphere; soil organic matter loss through erosion and tillage contributes to greenhouse gas emissions; healthy soils support diverse microbial, fungal, and invertebrate communities essential for nutrient cycling. (5) Infrastructure protection: erosion and gully formation undermine roads, bridges, buildings, and pipelines; Nigeria experiences severe annual infrastructure losses from gully erosion particularly in Anambra, Enugu, Imo, and Ebonyi states.

Fill in the blank: Soil conservation is the protection of soil from physical loss by ________ and from chemical deterioration through leaching, acidification, and compaction, while maintaining its capacity to support plant growth across generations.

1.1.2 Scope of soil and water engineering

Soil and water engineering (also called soil and water conservation engineering) is the branch of agricultural engineering that applies the principles of physics, hydrology, hydraulics, mechanics, and agronomy to the planning, design, construction, and management of structures, practices, and systems that conserve soil and water resources while supporting agricultural and other land uses. Its scope is broad and interdisciplinary, encompassing: (1) Erosion assessment and prediction: measuring and modelling the rates and patterns of soil erosion using empirical models (Universal Soil Loss Equation; Revised USLE), process-based models (WEPP; SWAT), and remote sensing data; identifying erosion hotspots and prioritising conservation interventions. (2) Conservation structure design: planning and designing terraces, contour bunds, grass waterways, check dams, gully plugs, and other physical structures that reduce erosion and manage runoff; requires knowledge of hydrology, soil mechanics, and construction materials. (3) Irrigation and drainage engineering: designing systems for delivering water to crops (gravity flow; sprinkler; drip) and removing excess water from waterlogged soils; managing salinity and waterlogging in irrigated areas.

(4) Watershed management: planning and coordinating land use, vegetation management, and conservation structures across entire catchments to optimise water yield, quality, and flood control; preparing watershed management plans that integrate engineering, biological, and agronomic measures. (5) Soil fertility and land improvement: designing and managing soil amendments, drainage works, and land levelling operations to improve the productive potential of degraded or inherently poor soils. (6) Environmental impact assessment: evaluating the potential environmental effects of agricultural development, irrigation schemes, and other land use changes on soil and water resources. In Nigeria, the Federal Ministry of Agriculture and Food Security (FMAFS), the Soil Science Society of Nigeria (SSSN), the River Basin Development Authorities (RBDAs), and the Nigerian Building and Road Research Institute (NBRRI) are among the institutions with mandates related to soil and water conservation engineering.

Fill in the blank: Soil and water conservation ________ applies principles of physics, hydrology, hydraulics, and agronomy to planning, designing, and managing structures and practices that conserve soil and water resources while supporting agricultural land use.

1.1.3 Soil conservation and crop production

The relationship between soil conservation and crop production is direct and profound. The productive capacity of agricultural land depends fundamentally on the quantity and quality of topsoil available to support crop growth. Topsoil, typically the uppermost 15 to 30 cm of the soil profile, contains the highest concentrations of organic matter, plant-available nutrients, soil microorganisms, and fine particles that retain water; it is the most valuable agricultural resource and the most vulnerable to erosion. When topsoil is lost to erosion at rates faster than it can be replaced by weathering and organic matter accumulation (which takes 200 to 1,000 years to form 1 cm of topsoil), agricultural productivity declines.

Evidence from Nigerian agricultural research: (1) Erosion impact on yields: studies on the Alfisols of south-western Nigeria show that for every centimetre of topsoil lost, maize yields decline by approximately 200 to 400 kg/ha; this decline intensifies as subsoil is exposed because subsoils have poorer physical and chemical properties. (2) Degradation cycle: unchecked erosion removes topsoil, exposing infertile subsoil or even parent material; farmers apply more fertiliser to maintain yields (increasing costs); the degraded soil retains fertiliser less well, accelerating nutrient losses; eventually the land is abandoned. (3) Positive feedback from conservation: conservation farming practices that maintain soil organic matter, residue cover, and soil structure have been shown to improve yields by 20 to 50 percent compared with conventional tillage in Nigerian conditions, while simultaneously reducing erosion rates by 60 to 90 percent; this demonstrates that conservation and productivity are complementary, not competing, objectives.

Fill in the blank: The topsoil (uppermost ________ to 30 cm) contains the highest concentrations of organic matter, nutrients, and microorganisms; for every centimetre of topsoil lost to erosion, maize yields in south-western Nigeria decline by approximately 200 to 400 kg/ha.

Pilot questions 1.1

1. Define soil conservation and state four reasons why it is important in Nigeria.

2. Describe the scope of soil and water engineering and name three Nigerian institutions with mandates in this area.
3. Explain how erosion affects crop production using evidence from Nigerian agricultural research.
4. Distinguish between soil conservation and soil fertility management.
5. State three ways in which soil erosion affects water quality and watershed function in Nigeria.

1.2 Soil Types, Formation, and Properties

1.2.1 Soil formation processes and factors

Soil formation (pedogenesis) is the process by which parent material (rock, sediment, or organic matter) is transformed into soil through the combined action of physical, chemical, and biological weathering processes over time. The five classic factors of soil formation, identified by Hans Jenny (1941), are: (1) Parent material: the mineral substrate from which soil develops; parent material determines the soil's initial mineralogy, texture, and chemical composition; soils derived from granite differ fundamentally from those derived from limestone, basalt, or alluvial sediments; in Nigeria, the parent materials range from Precambrian basement complex rocks (granite, gneiss, schist) in the north and south-west, to Cretaceous sedimentary formations (sandstone, shale, limestone) in the south-east and north-east, to alluvial and lacustrine sediments in river valleys and the Chad Basin. (2) Climate: temperature and rainfall control weathering rates and the type of soil-forming processes; high temperatures and high rainfall accelerate chemical weathering and leaching; Nigeria's humid south (above 1,500 mm/year) produces deeply weathered, leached Ferralsols and Nitisols; the semi-arid north (below 600 mm/year) produces shallower Lixisols and Cambisols with less leaching.

(3) Organisms: plants, animals, fungi, bacteria, and human activities are active agents of soil formation; plant roots penetrate and fragment rock; root exudates solubilise minerals; dead organic matter (litter, roots) contributes to soil organic matter; earthworms, termites, and other soil fauna mix and aerate the soil; microorganisms decompose organic matter and release plant-available nutrients. (4) Topography (relief): slope affects water movement, erosion, and

deposition; deep, well-developed soils form on flat, stable upland surfaces; thin, poorly developed soils form on steep slopes where erosion removes material as fast as it forms; valley bottoms receive eroded material and tend to have deeper, more fertile soils. (5) Time: soil formation is slow; a century of weathering produces millimetres of soil; thousands of years are required to develop a deep, well-differentiated soil profile with distinct horizons; young soils (Entisols; Inceptisols) have weakly differentiated profiles while old soils (Oxisols; Ultisols) are deeply weathered with highly differentiated horizons. The interaction of these five factors produces Nigeria's diverse soils.

Fill in the blank: The five factors of soil formation identified by Jenny (1941) are parent material, climate, ________, topography, and time; the interaction of these five factors determines the type, depth, and properties of soils formed in any location.

1.2.2 Soil texture, structure, and classification

Soil texture refers to the relative proportions of the three primary soil particle size fractions: sand (2.0 to 0.05 mm diameter); silt (0.05 to 0.002 mm); and clay (less than 0.002 mm). Texture is determined in the laboratory by hydrometer or pipette methods (particle size analysis) or in the field by the ribbon and feel method (experienced pedologists can estimate texture by the way a moistened soil ribbon between the fingers). The USDA textural triangle classifies soils into 12 textural classes (sandy, loamy sand, sandy loam, loam, silt loam, silt, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, clay) based on the percentage of sand, silt, and clay. In Nigeria, most smallholder agricultural soils are sandy loams to clay loams; the extreme clay soils (Vertisols) of the Benue Valley and cotton-growing areas of the north-east are notable exceptions.

Soil structure refers to the arrangement of individual soil particles into aggregates (peds) and the pore spaces between them. Structure types: granular (spherical; characteristic of topsoil rich in organic matter; excellent for root penetration and water movement); blocky (angular or subangular blocks; common in subsoil; moderate permeability); platy (thin horizontal plates; impedes water movement; common in compacted or sodium-affected soils); prismatic or columnar (vertical prisms; common in subsoil of semi-arid soils; restricts lateral water movement). A well-structured soil with abundant, stable aggregates is said to have good tilth: it is easy to till, allows rapid root penetration, has good water infiltration, retains adequate moisture, and is resistant to crusting and erosion. Organic matter is the most important factor maintaining good soil structure in Nigerian agricultural soils; its decline under continuous cultivation without organic amendments leads to aggregate breakdown, surface crusting, increased runoff, and accelerated erosion. Soil classification systems (FAO/UNESCO World Reference Base; USDA Soil Taxonomy) organise soils into hierarchical groups based on diagnostic properties (colour, texture, structure, chemistry, horizon sequence).

Fill in the blank: Soil ________ refers to the arrangement of individual soil particles into aggregates (peds); good structure with stable, granular aggregates promotes water infiltration, root penetration, and erosion resistance, and is maintained primarily by soil organic matter.

1.2.3 Soil drainage, aeration, and water retention

Soil drainage refers to the rate at which water moves through and out of the soil profile, and is determined by the soil's texture, structure, porosity, and the permeability of underlying layers. Well-drained soils allow excess water to percolate downward within 24 to 48 hours after rain; poorly drained soils remain waterlogged for days, weeks, or seasonally. Drainage classes (USDA): excessively drained (very coarse sandy soils; droughts stress plants); well-drained (good for most crops); moderately well-drained; somewhat poorly drained; poorly drained; very poorly drained (seasonally or permanently waterlogged; requires drainage for crop production). The hydraulic conductivity (K_s; saturated) of a soil quantifies its ability to transmit water under saturated conditions; sandy soils have K_s values of 10 to 100 mm/hour while clay soils have K_s values of 0.1 to 5 mm/hour.

Soil aeration refers to the exchange of gases (primarily oxygen in, carbon dioxide out) between the soil pore space and the atmosphere; adequate aeration is essential for root respiration and aerobic microbial activity; waterlogged soils become anaerobic, producing toxic compounds (ethanol, methane, hydrogen sulphide) that damage roots and inhibit nutrient uptake. Soil water retention describes the soil's capacity to hold water against gravity for plant use. Key water content values: field capacity (FC; the water content retained 24 to 48 hours after saturation; approximately -33 kPa matric potential); permanent wilting point (PWP; the water content at which plants wilt permanently; approximately -1,500 kPa); plant-available water capacity (AWC

= FC - PWP); expressed in mm of water per metre of soil depth. Loam soils have AWC of approximately 150 to 200 mm/m; sandy soils 60 to 100 mm/m; clay soils 100 to 160 mm/m. Drainage modification: installation of surface drains, subsurface tile drains, or mole drains improves drainage in poorly drained soils; raised beds reduce waterlogging for vegetable production; ridging and furrowing manage seasonal waterlogging in the humid south.

Fill in the blank: Plant-available water capacity (AWC) equals field capacity (FC) minus the permanent wilting point (________); it represents the soil water available for plant uptake and ranges from approximately 60 mm/m in sandy soils to 200 mm/m in loam soils.

Pilot questions 1.2

1. Name the five factors of soil formation and briefly explain how each influences the soils of Nigeria.
2. Explain the difference between soil texture and soil structure and state why each is important for agricultural production.
3. Define hydraulic conductivity and explain how soil texture affects it.
4. Define field capacity, permanent wilting point, and plant-available water capacity and explain their significance for irrigation scheduling.
5. Describe two methods of improving drainage in poorly drained Nigerian agricultural soils.

1.3 Soil Erosion: Processes and Agents

1.3.1 Agents and types of soil erosion

Soil erosion is the detachment, transport, and deposition of soil particles from their original position by natural agents (water, wind, gravity) or human activity. It is the primary form of soil degradation in Nigeria and in tropical agriculture globally. Types of erosion by agent: (1) Water erosion: the dominant form of erosion in most of Nigeria, driven by rainfall energy and surface runoff. Sub-types: splash erosion (raindrop impact detaches soil particles and flings them 1 to 2 m; breaks down surface aggregates and seals soil pores, reducing infiltration); sheet erosion (thin, uniform removal of surface soil by overland flow; difficult to see but collectively the most damaging; described as 'slow death' of soil productivity); rill erosion (concentrated flow forms small channels 1 to 30 cm deep that can be erased by tillage; intermediate stage between sheet and gully erosion); gully erosion (large permanent channels formed by concentrated runoff; cannot be crossed by farm machinery; destroys agricultural land; extremely common in south-eastern Nigeria, particularly in the soft sedimentary soils of Anambra, Enugu, Imo, and Cross River states; some Nigerian gullies exceed 50 m depth and 100 m width); streambank erosion (lateral erosion of river and stream banks by flowing water; particularly active during floods).

(2) Wind erosion: significant in the semi-arid and arid zones of northern Nigeria (Sokoto, Kebbi, Zamfara, Katsina, Kano, Jigawa, Borno, Yobe states) where vegetation cover is sparse and soils are dry and exposed during the harmattan season (November to March); wind erosion types: saltation (soil particles bounced along the surface; 50 to 75 percent of total wind erosion); suspension (fine clay and silt particles lifted and carried long distances by strong winds; harmattan dust deposited across Nigeria and even the South Atlantic Ocean); creep (slow rolling of large particles along the surface). (3) Gravity erosion (mass movement): includes slumping, slippage, and landslides on steep slopes; particularly relevant in the Jos Plateau, Mambilla Plateau, eastern highlands, and slopes near deeply incised rivers; triggered by saturation of slope materials during heavy rainfall. (4) Human-induced erosion: deforestation (removal of tree cover exposes soil to rainfall impact and reduces root binding); overgrazing (trampling destroys soil structure; removal of grass cover exposes soil to both water and wind erosion); poor tillage (deep tillage breaks up soil aggregates and leaves soil loose and vulnerable; tillage on slopes in the direction of steepest descent accelerates erosion).

Fill in the blank: The four sub-types of water erosion in order of increasing severity are: ________ erosion (raindrop impact), sheet erosion (uniform thin removal), rill erosion (small channels), and gully erosion (large permanent channels); gully erosion is the most visible and destructive form in south-eastern Nigeria.

1.3.2 Factors affecting soil erosion

The Universal Soil Loss Equation (USLE) and its revised version (RUSLE) express the average annual soil loss A as the product of six factors: $A = R \times K \times L \times S \times C \times P$, where: R = rainfall erosivity (the energy and intensity of rainfall; the driving force of water erosion; higher in humid south Nigeria than in semi-arid north); K = soil erodibility (the susceptibility of a soil to erosion given a standard set of slope, cover, and rainfall conditions; sandy loams and silt loams are more erodible than clays or soils with high organic matter content); L = slope length factor (longer slopes accumulate more runoff and erode more); S = slope steepness factor (steeper slopes generate faster runoff and higher shear stress on the soil surface); C = cover management factor (ranges from near 0.001 for permanent forest to 1.0 for bare, freshly tilled soil; reflects the protection provided by crop canopy, crop residues, and surface mulch); P = support practice factor (reflects erosion control practices such as contouring, terracing, and strip cropping; ranges from near 0 to 1.0 where 1.0 means no erosion control practice is applied).

Practical implications of the USLE factors for Nigerian conditions: (1) R is highest at the onset of the rainy season in southern Nigeria when intense convective storms arrive before crops have established canopy cover; this is the most critical period for erosion control. (2) K is particularly high for the sandy soils of the south-east and the exposed basement complex regolith soils of the north; K is reduced by organic matter additions and stable soil aggregation. (3) L and S are high in the dissected terrain of the Jos Plateau, eastern highlands, and hills of south-west Nigeria; terracing and contour farming reduce the effective slope length and steepness. (4) C is the most manageable factor: maintaining mulch cover, using minimum tillage, intercropping, and maintaining ground cover throughout the year can reduce the C factor by 90 percent or more. (5) P measures the added benefit of specific conservation structures and practices: contouring reduces erosion by 40 to 60 percent; terracing by 75 to 95 percent relative to straight-row farming on the same slope.

Fill in the blank: In the USLE formula A = R x K x L x S x C x P, the C factor (cover management) is the most ________ factor; maintaining mulch cover, minimum tillage, and year-round ground cover can reduce C by 90 percent or more compared with bare, tilled soil.

1.3.3 Effects of erosion on soil fertility and crop production

Soil erosion selectively removes the finest and most fertile components of the soil: clay particles (which carry most of the soil's cation exchange capacity and nutrient-holding ability), organic matter (the primary store of nitrogen, phosphorus, and sulphur in most Nigerian soils), and the finest silt particles (which have the greatest surface area for nutrient adsorption). The enrichment ratio (the ratio of nutrient concentration in eroded sediment to nutrient concentration in the source soil) typically ranges from 2 to 5, meaning eroded material is 2 to 5 times more nutrient-rich per unit weight than the soil left behind; this makes erosion especially damaging even when the volume of soil lost appears modest. Effects on physical properties: loss of topsoil exposes subsoil or parent material with lower organic matter, coarser texture, poorer structure, lower water retention, and greater compactibility; surface crusting increases on eroded soils (less organic matter, more exposed silt and fine sand); water infiltration declines sharply; runoff and re-erosion accelerate (positive feedback loop).

Effects on nutrient status: topsoil loss depletes nitrogen (primarily in organic forms), phosphorus (adsorbed to organic matter and clay), potassium (exchangeable), calcium, magnesium, and micronutrients in proportion to their concentration in the topsoil; studies in south-western Nigeria show that complete removal of the top 10 cm of an Alfisol reduces available phosphorus by 40 to 60 percent, exchangeable cations by 30 to 50 percent, and organic carbon by 60 to 80 percent. Effects on crop yields in Nigeria: measured yield losses from erosion in Nigerian conditions range from 5 to 50 percent depending on the depth of topsoil lost, the crop, and whether and how fertiliser is applied to compensate; long-term on-site productivity costs of erosion are severe and include the compounding effect of each season's further loss on an already depleted base; off-site costs include sedimentation of waterways, flooding, and reservoir capacity loss.

Fill in the blank: The enrichment ratio of eroded sediment (2 to 5) means that eroded material is 2 to 5 times more ________ per unit weight than the remaining soil, making erosion especially damaging to soil fertility even when the volume of soil lost appears relatively modest.

Pilot questions 1.3

1. Name and describe four types of water erosion and state which is most destructive in south-eastern Nigeria.
2. Name the six factors in the USLE and explain which factor is most easily managed by Nigerian farmers.
3. Explain why erosion selectively removes the most fertile components of the soil.
4. State three physical and three chemical effects of topsoil loss on agricultural soils.
5. Explain why gully erosion is particularly severe in south-eastern Nigeria.

1.4 Soil Fertility and Nutrient Management

1.4.1 Determining soil fertility

Soil fertility refers to the capacity of a soil to supply plant-available nutrients in adequate amounts and in the right balance to support crop growth without toxic accumulation of any element. It is a dynamic property that changes with cropping, organic matter management, weathering, and amendment inputs. Soil fertility is not the same as soil productivity, which also depends on physical properties (drainage, texture, depth), climate, and management; a soil may be chemically fertile but physically limited (waterlogged, compacted) and therefore unproductive. Methods of determining soil fertility: (1) Soil chemical analysis (soil testing): extraction of soil samples (typically 0 to 15 cm depth for annual crops; 0 to 30 cm for tree crops) using standardised sampling procedures (20 to 30 sub-samples per field composited into one representative sample); laboratory analysis for pH, organic carbon (Walkley-Black wet oxidation or loss-on-ignition methods), available phosphorus (Bray-1 or Olsen method), exchangeable cations (K, Ca, Mg, Na; ammonium acetate extraction), total nitrogen (Kjeldahl digestion), micronutrients (DTPA or EDTA extraction); results interpreted against critical threshold levels specific to the target crop.

(2) Nutrient deficiency symptoms: visual diagnosis of deficiency symptoms provides a rapid, low-cost indication of fertility problems; characteristic symptoms: nitrogen deficiency (yellowing starting from older leaves; uniform chlorosis; stunted growth); phosphorus deficiency (purple discolouration of leaves, particularly on undersides; delayed maturity); potassium deficiency (scorching and browning of leaf margins, starting from older leaves); iron deficiency (interveinal chlorosis on young leaves in alkaline soils; common on calcareous soils in northern Nigeria); zinc deficiency (small leaves; shortened internodes; leaf striping in maize; widespread on Nigerian soils due to low inherent zinc levels and high pH); boron deficiency (growing tip death; distorted young leaves; affecting many crops on light sandy soils). (3) Biological indicators: soil microbial biomass and activity, earthworm populations, and soil fauna diversity serve as indicators of biological fertility; active earthworm populations indicate good soil health; low microbial biomass indicates organic matter depletion. (4) Plant tissue analysis: analysing the

nutrient concentration in plant tissue (leaves, petioles, or whole shoots) at a standard growth stage provides information on actual nutrient uptake and can diagnose sub-clinical deficiencies not visible in plant symptoms.

Fill in the blank: Soil fertility is determined by soil chemical analysis (soil testing), visual ________ deficiency symptoms, biological indicators (microbial biomass, earthworm populations), and plant tissue analysis; soil testing provides the most precise basis for fertiliser recommendations.

1.4.2 Methods of improving soil fertility

Soil fertility improvement encompasses all management practices that increase the supply of plant-available nutrients, improve the physical environment for root growth, and enhance the biological activity that drives nutrient cycling. Organic matter management: (1) Green manuring: incorporating fast-growing leguminous plants (Mucuna pruriens/velvet bean; Calopogonium mucunoides; Tithonia diversifolia/Mexican sunflower; Centrosema pubescens) into the soil before planting; these add nitrogen (from atmospheric fixation by associated Rhizobium bacteria), organic carbon, and other nutrients; green manure crops have been widely tested in the forest-savanna transition zone of Nigeria with nitrogen contributions of 80 to 200 kg N/ha equivalent. (2) Composting: decomposition of organic wastes (crop residues, animal manure, kitchen waste, market waste) under controlled conditions to produce a stable, nutrient-rich organic amendment; compost improves soil structure, water retention, and nutrient supply; compost quality depends on the C:N ratio of the feedstock (optimal 25:1 to 30:1 for rapid decomposition), moisture content, and aeration.

(3) Manure application: animal manure (poultry, cattle, swine, and small ruminants) is the most widely available organic amendment for Nigerian smallholders; poultry manure contains 3 to 4 percent nitrogen (dry weight basis); cattle manure 1.5 to 2 percent nitrogen; fresh manure must be composted or allowed to age before incorporation to prevent ammonia burn and pathogen transfer; recommended application rates of 5 to 10 t/ha significantly improve soil organic matter and crop yields in Nigerian conditions. (4) Crop residue retention: leaving crop residues (maize stover, sorghum stalks, cowpea haulms) on the soil surface as mulch or incorporating them into the soil; residues feed soil organisms, improve structure, reduce erosion, and contribute nutrients

upon decomposition; burning residues (common practice among Nigerian farmers) destroys organic matter and nutrients. (5) Agroforestry: integrating leguminous multipurpose trees (Gliricidia sepium; Leucaena leucocephala; Acacia species; Faidherbia albida) into farming systems to provide nitrogen through leaf litter, improve soil structure, and reduce erosion; widely promoted in Nigerian farming systems research.

Fill in the blank: Green manuring involves incorporating fast-growing ________ plants into the soil before planting; they add nitrogen through atmospheric fixation by Rhizobium bacteria and contribute organic carbon, with Nigerian studies showing nitrogen contributions of 80 to 200 kg N/ha equivalent.

1.4.3 Adding nutrients for plant growth

Crops remove nutrients from the soil with each harvest; these must be replaced to maintain soil fertility and sustain crop yields. Plant nutrition fundamentals: plants require 17 essential elements, classified as macronutrients (required in large amounts) and micronutrients (required in small amounts but equally essential). Macronutrients: (1) Primary macronutrients: nitrogen (N; component of amino acids, proteins, chlorophyll, nucleic acids; most frequently deficient in Nigerian soils; applied as urea $CO(NH_2)_2$; ammonium sulphate $(NH_4)_2SO_4$; calcium ammonium nitrate CAN; diammonium phosphate DAP); phosphorus (P; essential for root development, energy transfer (ATP), and seed formation; highly fixed in acid tropical soils; applied as single superphosphate SSP; triple superphosphate TSP; DAP); potassium (K; essential for stomatal regulation, enzyme activation, and stress tolerance; applied as muriate of potash KCl; sulphate of potash K_2SO_4). (2) Secondary macronutrients: calcium (Ca; cell wall structure; applied as lime $CaCO_3$ or gypsum $CaSO_4$); magnesium (Mg; chlorophyll core; applied as dolomite or magnesium sulphate); sulphur (S; protein synthesis; supplied as sulphate fertilisers or elemental sulphur).

Micronutrients: iron (Fe; chlorophyll synthesis; deficient on alkaline soils; applied as iron sulphate $FeSO_4$ or chelated iron); zinc (Zn; enzyme activation, auxin synthesis; most widespread micronutrient deficiency in Nigerian soils; applied as zinc sulphate $ZnSO_4$); boron (B; cell wall formation, pollen germination; applied as borax $Na_2B_4O_7$); manganese (Mn; photosynthesis; deficient on alkaline or organic soils); copper (Cu); molybdenum (Mo); chlorine (Cl). Fertiliser application principles: (1) Right source: match the nutrient form to the soil and crop requirements (urea is efficient on most soils; ammonia-based fertilisers acidify soils; avoid chloride-sensitive crops with KCl). (2) Right rate: based on yield goal, soil test values, and crop response curves; over-application wastes money and causes environmental damage (nitrate leaching, phosphorus runoff). (3) Right time: apply nitrogen close to periods of maximum crop uptake (split application for maize: basal NPK at planting + urea top-dressing at 4 to 6 weeks); avoid early pre-season application that allows leaching before crop establishment. (4) Right place: banding fertiliser close to roots (5 to 10 cm beside and below seed) increases efficiency compared with broadcasting; reduces phosphorus fixation.

Fill in the blank: The four principles of efficient fertiliser application are right ________, right rate, right time, and right place; applying nitrogen in split doses (basal at planting + top-dressing at 4 to 6 weeks) maximises uptake efficiency and reduces losses.

Nutrient	Symbol	Role in Plants	Deficiency Symptom	Fertiliser Source in Nigeria
Nitrogen	N	Promotes leaf growth, chlorophyll formation	Yellowing of older leaves (chlorosis)	Urea, ammonium sulphate, NPK fertiliser
Phosphorus	P	Root development, energy transfer (ATP)	Stunted growth, purplish leaves	Single superphosphate (SSP), diammonium phosphate (DAP)
Potassium	K	Enzyme activation, water regulation	Leaf scorching, weak stems	Muriate of potash (KCl), NPK blends
Calcium	Ca	Cell wall strength, root and shoot growth	Blossom end rot, distorted leaves	Agricultural lime, gypsum
Magnesium	Mg	Central atom in chlorophyll, enzyme cofactor	Interveinal chlorosis in older leaves	Dolomitic lime, magnesium sulphate
Sulphur	S	Protein synthesis, enzyme function	Yellowing of young leaves	Ammonium sulphate, gypsum
Iron	Fe	Chlorophyll synthesis, electron transport	Interveinal chlorosis in young leaves	Ferrous sulphate, chelated iron sprays

Zinc	Zn	Hormone regulation, enzyme activation	Stunted growth, small leaves, rosetting	Zinc sulphate, foliar zinc sprays
Boron	B	Cell wall formation, reproductive growth	Poor fruit set, hollow stems	Borax, boric acid
Manganese	Mn	Photosynthesis, enzyme activation	Interveinal chlorosis with brown spots	Manganese sulphate
Copper	Cu	Enzyme activity, lignin synthesis	Dieback of shoots, pale leaves	Copper sulphate, Bordeaux mixture
Molybdenum	Mo	Nitrogen fixation, nitrate reduction	Poor nodulation in legumes, yellow leaves	Ammonium molybdate, sodium molybdate

Box 1.1: Essential plant nutrients and their management in Nigerian agricultural soils

Pilot questions 1.4

1. State four methods of determining soil fertility and explain one in detail.
2. Describe three organic methods of improving soil fertility in Nigerian farming systems.
3. Name the three primary macronutrients and state one role and one fertiliser source for each.
4. Explain the four principles of efficient fertiliser application (4Rs) with one Nigerian crop example.
5. Explain why zinc deficiency is widespread in Nigerian soils and how it can be corrected.

Series Summary

This Series examined **soil conservation as the protection of soil against erosion, nutrient loss, structural damage, and chemical deterioration**. It is essential for food security, water quality, watershed protection, biodiversity, carbon storage, and infrastructure stability. Soil and water engineering applies hydrology, hydraulics, physics, and agronomy to erosion control, irrigation, drainage, watershed management, and environmental assessment. Soil formation is influenced by parent material, climate, organisms, topography, and time. Soil texture depends on the proportions of sand, silt, and clay, while soil structure refers to how particles are arranged into aggregates such as granular, blocky, platy, and prismatic forms. Soil water availability is expressed as **AWC = Field Capacity − Permanent Wilting Point**, and good organic matter management helps maintain favourable structure and drainage.

The Series also covered **erosion, soil fertility assessment, and fertility improvement**. Major erosion forms include splash, sheet, rill, gully, streambank, wind, gravity, and human-induced erosion. The Universal Soil Loss Equation is **A = R × K × L × S × C × P**, with vegetation cover being one of the most manageable factors. Erosion removes fertile topsoil, organic matter, clay, and nutrients, thereby reducing crop yield. Soil fertility may be assessed through soil testing, deficiency symptoms, tissue analysis, and biological indicators. Improvement methods include green manuring, composting, manure application, crop-residue retention, agroforestry, and balanced fertiliser use. Important nutrient sources include urea and CAN for nitrogen, SSP and DAP for phosphorus, KCl for potassium, lime and gypsum for calcium, dolomite for magnesium, and zinc sulphate for zinc. Efficient nutrient management follows the **4R principles: right source, right rate, right time, and right place**.

Glossary of Terms

- **Available water capacity (AWC):** the amount of water in the soil available for plant uptake; calculated as field capacity (FC) minus permanent wilting point (PWP); ranges from approximately 60 mm/m in sandy soils to 200 mm/m in loam soils.

- **Enrichment ratio:** the ratio of nutrient concentration in eroded sediment to nutrient concentration in the source soil; typically 2 to 5; indicates that erosion preferentially removes the most nutrient-rich fine particles.
- **Field capacity (FC):** the soil water content retained 24 to 48 hours after saturation, when free drainage has ceased; corresponds to approximately -33 kPa matric potential; the upper limit of plant-available soil water.
- **Green manure:** a fast-growing crop (usually leguminous) grown specifically to be incorporated into the soil before planting to improve fertility; provides nitrogen (80 to 200 kg N/ha equivalent in Nigerian conditions), organic carbon, and soil structure improvement.
- **Gully erosion:** the most destructive form of water erosion; large permanent channels formed by concentrated surface runoff; cannot be crossed by farm machinery and destroys agricultural land; particularly severe in south-eastern Nigeria (Anambra, Enugu, Imo, Cross River states).
- **Hydraulic conductivity (K_s):** the rate at which water moves through saturated soil; measured in mm/hour; sandy soils: 10 to 100 mm/hour; clay soils: 0.1 to 5 mm/hour; determines drainage speed and irrigation response.
- **Permanent wilting point (PWP):** the soil water content at which plants wilt permanently and cannot recover; corresponds to approximately -1,500 kPa matric potential; the lower limit of plant-available soil water.
- **Pedogenesis:** the process of soil formation through physical, chemical, and biological weathering of parent material over time; controlled by five factors: parent material, climate, organisms, topography, and time (Jenny 1941).
- **Soil conservation:** the protection of soil from physical loss by erosion and from chemical deterioration, while maintaining or improving its capacity to support plant growth; encompasses practices, policies, and technologies to keep soil productive across generations.
- **Soil erodibility (K factor):** the susceptibility of a soil to detachment and transport by rainfall and runoff under a standard set of conditions; sandy loams and silt loams are more erodible than clays; reduced by organic matter additions and stable aggregation.
- **Soil erosion:** the detachment, transport, and deposition of soil particles from their original position by water, wind, or gravity; the primary form of soil degradation in Nigeria.
- **Soil fertility:** the capacity of a soil to supply plant-available nutrients in adequate amounts and in the right balance for crop growth; determined by chemical analysis, deficiency symptoms, biological indicators, and plant tissue analysis.

- **Soil structure:** the arrangement of individual soil particles into aggregates (peds); types: granular, blocky, platy, prismatic; good granular structure promotes water infiltration, root penetration, and erosion resistance.
- **Soil texture:** the relative proportions of sand (2 to 0.05 mm), silt (0.05 to 0.002 mm), and clay (less than 0.002 mm) in a soil; classified into 12 textural classes using the USDA textural triangle.
- **USLE (Universal Soil Loss Equation):** A = R x K x L x S x C x P; predicts average annual soil loss based on rainfall erosivity (R), soil erodibility (K), slope length (L), slope steepness (S), cover management (C), and support practice (P).

Concept Check Questions [Series 1]

Objective Questions

1. Soil conservation protects soil from physical loss by ________ and from chemical deterioration through leaching, acidification, and compaction. (Linked to SLO 1.1)
2. The five factors of soil formation identified by Jenny (1941) are parent material, climate, organisms, topography, and ________. (Linked to SLO 1.2)
3. In the USDA textural classification, the three primary particle size fractions are sand (2 to 0.05 mm), silt (0.05 to 0.002 mm), and ________ (less than 0.002 mm). (Linked to SLO 1.2)
4. In the USLE formula A = R x K x L x S x C x P, the ________ factor (cover management) is the most easily managed by Nigerian farmers; maintaining year-round mulch cover can reduce it by 90 percent. (Linked to SLO 1.3)
5. The enrichment ratio of eroded sediment (typically 2 to 5) means that eroded material is 2 to 5 times more ________ per unit weight than the remaining soil. (Linked to SLO 1.3)

Short-Answer Questions

1. Define soil conservation and state three reasons why it is important in Nigeria. (Linked to SLO 1.1)
2. Explain the difference between soil texture and soil structure and state why each matters for agriculture. (Linked to SLO 1.2)
3. Name the six factors in the USLE and state which is most manageable by farmers. (Linked to SLO 1.3)
4. State three physical and two chemical effects of topsoil loss by erosion on agricultural soils. (Linked to SLO 1.3)
5. Describe three organic methods of improving soil fertility in Nigerian farming systems. (Linked to SLO 1.4)

Long-Answer Questions

1. Describe the importance and scope of soil conservation in Nigeria. Explain soil formation factors, soil texture and structure, and soil drainage and water retention. (Linked to SLOs 1.1, 1.2)
2. Describe the agents, types, and factors affecting soil erosion. Explain the effects of erosion on soil fertility. Describe methods of determining and improving soil fertility and the principles of nutrient management. (Linked to SLOs 1.3, 1.4)

Answers to Concept Check Questions [Series 1]

Objective Questions

1. Erosion.
2. Time.
3. Clay.
4. C.
5. Nutrient-rich.

Short-Answer Questions

1. Soil conservation protects soil from erosion and chemical deterioration while maintaining its capacity to support plant growth. Three reasons: food security (erosion costs Nigeria 3 to 5 percent of agricultural GDP annually in lost productivity); water quality (eroded sediment increases turbidity and causes eutrophication of streams and reservoirs); infrastructure protection (gully erosion undermines roads and buildings, causing severe annual losses in south-eastern Nigeria).
2. Texture is the relative proportions of sand, silt, and clay; it is a permanent property that determines water retention, drainage speed, and erodibility. Structure is the arrangement of particles into aggregates (peds); it is dynamic and influenced by organic matter and tillage; good granular structure improves infiltration, root penetration, and erosion resistance. Texture cannot be changed by management; structure can be improved by adding organic matter.
3. R (rainfall erosivity), K (soil erodibility), L (slope length), S (slope steepness), C (cover management), P (support practice). C factor is most manageable; maintaining mulch cover and crop residues can reduce it by up to 90 percent.
4. Physical effects: exposed subsoil has poorer structure and lower water retention; surface crusting increases and infiltration declines; runoff and re-erosion accelerate. Chemical effects: available phosphorus is reduced by 40 to 60 percent; soil organic carbon declines by 60 to 80 percent when the top 10 cm of Alfisols in south-western Nigeria is lost.
5. Green manuring (incorporating leguminous crops; contributes 80 to 200 kg N/ha equivalent in Nigerian conditions). Composting (decomposing organic wastes at optimal C:N ratio of 25:1 to 30:1; improves structure and nutrient supply). Manure application (poultry manure at 5 to 10 t/ha; supplies nitrogen, phosphorus, and organic matter; improves soil health).

Long-Answer Questions

1. Soil conservation protects soil from erosion and chemical deterioration; important for food security (erosion costs 3 to 5 percent of agricultural GDP), water quality (sedimentation,

eutrophication), watershed function (flood regulation), biodiversity and carbon storage, and infrastructure protection (gully erosion in south-east Nigeria). Scope of soil and water engineering: erosion assessment (USLE, RUSLE, SWAT); conservation structure design (terraces, bunds, check dams); irrigation and drainage; watershed management; soil fertility and land improvement; environmental impact assessment; Nigerian institutions: FMAFS, SSSN, RBDAs. Soil formation factors (Jenny 1941): parent material (determines mineralogy; Nigerian soils from Precambrian basement complex, Cretaceous sedimentary formations, alluvial sediments); climate (high rainfall in south produces Ferralsols; semi-arid north produces Lixisols); organisms (roots, soil fauna, microbes add organic matter and mix soil); topography (valley bottoms accumulate deeper, more fertile soils; steep slopes thin and eroded); time (thousands of years for full profile development). Texture: sand (2 to 0.05 mm), silt (0.05 to 0.002 mm), clay (less than 0.002 mm); 12 USDA classes. Structure: granular (topsoil; best for agriculture); blocky; platy (impedes drainage; compaction); prismatic; maintained by organic matter. Drainage: hydraulic conductivity (sandy 10 to 100 mm/hr; clay 0.1 to 5 mm/hr); AWC = FC minus PWP; loam AWC 150 to 200 mm/m; drainage improvement by surface drains, subsurface tiles, raised beds.

2. Erosion agents: water (splash, sheet, rill, gully, streambank; dominant in most of Nigeria); wind (semi-arid north; saltation, suspension, creep); gravity (mass movement on steep slopes); human-induced (deforestation, overgrazing, poor tillage). USLE: A = R x K x L x S x C x P; R highest at onset of rainy season; K high on sandy south-eastern soils; C most manageable (90 percent reduction with mulch cover); contouring reduces erosion 40 to 60 percent; terracing 75 to 95 percent. Erosion effects: selective removal of clay, organic matter, and silt (enrichment ratio 2 to 5); loss of top 10 cm reduces available P by 40 to 60 percent and organic C by 60 to 80 percent; surface crusting increases; infiltration declines; yield losses 5 to 50 percent in Nigeria. Fertility determination: soil testing (pH, OC, available P, exchangeable cations, N, micronutrients); deficiency symptoms (N: yellowing old leaves; P: purpling; K: scorched leaf margins; Zn: striping in maize); biological indicators; tissue analysis. Fertility improvement: green manuring (legumes; 80 to 200 kg N/ha); composting (C:N 25:1 to 30:1); manure (poultry 3 to 4 percent N; 5 to 10 t/ha); residue retention; agroforestry (Gliricidia, Leucaena). Nutrients: N (urea, CAN, DAP); P (SSP, TSP); K (KCl); Zn (ZnSO4; most widespread micronutrient deficiency). 4R principles: right source; right rate (soil test-based); right time (split N: basal + top-dress); right place (banding improves P efficiency).

Answers to Pilot Questions [Series 1]

Part 1.1

1. Soil conservation is the protection of soil from erosion and chemical deterioration while maintaining its capacity to support plant growth. Four reasons it is important in Nigeria: food security (erosion costs 3 to 5 percent of agricultural GDP; reduces crop yields); water quality (eroded sediment causes turbidity and eutrophication of streams and reservoirs); watershed function (healthy soils regulate stream flow and reduce flooding); infrastructure protection (gully erosion undermines roads and buildings in south-eastern Nigeria).
2. Soil and water engineering applies physics, hydrology, hydraulics, and agronomy to: erosion assessment and prediction; conservation structure design (terraces, bunds, check dams); irrigation and drainage engineering; watershed management; soil fertility and land improvement; and environmental impact assessment. Three Nigerian institutions: FMAFS (Federal Ministry of Agriculture and Food Security); SSSN (Soil Science Society of Nigeria); RBDAs (River Basin Development Authorities).
3. Studies on Alfisols in south-western Nigeria show that for each centimetre of topsoil lost, maize yields decline by 200 to 400 kg/ha. Loss of topsoil exposes infertile subsoil; farmers must apply more fertiliser to maintain yields; degraded soils retain fertiliser poorly, accelerating nutrient losses. Conservation farming practices that maintain soil cover and organic matter improve yields by 20 to 50 percent while reducing erosion by 60 to 90 percent.
4. Soil conservation focuses on preventing the physical loss of soil through erosion and its chemical deterioration (preventing the problem). Soil fertility management focuses on supplying and maintaining adequate plant-available nutrients (restoring or maintaining productivity); fertility management may be needed even in the absence of erosion, and conservation alone does not restore depleted nutrients.
5. Sedimentation (eroded sediment increases turbidity and deposits in rivers, streams, and reservoirs, reducing storage capacity and hydropower output). Eutrophication (nutrient-rich eroded material enriches water bodies, stimulating algal blooms that deplete oxygen and harm aquatic life). Flash flooding (degraded soil surfaces with low infiltration generate rapid runoff, increasing peak flood flows that damage downstream infrastructure and communities).

Part 1.2

1. Parent material (determines initial mineralogy and texture; Nigerian soils from Precambrian basement complex, Cretaceous sedimentary formations, and alluvial sediments). Climate

(high rainfall in humid south produces deeply leached Ferralsols; semi-arid north produces shallower Lixisols). Organisms (plants and soil fauna add organic matter; microbes decompose litter and release nutrients). Topography (valley bottoms accumulate deeper, more fertile soils; steep slopes develop thin soils due to erosion). Time (thousands of years needed for deep, well-differentiated profiles; young soils have weakly developed horizons).

2. Texture is the relative proportions of sand, silt, and clay; it is permanent and determines water retention, drainage speed, and inherent erodibility. Structure is the arrangement of particles into aggregates; it is dynamic and influenced by organic matter, tillage, and biological activity. Texture matters because it determines AWC, drainage class, and tilling difficulty; structure matters because good granular structure improves infiltration, root penetration, and erosion resistance.
3. Hydraulic conductivity (K_s) is the rate at which water moves through saturated soil (mm/hour). Sandy soils (large pores, little tortuosity): K_s = 10 to 100 mm/hour; water drains quickly but soil dries rapidly. Clay soils (small pores, high tortuosity): K_s = 0.1 to 5 mm/hour; water moves slowly; soils remain waterlogged after rain.
4. Field capacity (FC): water content retained 24 to 48 hours after saturation when free drainage has ceased (approximately -33 kPa); upper limit of plant-available water. Permanent wilting point (PWP): water content at which plants wilt permanently (approximately -1,500 kPa); lower limit. AWC = FC minus PWP; significance for irrigation: scheduling irrigations when soil moisture approaches PWP; AWC determines how much water can be stored between irrigations.
5. Installation of subsurface tile drains (perforated pipes buried 0.6 to 1.2 m deep to intercept and remove excess subsoil water). Construction of surface drains and open ditches (channels excavated to collect and divert surface water away from the field; effective for removing ponded water from flat, clay-dominated soils such as those in the Niger Delta and Benue floodplain).

Part 1.3

1. Splash erosion (raindrop impact detaches particles; seals surface pores). Sheet erosion (uniform thin removal of surface soil by overland flow; ‘slow death’ of productivity). Rill erosion (concentrated flow forms small channels 1 to 30 cm deep; erasable by tillage). Gully erosion (large permanent channels; cannot be crossed by machinery; most destructive). Most destructive in south-eastern Nigeria: gully erosion; the soft Cretaceous sedimentary soils (sandstone, shale) of Anambra, Enugu, and Imo states are highly erodible and produce some of the worst gullies in Africa.

2. R (rainfall erosivity), K (soil erodibility), L (slope length), S (slope steepness), C (cover management), P (support practice). Most manageable factor: C (cover management); maintaining mulch cover, residues, and minimum tillage can reduce C by up to 90 percent compared with bare tilled soil at minimal cost to the farmer.
3. Erosion selectively removes clay particles (carry most cation exchange capacity), organic matter (primary store of N, P, and S), and fine silt (highest surface area for nutrient adsorption); these are the most fertile components of the soil. The enrichment ratio of 2 to 5 means eroded sediment is 2 to 5 times more nutrient-rich per unit weight than the source soil; so even modest volume loss causes disproportionate nutrient depletion.
4. Physical effects: exposed subsoil has poorer structure and lower water retention; surface crusting increases, reducing infiltration; runoff and re-erosion accelerate. Chemical effects: available phosphorus declines by 40 to 60 percent; soil organic carbon declines by 60 to 80 percent; exchangeable cations (K, Ca, Mg) decline by 30 to 50 percent when the top 10 cm of south-western Nigerian Alfisols is removed.
5. South-eastern Nigeria (Anambra, Enugu, Imo, Cross River states) is underlain by soft, unconsolidated Cretaceous sedimentary formations (sandstone, sandy shale) that are highly susceptible to detachment and transport. High seasonal rainfall (1,500 to 2,500 mm) combined with deforestation and loss of protective vegetation exposes these erodible soils to intense convective storms. Once a rill forms in these materials, it rapidly enlarges into a gully because the sandy subsoil has very low cohesion and high infiltration that generates concentrated seepage erosion (piping) below the surface.

Part 1.4

1. Soil testing (chemical analysis of pH, OC, available P, exchangeable cations, N, micronutrients; most precise basis for fertiliser recommendations). Visual deficiency symptoms (rapid, low-cost; N: yellowing old leaves; P: purpling; K: scorched leaf margins; Zn: leaf striping in maize). Biological indicators (earthworm populations; microbial biomass; indicate overall soil health). Plant tissue analysis (nutrient concentration in leaves or shoots at a standard growth stage; diagnoses sub-clinical deficiencies). Soil testing in detail: soil samples (20 to 30 sub-samples composited) are extracted with standardised reagents and analysed by laboratory for key parameters; results are interpreted against crop-specific critical threshold levels to generate fertiliser recommendations.
2. Green manuring (leguminous crops incorporated before planting; contribute 80 to 200 kg N/ha equivalent through Rhizobium fixation; improve organic carbon and structure). Composting (organic wastes decomposed at C:N 25:1 to 30:1 to produce stable amendment;

improves structure, water retention, and nutrient supply). Manure application (poultry manure at 5 to 10 t/ha; supplies N, P, and organic matter; most widely available organic amendment for Nigerian smallholders).

3. Nitrogen (component of proteins, chlorophyll, nucleic acids; applied as urea, CAN, or DAP). Phosphorus (essential for root development, energy transfer as ATP, and seed formation; applied as SSP, TSP, or DAP). Potassium (stomatal regulation, enzyme activation, and stress tolerance; applied as KCl or K_2SO_4).
4. Right source: match nutrient form to soil and crop (urea is efficient on most Nigerian soils; avoid chloride-sensitive crops with KCl). Right rate: based on soil test and yield goal (over-application wastes money and causes nitrate leaching). Right time: apply N close to maximum uptake periods (split application: basal NPK at planting + urea top-dress at 4 to 6 weeks for maize). Right place: band fertiliser 5 to 10 cm beside and below seed to improve efficiency and reduce phosphorus fixation.
5. Zinc deficiency is widespread because Nigerian soils are inherently low in plant-available zinc (low total Zn in the parent material; high pH in calcareous soils reduces Zn solubility; continuous cropping without Zn replacement further depletes supplies); it is the most common micronutrient deficiency affecting maize, sorghum, and vegetables. Correction: apply zinc sulphate ($ZnSO_4$) at 5 to 10 kg Zn/ha as a soil application or foliar spray; ensure soil pH is not excessively high (above 7.5) where Zn becomes insoluble.

References and Attributions [Series 1]

Textual References (Books and External Sources)

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Figures, Plates, Tables, and Boxes

- Box 1.1: Essential plant nutrients and their management in Nigerian agricultural soils. Attribution: AI generated. Suggested OER search string: “essential plant nutrients deficiency symptoms fertiliser sources Nigeria soil table OER⇓.

Series 3: Water Use and Runoff Principles

- **Part 3.1: Consumptive Use of Water by Crops**
  - Sub Part 3.1.1: Definition and components of consumptive use
  - Sub Part 3.1.2: Crop coefficients and crop water requirements
  - Sub Part 3.1.3: Factors affecting crop water use in Nigeria
- **Part 3.2: Infiltration and Percolation**
  - Sub Part 3.2.1: Infiltration: definition, process, and measurement
  - Sub Part 3.2.2: Factors affecting infiltration rates
  - Sub Part 3.2.3: Percolation and its role in soil water and groundwater recharge
- **Part 3.3: Principles of Runoff in Conservation Measures**
  - Sub Part 3.3.1: Runoff generation mechanisms
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  - Sub Part 3.3.3: Runoff estimation methods
- **Part 3.4: Irrigation Principles and Water Management**
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  - Sub Part 3.4.3: Water quality for irrigation

Introduction

The relationship between water and agricultural production is fundamental: plants require water for photosynthesis, nutrient transport, and metabolic processes, and the management of water determines crop yields across the spectrum from rainfed smallholder farming to high-technology irrigated agriculture. Understanding how much water crops use, how water moves into and through the soil (infiltration and percolation), and under what conditions and in what quantities water moves over the land surface as runoff is essential for both optimising agricultural water use and designing effective conservation measures.

This Series covers the consumptive use of water by crops (crop water requirements, crop coefficients, and the factors that influence water use in Nigerian conditions); infiltration and percolation (the processes, measurement methods, and management factors that determine whether precipitation becomes runoff or recharges soil water and groundwater); runoff generation and estimation (the mechanisms, governing factors, and quantitative methods used in conservation design); and the principles of irrigation water management (scheduling, methods, efficiencies, and water quality considerations).

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 3.1** define consumptive use, explain crop water requirements and crop coefficients, and describe the factors affecting crop water use in Nigeria (Linked to Part 3.1),
- **SLO 3.2** define infiltration and percolation, describe infiltration measurement methods, explain the factors that affect infiltration rates, and describe the role of percolation in soil water and groundwater recharge (Linked to Part 3.2),
- **SLO 3.3** explain the mechanisms of runoff generation, describe the factors affecting runoff volume and rate, and apply runoff estimation methods to Nigerian conservation problems (Linked to Part 3.3), and
- **SLO 3.4** explain the principles of irrigation scheduling using the water balance method, describe the main irrigation methods and their efficiencies, and explain the key water quality parameters for irrigation (Linked to Part 3.4).

3.1 Consumptive Use of Water by Crops

3.1.1 Definition and components of consumptive use

Consumptive use (CU) of water by a crop refers to the total amount of water used by the crop in transpiration and in building plant tissue (growth), plus the water evaporated from the soil and water surfaces in the field during the growing season. It is essentially equivalent to actual evapotranspiration (AET) under field conditions plus the small amount of water incorporated into plant tissue (which is negligible, typically less than 1 percent of total water use, so consumptive use is practically equated with crop evapotranspiration, ETc). Components: (1) Transpiration (T): water absorbed by roots, transported through the plant, and released as vapour through leaf stomata; the biologically active component of consumptive use; driven by the vapour pressure deficit between leaf interior and surrounding air, and regulated by stomatal conductance; represents the productive use of water linked directly to carbon fixation and growth. (2) Soil evaporation (E): water evaporated directly from the soil surface; occurs between plant rows and before canopy closure; unproductive in the sense that it does not contribute to crop growth; reduced by mulching, close spacing, or early canopy closure.

(3) Interception evaporation: water intercepted on leaf and stem surfaces during rainfall and evaporated before reaching the soil; minor component in most agricultural crops but significant in dense canopy systems. The sum T + E = ETc (crop evapotranspiration) is the standard measure of crop consumptive use and is the fundamental variable for irrigation scheduling. Seasonal crop consumptive use values in Nigeria: maize (full season approximately 400 to 550 mm); rice (paddy; 800 to 1,200 mm including percolation losses); sorghum (350 to 500 mm); cotton (550 to 700 mm); groundnut (400 to 550 mm); tomato (300 to 450 mm); sugarcane (annual crop; 1,200 to 1,500 mm); these values vary with variety, climate, and season. Measurement of consumptive use: lysimeters (large containers of soil planted with the crop of interest; ETc = precipitation + irrigation - drainage - change in soil moisture); water balance method at field scale; eddy covariance systems (research-grade direct measurement of ET flux).

Fill in the blank: Consumptive use of water by crops is practically equated with crop evapotranspiration (ETc = T + E), where T is ________ (water vapour released through stomata) and E is soil evaporation from between plant rows; transpiration is the productive component linked directly to carbon fixation.

3.1.2 Crop coefficients and crop water requirements

Crop water requirement (CWR) is the amount of water needed by a crop to meet its full transpiration and soil evaporation demand (ETc) under disease-free, well-fertilised conditions in a large field and with soil water not limiting growth. It is the crop's theoretical maximum water demand and forms the basis for irrigation scheduling. The FAO-56 approach calculates ETc from the reference ET (ET0) and a crop coefficient (Kc): ETc = Kc x ET0; where ET0 is calculated by the Penman-Monteith method and represents the ET from a reference grass surface. The crop coefficient Kc encapsulates all the differences between the actual crop and the reference grass: leaf area, stomatal characteristics, canopy albedo, aerodynamic roughness, and crop development stage. Kc varies through the crop growth season in a characteristic pattern: (1) Initial stage (Kc ini): germination and early growth; small plants with low leaf area index; soil evaporation dominates; Kc approximately 0.3 to 0.5 for most crops with bare soil between rows. (2) Crop development stage: rapid vegetative growth; increasing canopy cover; Kc rises progressively from Kc ini to Kc mid. (3) Mid-season stage (Kc mid): full canopy cover; maximum growth rate; Kc at maximum value (Kc mid: maize 1.15 to 1.20; tomato 1.05 to 1.15; rice 1.05 to 1.20; sorghum 1.00 to 1.10; cotton 1.10 to 1.20). (4) Late season stage (Kc end): crop maturation; senescence; leaf area declining; Kc decreasing (Kc end: maize 0.35 to 0.60; cotton 0.60 to 0.70; tomato 0.60 to 0.80).

Seasonal ETc calculation example: maize grown at Kano in the dry season (October to February); monthly ET0 from Penman-Monteith: October 5.2; November 5.0; December 4.8; January 5.4; February 6.2 mm/day; crop stages and Kc: initial (October weeks 1 to 2; Kc = 0.35); development (October weeks 3 to 4, November; Kc increasing from 0.35 to 1.15); mid-season (December; Kc = 1.15); late (January weeks 1 to 2; Kc = 1.15 to 0.55); end (January weeks 3 to 4; Kc = 0.55); total seasonal ETc calculated by multiplying daily ET0 by Kc for each day. Dual crop coefficient approach (Kcb x ET0 + Ke x ET0): separates the basal crop coefficient (Kcb; transpiration component only) from the soil evaporation coefficient (Ke; evaporation from wet soil after rain or irrigation); more precise but requires more data; useful for drip and sprinkler irrigation design where soil wetting pattern differs from surface irrigation.

Fill in the blank: The FAO-56 approach calculates crop evapotranspiration as ETc = ________ x ET0, where ET0 is reference evapotranspiration from a grass surface and Kc is the crop coefficient that accounts for differences in crop canopy, stomata, and growth stage.

3.1.3 Factors affecting crop water use in Nigeria

Several climatic, soil, crop, and management factors modulate crop water use in Nigerian conditions: (1) Climate: temperature (higher temperatures increase stomatal vapour pressure deficit and raise ET0; dry-season crops in northern Nigeria face very high ET0 demands of 6 to 9 mm/day in March to April); vapour pressure deficit (low RH in the harmattan season sharply increases ET demand); wind speed (higher wind speeds increase aerodynamic transport of vapour, raising ET); solar radiation (the primary energy source for ET; Nigeria's high solar radiation throughout the year maintains high ET demand). (2) Soil water availability: when soil moisture is above a threshold (approximately 50 to 60 percent of plant-available water capacity), ET proceeds at the potential rate (AET = PET); below this threshold, stomatal closure reduces transpiration (AET falls below PET); the timing and intensity of soil water stress depends on the crop's sensitivity at different growth stages; water stress at flowering and grain filling is particularly damaging in cereals.

(3) Crop type and variety: C4 crops (maize, sorghum, millet, sugarcane) are more water-use-efficient than C3 crops (rice, wheat, cowpea) because their carbon-concentrating mechanism allows stomata to close more (reducing transpiration) without greatly reducing photosynthesis; drought-tolerant varieties of maize and sorghum bred for Nigerian conditions maintain higher water-use efficiency under water stress. (4) Crop growth stage: water use is highest during the vegetative and reproductive phases and declines during maturation; efficient irrigation scheduling targets water delivery to the highest-demand periods. (5) Management practices: mulching (reduces soil evaporation by 20 to 40 percent; particularly important for dry-season vegetable production in Nigeria); minimum tillage (preserves soil structure and water-holding capacity; reduces soil evaporation); plant density (higher plant density increases canopy cover and reduces soil evaporation but may increase total transpiration); irrigation method (drip

irrigation applies water directly to the root zone; eliminates soil evaporation from inter-row soil and greatly improves crop water-use efficiency).

Fill in the blank: C4 crops such as maize, sorghum, millet, and sugarcane are more ________ efficient than C3 crops because their carbon-concentrating mechanism allows stomata to close further, reducing transpiration without proportionately reducing photosynthesis; this makes them better adapted to the water-limited conditions of Nigerian semi-arid agriculture.

Pilot questions 3.1

1. Define consumptive use and state its two main components.
2. Explain the concept of the crop coefficient (Kc) and describe how it changes during the four crop growth stages.
3. If ET0 = 6.0 mm/day and Kc = 1.10 for maize at mid-season, calculate ETc and state what this means for irrigation scheduling.
4. State four factors that affect crop water use in Nigeria.
5. Explain why mulching is effective at reducing crop water use in Nigerian dry-season production.

3.2 Infiltration and Percolation

3.2.1 Infiltration: definition, process, and measurement

Infiltration is the process by which water enters the soil surface and moves into the soil profile. It is one of the most important processes in hydrology and soil conservation because it determines whether precipitation becomes runoff (if infiltration is exceeded) or becomes available for plant use and groundwater recharge (if fully infiltrated). The infiltration rate (f; mm/hr) is the rate at which water enters the soil at a given time; the infiltration capacity (fp; mm/hr) is the maximum rate at which a soil can absorb water under a given condition. When rainfall intensity exceeds infiltration capacity, the excess becomes surface runoff (Horton overland flow). The cumulative infiltration (F; mm) is the total depth of water that has infiltrated over a given time period.

Infiltration process: initially, when a dry soil surface is wetted, infiltration rates are very high (driven by both gravity and matric suction; water is rapidly pulled into the soil pores); as the soil wets and pores fill, matric suction decreases and the only driving force is gravity; infiltration rate declines exponentially toward a steady-state value (basic infiltration rate, fc) that equals the saturated hydraulic conductivity (Ks) of the soil. Empirical infiltration equations: (1) Kostiakov equation: F = a t^b (cumulative infiltration as power function of time); simple, widely used; a and b are empirically determined constants; differentiated to give f = abt^(b-1). (2) Horton's equation: f = fc + (f0 - fc) e^(-kt); where f0 = initial infiltration rate; fc = final steady-state rate; k = decay constant; describes the exponential decline from f0 to fc. (3) Green-Ampt equation: physically based; uses soil hydraulic properties (Ks, matric suction, initial moisture) to predict f; preferred for process-based modelling. Infiltration measurement: (1) Double-ring infiltrometer: two concentric metal rings driven into the soil (inner ring typically 30 cm diameter; outer ring 60 cm diameter); water maintained at a constant head (typically 5 to 10 mm) in both rings; water added to the inner ring to maintain level is measured over time as cumulative infiltration; the outer ring prevents lateral flow from the inner ring; standard field method used across Nigeria. (2) Tension infiltrometer (disc permeameter): measures unsaturated hydraulic conductivity at specific tensions; provides more realistic estimate of field infiltration than the ponded ring infiltrometer.

Fill in the blank: Horton's infiltration equation f = fc + (f0 - fc) e^(-kt) describes the ________ decline of the infiltration rate from the initial high rate (f0) to the final steady-state rate (fc); f0 is always greater than fc because initial matric suction pulls water rapidly into the dry soil.

3.2.2 Factors affecting infiltration rates

Infiltration rates vary greatly across soils and landscapes and are influenced by: (1) Soil texture: coarse-textured soils (sandy soils) have large, interconnected pores and very high initial and steady-state infiltration rates (Ks values of 20 to 100 mm/hr); fine-textured soils (clay soils) have small, tortuous pores and low Ks values (0.1 to 5 mm/hr); silty soils are intermediate but may crust rapidly. (2) Soil structure and macroporosity: well-aggregated soils with large macropores (created by earthworms, root channels, soil fauna tunnels, and desiccation cracks) have much higher infiltration rates than would be predicted from texture alone; macropore flow (preferential flow) allows rapid downward movement of water through large channels bypassing the soil matrix. (3) Soil organic matter content: higher organic matter improves soil aggregation and porosity, directly increasing infiltration rates; degraded soils with low organic matter have collapsed aggregate structure, low porosity, and low infiltration rates; the loss of organic matter through erosion and burning of crop residues is a major cause of declining infiltration on Nigerian agricultural soils. (4) Antecedent soil moisture: wetter soils have lower initial infiltration rates (matric suction already partially satisfied) but similar final rates; very dry soils may initially repel water (hydrophobic layer) but quickly become wettable.

(5) Surface conditions: surface crusts (formed by raindrop impact breaking aggregates and sealing pores with dispersed clay and silt) dramatically reduce infiltration rates; a 2 to 5 mm crust can reduce infiltration from 20 to 30 mm/hr to less than 1 to 2 mm/hr; crusting is particularly severe on bare soils with low organic matter, common on Nigerian Alfisols after the first rains of the season. Compaction: trafficking by farm machinery or animal hooves compacts the soil, reducing large pores and infiltration; soil bulk density above 1.6 to 1.8 g/cm3 severely restricts infiltration and root growth. (6) Slope: on steeper slopes, water drains away more rapidly before it can infiltrate (shorter contact time between water and soil); however, slope itself does not change soil porosity; it is the reduced contact time that lowers effective infiltration. (7) Vegetation and land use: forested and well-grassed soils have high infiltration rates due to organic matter accumulation, root channels, and protection from surface crusting; deforested and overgrazed soils have much lower infiltration rates, generating more runoff and erosion. Management practices to improve infiltration in Nigeria: mulching (protects surface against crust formation; maintains organic matter); minimum tillage (preserves aggregate structure and macropores); cover crops (protect surface; add organic matter); contour ripping or subsoiling (breaks compaction layers and improves infiltration).

Fill in the blank: Surface ________ formed by raindrop impact breaking aggregates and sealing pores with dispersed clay and silt can reduce infiltration from 20 to 30 mm/hr to less than 2 mm/hr; mulching and minimum tillage prevent crust formation on Nigerian agricultural soils.

3.2.3 Percolation and its role in soil water and groundwater recharge

Percolation is the downward movement of water through the soil profile below the root zone, eventually reaching and recharging the groundwater table (phreatic surface). It occurs when the soil profile has been wetted to field capacity and additional water continues to move downward under gravity. In the soil water balance at field scale: P + I (irrigation) = ETc + Runoff + DeltaS (change in soil moisture) + D (deep percolation); percolation is a loss from the root zone perspective (water has moved below the depth accessible to crop roots) but an essential input to groundwater from the watershed perspective. Distinction from infiltration: infiltration is the entry of water at the soil surface (surface process); percolation is the movement of water downward through the profile after infiltration (subsurface process); percolation begins only after the near-surface soil layers are wetted to field capacity.

Percolation rates in Nigeria: sandy soils (high Ks; 20 to 100 mm/hr) can percolate large volumes rapidly; clay soils (low Ks; 0.1 to 5 mm/hr) restrict percolation and are subject to prolonged waterlogging; percolation rates also depend on the presence of hardpans or fragipans (indurated subsoil layers that restrict downward water movement and cause perched water tables above them). Importance of percolation for groundwater recharge: most of Nigeria's rural population depends on wells and boreholes for drinking water; recharge of the shallow aquifer (often 5 to 30 m below the surface in the basement complex terrain) occurs primarily through percolation; practices that reduce percolation (deforestation, surface sealing, heavy compaction) reduce recharge and cause groundwater depletion; conservation structures such as check dams and contour bunds that slow surface runoff and promote infiltration also increase percolation and groundwater recharge. Paddy rice percolation: in lowland paddy rice production, deliberate flooding of fields saturates the soil and produces very high percolation losses (2 to 10 mm/day through the puddled layer); these losses are a major component of water demand for paddy irrigation and a major consideration in irrigation system design.

Fill in the blank: ________ is the downward movement of water through the soil profile below the root zone to recharge the groundwater table; it occurs only after the soil profile above has been wetted to field capacity and is driven by gravity through the saturated soil.

Pilot questions 3.2

1. Define infiltration capacity and explain the difference between the initial and final infiltration rates.
2. Describe the double-ring infiltrometer method of measuring infiltration rate.

3. State five factors that affect soil infiltration rates in Nigeria and explain how each affects the rate.
4. Distinguish between infiltration and percolation and explain the role of percolation in groundwater recharge.
5. Explain how surface crusting reduces infiltration and state two management practices that prevent it.

3.3 Principles of Runoff in Conservation Measures

3.3.1 Runoff generation mechanisms

Surface runoff is the portion of precipitation that flows over the land surface to streams and rivers without entering the soil. Understanding the mechanisms by which runoff is generated is essential for designing conservation structures that control it effectively. Two primary mechanisms of runoff generation: (1) Infiltration excess overland flow (Horton overland flow): occurs when rainfall intensity exceeds the infiltration capacity of the soil surface; excess water ponds on the surface and flows downslope as sheet flow; the dominant runoff mechanism in areas with low infiltration soils (crusted, compacted, or clay-rich soils) and high-intensity rainfall; very common on degraded agricultural soils in Nigeria, particularly at the start of the rainy season when soils may be crusted and bare from the previous dry season. The amount of runoff generated = (rainfall intensity - infiltration capacity) x duration = excess rainfall depth; requires a soil with spatially uniform, low infiltration capacity over a large area for widespread Horton flow to develop.

(2) Saturation excess overland flow (Dunne overland flow): occurs when the soil becomes fully saturated (all pores filled with water) so that further rainfall cannot infiltrate regardless of intensity; most common in valley bottoms, convergent topography, and areas with shallow water tables; the saturated area expands from topographic hollows and convergent zones outward as a storm progresses; characterises runoff generation on permeable soils in humid Nigeria where infiltration rates are high but the water table is close to the surface (e.g. low-lying areas in the Niger Delta, fadama systems, and river valley floors). Subsurface stormflow (interflow): rapid lateral flow of water through the soil just above an impermeable horizon or saturated zone;

contributes to streamflow during and shortly after storms; does not appear as surface runoff but bypasses deep percolation; important in humid areas with well-structured topsoil over impermeable subsoil. Depression storage: water that fills surface depressions (furrows, ruts, animal hoof prints) before any slope runoff can develop; typically 5 to 15 mm; must be satisfied before Horton overland flow commences.

Fill in the blank: Infiltration ________ overland flow (Horton flow) occurs when rainfall intensity exceeds the soil infiltration capacity; it is the dominant runoff mechanism on degraded, crusted, and compacted agricultural soils in Nigeria, particularly at the beginning of the rainy season.

3.3.2 Factors affecting runoff volume and rate

The volume and rate of surface runoff from a watershed are determined by precipitation characteristics and watershed properties. Precipitation factors: (1) Rainfall intensity and duration: higher intensity rainfall exceeds infiltration capacity more quickly and generates more runoff per unit of rain; longer duration storms saturate larger areas of the watershed and increase runoff volume; intense short-duration convective storms (common in southern Nigeria) generate very high runoff rates but shorter duration hydrographs than low-intensity long-duration frontal rains. (2) Antecedent moisture condition: wet antecedent soils have already exhausted some of their infiltration capacity; the same storm on a wet soil generates more runoff (and a higher, faster-rising hydrograph) than on a dry soil; in the SCS CN method, antecedent moisture condition is reflected in three classes: AMC I (dry; previous 5 days rainfall below 36 mm); AMC II (average; 36 to 53 mm); AMC III (wet; above 53 mm). (3) Storm pattern (temporal distribution): storms with higher intensities concentrated in the first period generate more runoff than the same total depth distributed more uniformly.

Watershed factors: (4) Slope: steeper slopes generate faster overland flow, which reduces time available for infiltration; runoff rates are higher; increased erosive velocity. (5) Soil infiltration capacity and texture: low-infiltration soils (clay, compacted, crusted) generate more runoff; high-infiltration soils (sandy, well-structured) generate less runoff; the most critical watershed property for Horton flow generation. (6) Land use and vegetation cover: forests and dense grass cover have high infiltration rates, significant interception storage (5 to 30 mm), and produce little surface runoff; bare or sparsely vegetated agricultural soils (common on Nigerian farms in early rainy season) produce large runoff volumes; deforestation dramatically increases runoff coefficients. (7) Watershed area and shape: larger watersheds generally produce higher peak discharges; compact (circular) watersheds produce flashier responses than elongated watersheds. (8) Drainage density: high drainage density means runoff reaches the stream network quickly, producing sharper peaks and greater flood risk. Runoff coefficient (C): the ratio of runoff depth to rainfall depth for a given storm or period; ranges from near 0 (permeable forest soil) to 0.90 or above (impervious surfaces, saturated clay); used in the Rational Method (Q = CiA/360).

Fill in the blank: The runoff ________ (C) is the ratio of runoff depth to rainfall depth; it ranges from near 0 for permeable forested soils to above 0.9 for impervious or saturated clay surfaces; it is the key parameter in the Rational Method for estimating peak discharge.

3.3.3 Runoff estimation methods

Several methods are used to estimate runoff volumes and peak discharges for conservation design. (1) Rational Method (Q = CiA/360): covered in Series 2; estimates peak discharge (m3/s) from a small catchment (below 80 to 100 ha); requires the runoff coefficient C, design rainfall intensity i (mm/hr) for the storm duration equal to the time of concentration, and catchment area A (ha). C values for Nigerian land uses: dense forest 0.05 to 0.20; grassland 0.15 to 0.40; row crops on sandy loam 0.25 to 0.50; row crops on clay 0.40 to 0.70; bare eroded soil 0.70 to 0.90; paved urban surface 0.80 to 0.95. (2) SCS Curve Number (CN) method: described in Series 2; estimates direct runoff depth from storm rainfall; Q = (P - 0.2S)2 / (P + 0.8S); appropriate for estimating runoff volume from storms of any size on catchments up to several hundred km2; CN reflects land use, soil type, and antecedent moisture; widely used for conservation structure design in Nigeria.

(3) Regression equations: empirical relationships between peak discharge and catchment area derived from gauged catchment data in similar hydroclimatic regions; example: Q10 = C10 x A^n, where Q10 is the 10-year peak discharge, A is catchment area, and C10 and n are regional constants; used for ungauged catchments when regional regression equations have been developed; limited regional regression equations exist for Nigerian catchments. (4) Runoff measurement in the field: direct measurement of runoff from small plots using bounded runoff

plots (metal or concrete borders on all sides; water outlet with flume or tipping bucket gauge; plots typically 2 m wide x 10 to 22 m long on representative slopes); runoff plots are fundamental tools for calibrating erosion prediction models and evaluating conservation practices in Nigeria; major research centres with runoff plot facilities include IITA Ibadan, IAR Zaria, and various Nigerian university farms. Application to conservation measures: runoff estimation underpins the design of all conservation structures; the design flow determines the minimum channel dimensions, spillway capacity, and pond volume; underestimating peak design flows leads to structural failure and erosion damage; overestimating wastes material and money.

Fill in the blank: Runoff plots (bounded metal or concrete plots typically 2 m wide x 10 to 22 m long) are used to directly ________ runoff and soil loss under different land management conditions; they are fundamental tools for calibrating erosion models and evaluating conservation practices at Nigerian research stations.

Pilot questions 3.3

1. Distinguish between infiltration excess (Horton) and saturation excess (Dunne) overland flow with one Nigerian example of each.
2. State five factors that affect runoff volume and explain the effect of each.
3. Define the runoff coefficient (C) and give C values for three different land uses in Nigeria.
4. A 50 ha watershed has C = 0.45 and receives a 25-year return period storm with i = 60 mm/hr. Calculate the peak discharge using the Rational Method.
5. Describe runoff plot measurements and explain their importance for conservation research in Nigeria.

3.4 Irrigation Principles and Water Management

3.4.1 Irrigation scheduling and water balance

Irrigation scheduling determines when to irrigate (timing) and how much water to apply (depth) to maintain soil moisture within a favourable range for crop growth while avoiding over-irrigation (waterlogging, leaching, salinisation) and under-irrigation (water stress). The soil water balance method is the most systematic approach to irrigation scheduling: SMD(t) = SMD(t-1) +

ETc(t) - P(t) - I(t), where SMD = soil moisture deficit (the depth of water below field capacity; mm); ETc = crop evapotranspiration (mm/day); P = effective rainfall (mm/day); I = irrigation applied (mm/day); irrigation is triggered when SMD reaches a threshold (the management allowed deficit, MAD = 50 to 60 percent of AWC for most crops; 30 to 40 percent for sensitive crops) to prevent crop water stress. The gross irrigation requirement (GIR) is the depth of water that must be applied to replace the SMD: GIR = SMD / Ea, where Ea is irrigation application efficiency (fraction; 0 to 1); the additional water in the numerator accounts for distribution non-uniformity and deep percolation losses. Example: SMD = 50 mm; Ea = 0.70 (surface irrigation); GIR = 50/0.70 = 71.4 mm to be applied.

Irrigation scheduling in practice in Nigeria: real-time scheduling uses daily soil moisture monitoring (tensiometers; capacitance sensors; gravimetric sampling) to track SMD and trigger irrigation when the threshold is reached; calendar-based scheduling (fixed intervals of 5, 7, or 10 days regardless of actual SMD) is simpler and more widely practised by smallholders but wastes water when rainfall occurs between scheduled irrigations and stresses crops during hot dry spells. FAO water balance spreadsheet tools (CROPWAT; IrriSAT; AQUACROP) allow scheduling for Nigerian conditions when ET0 and rainfall data are available. Irrigation water requirement (IWR): the total depth of irrigation water to be applied over the season to meet crop water requirement not met by rainfall; IWR = ETc - effective rainfall (Pe), where Pe is the fraction of rainfall that enters the crop root zone (rainfall minus runoff and evaporation before soil entry); for dry-season crops in northern Nigeria with near-zero rainfall, IWR approximately equals seasonal ETc; for rainfed crops in southern Nigeria receiving 1,200 to 1,500 mm, supplemental irrigation IWR may be only 50 to 150 mm during dry spells.

Fill in the blank: The soil moisture deficit (SMD) is the depth of water below ________ capacity; irrigation is triggered when SMD reaches the management allowed deficit (MAD = 50 to 60 percent of AWC); the gross irrigation requirement (GIR) = SMD / application efficiency (Ea).

3.4.2 Irrigation methods and efficiencies

Irrigation methods differ in how they apply water to the field and in their efficiency of water use. Application efficiency (Ea): the fraction of water delivered to the field that is actually stored in the root zone and available to the crop; Ea = water stored in root zone / water applied to the field head. (1) Surface irrigation (gravity; flood; furrow; basin): water flows over the soil surface and infiltrates as it advances; the oldest and most widely used method in Nigeria (fadama irrigation in northern Nigeria; basin irrigation for paddy rice); low infrastructure cost but low application efficiency (Ea typically 0.45 to 0.65 for flood; 0.55 to 0.70 for furrow irrigation); non-uniform application because the water application time varies across the field (more water at the head end, less at the tail end unless sufficient time is allowed for runoff to advance to the tail end); requires well-levelled fields for efficient operation. (2) Sprinkler irrigation: water is pressurised and distributed through nozzles or sprinkler heads to simulate rainfall; application can be uniform across the field; Ea typically 0.70 to 0.85; suitable for undulating terrain (does not require levelling); more efficient than surface irrigation but requires energy for pumping; limited by wind (distorts spray pattern and increases evaporation losses); types: solid set systems (pipes and sprinklers permanently installed); centre pivot (motorised lateral moves around a central pivot point; large capacity; used on some Nigerian large-scale farms); hand-move laterals (portable pipes; labour-intensive).

(3) Drip (trickle) irrigation: water delivered directly to the plant root zone through emitters (drippers) at very low flow rates (2 to 8 L/hr per emitter); highest application efficiency (Ea 0.85 to 0.95); no wetting of inter-row soil (reduces soil evaporation); reduces foliar disease by keeping leaves dry; highly uniform application; reduces weed growth in unirrigated inter-rows; can be combined with fertigation (fertiliser application through the drip system); higher capital cost (pipes, emitters, filters, pressure regulators) limits adoption among Nigerian smallholders but adoption is growing for vegetables and fruit production. Irrigation efficiency levels: conveyance efficiency (Ec): fraction of water released at the source that reaches the field (losses in canals and pipes; open earthen canals Ec 0.6 to 0.7; lined canals 0.8 to 0.9; pipes 0.95 to 0.99). Project (overall) efficiency = Ec x Ea; for a typical Nigerian surface irrigation project: 0.65 x 0.55 = 0.36 (only 36 percent of water released from the river reaches the crop root zone as productive water use). Improving irrigation efficiency in Nigeria is a national priority given the severe water scarcity in the semi-arid north: rehabilitation of unlined canals (reducing seepage losses), adoption of drip irrigation for high-value crops, and training of water users in proper irrigation management are key interventions.

Fill in the blank: Drip irrigation delivers water directly to the plant root zone through emitters at very low flow rates and achieves the highest application efficiency (Ea 0.85 to ________); it reduces soil evaporation, foliar disease, and weed growth but has higher capital cost than surface irrigation.

3.4.3 Water quality for irrigation

Irrigation water quality determines its suitability for crop production and its long-term effect on soil properties. Poor-quality irrigation water can cause soil salinisation, sodification, toxicity to crops, and clogging of irrigation systems. Key water quality parameters: (1) Electrical conductivity (EC_w): measures the total dissolved salt concentration (dS/m); good-quality water: EC_w below 0.7 dS/m; moderately saline: 0.7 to 3.0 dS/m; severely saline: above 3.0 dS/m; salinity reduces crop water uptake osmotically (the plant must work harder to extract water from salty soil solution) and causes ionic toxicity at high concentrations; Nigerian irrigation water from rivers and groundwater is generally low in salinity (EC_w 0.1 to 0.5 dS/m) but groundwater in some semi-arid areas (particularly in Sokoto, Borno, and Lake Chad Basin) may have elevated salinity. (2) Sodium Adsorption Ratio (SAR): SAR = Na / sqrt((Ca + Mg)/2) (all in mmol/L or meq/L); measures the sodium hazard relative to calcium and magnesium; high sodium displaces calcium and magnesium from soil exchange sites (sodification), causing soil aggregates to collapse, permeability to decline, and surface crusting to intensify; SAR below 10 is generally safe; 10 to 18 is moderate hazard; above 18 is severe hazard.

(3) pH: irrigation water pH 6.5 to 8.4 is generally acceptable; very low pH water (below 5.5) is corrosive to metallic irrigation equipment and may acidify soil; high pH water (above 8.5) may precipitate calcium and cause emitter clogging in drip systems. (4) Specific ion toxicity: sodium (affects sensitive crops such as citrus at SAR above 3; causes leaf scorch and tip burn); chloride (accumulates in leaves; toxic to citrus, avocado, stone fruits at above 4 to 10 meq/L); boron (essential micronutrient but toxic at above 0.75 to 2.0 mg/L depending on crop sensitivity); bicarbonate (HCO3; causes calcium and magnesium to precipitate in the soil, increasing relative sodium and raising pH). (5) Biological contamination: irrigation water contaminated with faecal coliforms (from untreated wastewater commonly used in urban and peri-urban farming in Nigeria) poses food safety risks for leafy vegetables consumed raw; WHO guidelines

recommend faecal coliform below 1,000 per 100 mL for restricted irrigation (cooked crops); below 200 per 100 mL for unrestricted irrigation (raw salad crops). Monitoring irrigation water quality: field tests (handheld EC/pH meters) and laboratory analysis (full ion analysis for SAR, specific ions); NiMet and FMARD provide some water quality monitoring, but routine monitoring is limited at the smallholder level in Nigeria.

Fill in the blank: The Sodium Adsorption ________ (SAR) measures the sodium hazard of irrigation water; high SAR causes sodification of the soil (sodium displacing calcium and magnesium from exchange sites), collapsing soil aggregates and reducing infiltration; SAR below 10 is generally safe for irrigation.

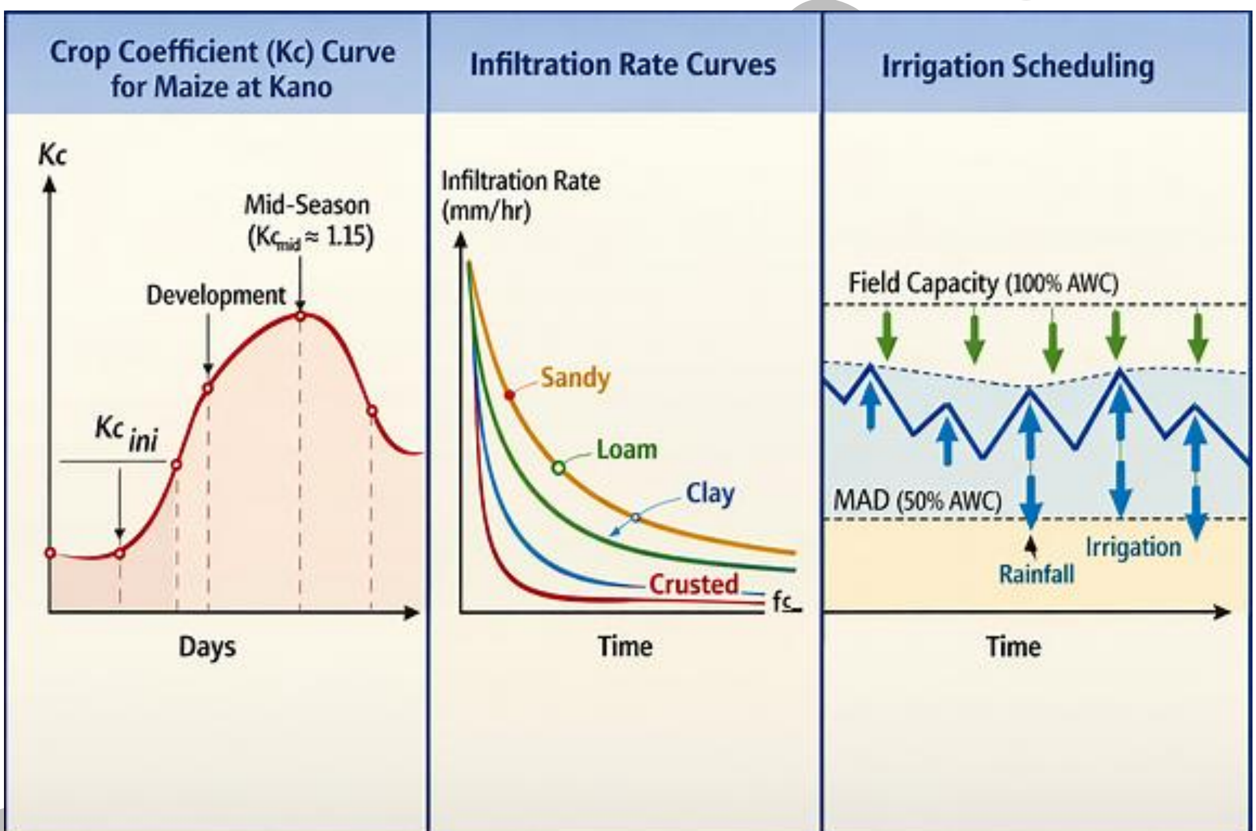

Figure 3.1: Crop coefficient curve (left), infiltration rate curves for different soils (centre), and irrigation scheduling graph (right)

Pilot questions 3.4

1. Define irrigation scheduling and explain the soil water balance method.

2. Calculate the gross irrigation requirement (GIR) if the soil moisture deficit (SMD) = 60 mm and application efficiency (Ea) = 0.65.
3. Compare surface irrigation, sprinkler irrigation, and drip irrigation in terms of application efficiency, infrastructure cost, and suitability for Nigerian conditions.
4. Define electrical conductivity (EC_w) and explain its significance as an irrigation water quality parameter.
5. Explain the Sodium Adsorption Ratio (SAR) and state the SAR value above which sodification becomes a serious risk.

Series Summary

This Series examined **crop water use as the total water consumed through transpiration and soil evaporation**, expressed as $\mathbf{ETc = T + E}$ or $\mathbf{ETc = Kc \times ET_0}$. Crop coefficients change across the initial, development, mid-season, and late-season growth stages, with maximum water demand usually occurring at mid-season. Water use is influenced by climate, soil moisture, crop type, growth stage, and management practices such as mulching and drip irrigation. The Series also covered **infiltration as the entry of water into the soil**, described by the Horton equation, $\mathbf{f = fc + (f_0 - fc)e^{-kt}}$. Infiltration depends on soil texture, structure, organic matter, compaction, surface crusting, slope, vegetation, and antecedent moisture. Water that moves below the root zone after field capacity is reached is called percolation and may recharge groundwater.

The Series further examined **runoff, irrigation scheduling, irrigation methods, and water quality**. Runoff may occur when rainfall intensity exceeds infiltration capacity or when the soil becomes saturated, and it is affected by rainfall, soil, slope, vegetation, land use, and watershed characteristics. It may be estimated using the Rational Method, $\mathbf{Q = CiA/360}$, or the SCS Curve Number method, $\mathbf{Q = (P - 0.2S)^2/(P + 0.8S)}$. Irrigation is commonly scheduled when soil moisture depletion reaches about 50–60% of available water, with $\mathbf{GIR = SMD/Ea}$. Surface irrigation has the lowest efficiency, sprinkler irrigation offers better uniformity, and drip irrigation provides the highest efficiency but requires greater capital. Irrigation water quality is assessed using electrical conductivity, sodium adsorption ratio, pH, specific-ion toxicity, and biological contamination to prevent salinity, sodicity, crop damage, and health risks.

Glossary of Terms

- **Application efficiency (Ea):** the fraction of irrigation water applied at the field boundary that is stored in the root zone and available for crop use; surface irrigation Ea 0.45 to 0.65; sprinkler 0.70 to 0.85; drip 0.85 to 0.95.
- **Consumptive use (CU):** the total water used by a crop through transpiration and soil evaporation during the growing season; practically equated with crop evapotranspiration ETc = T + E.

- **Crop coefficient (Kc):** a dimensionless factor used to convert reference ET0 to crop-specific ETc; varies with crop type and growth stage; Kc = ETc / ET0; typical mid-season values: maize 1.15 to 1.20; rice 1.05 to 1.20.
- **Crop water requirement (CWR):** the amount of water needed by a crop to meet its full ETc demand under disease-free, non-limiting conditions; the basis for irrigation scheduling and system design.
- **Double-ring infiltrometer:** a field instrument for measuring infiltration rate; consists of inner ring (30 cm diameter) and outer ring (60 cm diameter) driven into soil; water added to inner ring at constant head; rate of addition measured over time.
- **Drip irrigation:** irrigation method that delivers water directly to the plant root zone through emitters at very low flow rates (2 to 8 L/hr); achieves application efficiency of 0.85 to 0.95; highest efficiency method.
- **Electrical conductivity (EC_w):** measure of total dissolved salt concentration in irrigation water (dS/m); below 0.7 dS/m is good quality; above 3.0 dS/m is severely saline; high EC_w reduces plant water uptake through osmotic effects.
- **Gross irrigation requirement (GIR):** the depth of water to apply at the field to restore soil moisture to field capacity; GIR = SMD / Ea; greater than the net irrigation requirement due to application inefficiency.
- **Horton overland flow:** surface runoff generated when rainfall intensity exceeds the soil infiltration capacity; the dominant runoff mechanism on degraded, crusted, and compacted soils in Nigeria.
- **Infiltration capacity (fp):** the maximum rate at which a soil can absorb water at a given time; initially high (driven by gravity and matric suction) and declines exponentially toward the basic infiltration rate (fc = Ks).
- **Infiltration excess:** the depth of water from a storm that exceeds the soil infiltration capacity and becomes surface runoff; = (rainfall intensity - infiltration capacity) x duration when rainfall intensity exceeds fp.
- **Management allowed deficit (MAD):** the soil moisture deficit at which irrigation is triggered; typically 50 to 60 percent of AWC for most crops; allows some depletion before crop stress occurs while avoiding excessive irrigation.

- **Percolation:** the downward movement of water through the soil profile below the root zone toward the groundwater table; occurs after the soil above field capacity; recharges groundwater and aquifers.
- **Runoff coefficient (C):** the ratio of surface runoff depth to rainfall depth for a given storm; ranges from 0.05 (dense forest) to 0.90 (bare eroded soil or impervious surfaces); used in the Rational Method.
- **Saturation excess overland flow:** surface runoff generated when the entire soil profile becomes saturated and cannot absorb more water; common in valley bottoms, fadama areas, and near rivers in humid Nigeria.
- **Sodium Adsorption Ratio (SAR):** measures the sodium hazard of irrigation water; SAR = Na / sqrt((Ca+Mg)/2) (mmol/L); SAR below 10 is safe; above 18 is severe sodification risk; high SAR destroys soil structure.
- **Soil moisture deficit (SMD):** the depth of water required to restore the soil to field capacity; SMD = 0 when soil is at FC; increases daily by ETc minus rainfall; irrigation is triggered when SMD reaches the MAD.

Concept Check Questions [Series 3]

Objective Questions

1. Crop consumptive use is practically equated with ETc = T + E, where T is ________ through stomata and E is soil evaporation from between plant rows. (Linked to SLO 3.1)
2. The FAO-56 formula ETc = Kc x ET0 uses the crop ________ (Kc) which accounts for differences between the crop and the reference grass surface; Kc is highest during the mid-season stage. (Linked to SLO 3.1)
3. Horton's infiltration equation f = fc + (f0 - fc) e^(-kt) shows an exponential ________ from the initial rate (f0) to the final steady-state rate (fc); fc equals the saturated hydraulic conductivity. (Linked to SLO 3.2)
4. Infiltration ________ overland flow (Horton flow) is generated when rainfall intensity exceeds soil infiltration capacity; it is the dominant runoff mechanism on degraded Nigerian agricultural soils. (Linked to SLO 3.3)

5. The Sodium Adsorption ________ (SAR) of irrigation water measures the sodium hazard relative to calcium and magnesium; SAR above 18 poses a severe sodification risk to soil structure and infiltration. (Linked to SLO 3.4)

Short-Answer Questions

1. Define consumptive use, state its two components, and give the seasonal ETc value for maize in Nigeria. (Linked to SLO 3.1)
2. Describe how the crop coefficient Kc changes across the four growth stages and state mid-season Kc values for maize and rice. (Linked to SLO 3.1)
3. State five factors that affect soil infiltration rates in Nigeria. (Linked to SLO 3.2)
4. Distinguish between Horton and Dunne overland flow with one Nigerian example of each. (Linked to SLO 3.3)
5. Compare surface, sprinkler, and drip irrigation on application efficiency and suitability for Nigerian smallholders. (Linked to SLO 3.4)
6. **Long-Answer Questions**
7. Explain consumptive use, crop coefficients, and the factors affecting crop water use in Nigeria. Describe infiltration processes, measurement methods, and the factors affecting infiltration rates. (Linked to SLOs 3.1, 3.2)
8. Explain runoff generation mechanisms, the factors affecting runoff, and runoff estimation methods. Describe irrigation scheduling, methods and efficiencies, and water quality parameters for irrigation. (Linked to SLOs 3.3, 3.4)

Answers to Concept Check Questions [Series 3]

Objective Questions

1. Transpiration.
2. Coefficient.
3. Decline.
4. Excess.
5. Ratio.

Short-Answer Questions

1. Consumptive use = total water used by a crop through transpiration (T) and soil evaporation (E); ETc = T + E. Seasonal ETc for maize in Nigeria: approximately 400 to 550 mm.

2. Initial stage: Kc ini approximately 0.35 to 0.50 (sparse canopy; soil evaporation dominates). Development stage: Kc rises from Kc ini to Kc mid. Mid-season stage: Kc mid maximum (maize 1.15 to 1.20; rice 1.05 to 1.20). Late season: Kc end declines (maize 0.35 to 0.60 at maturity).
3. Soil texture (sandy soils high infiltration; clay soils low). Surface crusting (can reduce f from 30 mm/hr to below 2 mm/hr). Organic matter content (higher OM improves aggregation and macroporosity). Compaction (bulk density above 1.6 g/cm3 severely restricts infiltration). Antecedent moisture (wetter soils have lower initial infiltration rates).
4. Horton overland flow: rainfall intensity exceeds soil infiltration capacity; excess water flows over surface; common on degraded, crusted Alfisols in south-western Nigeria at the start of the rainy season. Dunne overland flow: soil becomes fully saturated before runoff occurs; occurs in valley bottoms and fadama areas in northern Nigeria where water table is close to the surface.
5. Surface irrigation: Ea 0.45 to 0.65; low cost; requires level fields; dominant in Nigerian fadama. Sprinkler: Ea 0.70 to 0.85; suits undulating terrain; requires pressure and energy; moderate cost. Drip: Ea 0.85 to 0.95; highest efficiency; reduces E and disease; high capital cost; growing adoption for vegetables and fruit in Nigeria.

Long-Answer Questions

1. Consumptive use = ETc = T + E; T is transpiration (productive; linked to carbon fixation); E is soil evaporation (unproductive). Seasonal values: maize 400 to 550 mm; rice 800 to 1,200 mm; sugarcane 1,200 to 1,500 mm. ETc = Kc x ET0; four Kc stages: initial (0.35 to 0.50; bare soil); development (Kc rising); mid-season (1.0 to 1.2; maximum); late-season (0.35 to 0.70; senescence). Factors affecting CU: climate (temperature, VPD, wind, radiation; dry-season ET0 up to 6 to 9 mm/day in northern Nigeria); soil water (AET falls below PET below 50 to 60 percent AWC threshold); crop type (C4 crops: maize, sorghum more efficient than C3: rice, cowpea); growth stage; management (mulching reduces E by 20 to 40 percent; drip eliminates inter-row evaporation). Infiltration: entry of water into soil at the surface; initial rate f0 (high; gravity + matric suction); final rate fc = Ks (gravity only); Horton equation: f = fc + (f0 - fc) e^(-kt). Measurement: double-ring infiltrometer (inner ring 30 cm; outer ring 60 cm; constant head; water addition measured over time). Factors: texture (sandy 20 to 100 mm/hr; clay 0.1 to 5 mm/hr); structure and macroporosity; organic matter; antecedent moisture; surface crusting (reduces from 30 to below 2 mm/hr; mulching and minimum tillage prevent it); compaction; slope; vegetation. Percolation: downward below root zone after FC; recharges groundwater; paddy rice 2 to 10 mm/day percolation.

2. Runoff mechanisms: Horton overland flow (rainfall intensity exceeds fp; dominant on degraded Nigerian soils at start of rainy season); Dunne saturation flow (soil fully saturated; valley bottoms, fadama); interflow (lateral below surface); depression storage (5 to 15 mm before runoff). Factors: rainfall intensity and duration (high intensity exceeds fp; longer storms saturate larger areas); antecedent moisture (AMC I/II/III; wet soils generate more runoff); slope (steeper = faster flow, less infiltration time); soil texture and infiltration (low Ks soils: high runoff); land use (forest: C 0.05 to 0.20; bare eroded soil: C 0.70 to 0.90); watershed area and drainage density. Runoff estimation: Rational Method Q = CiA/360 (below 80 to 100 ha); SCS CN method Q = (P - 0.2S)2/(P + 0.8S); regression equations; runoff plots (2 m x 10 to 22 m; measure runoff and soil loss directly; used at IITA Ibadan, IAR Zaria). Irrigation scheduling: SMD method; MAD = 50 to 60 percent AWC; irrigate when SMD = MAD; GIR = SMD/Ea. Methods: surface (Ea 0.45 to 0.65; flood and furrow; low cost; requires levelling; dominant in Nigerian fadama); sprinkler (Ea 0.70 to 0.85; pressurised; suits undulating terrain); drip (Ea 0.85 to 0.95; highest efficiency; reduces E and foliar disease; high capital cost). Project efficiency = Ec x Ea; typical Nigeria surface project 0.36. Water quality: EC_w (below 0.7 good; above 3.0 severe); SAR = Na/sqrt((Ca+Mg)/2); SAR below 10 safe; above 18 severe; pH 6.5 to 8.4; specific ion toxicity (Na, Cl, B); biological contamination (faecal coliforms; WHO guidelines).

Answers to Pilot Questions [Series 3]

Part 3.1

1. Consumptive use = water used in transpiration + soil evaporation + water in plant tissue (negligible); ≈ ETc = T + E. Two components: transpiration (T; productive; linked to carbon fixation through stomata); soil evaporation (E; unproductive; from bare soil between rows).
2. Kc is the crop coefficient in ETc = Kc x ET0; it accounts for differences between the actual crop and the reference grass. Four stages: initial (Kc ini approximately 0.35 to 0.50; bare soil, small plants; soil evaporation dominates); development (Kc rising as canopy covers soil); mid-season (Kc mid approximately 1.0 to 1.2; full canopy; maximum water use); late season (Kc end approximately 0.35 to 0.70; senescence and maturation).
3. ETc = Kc x ET0 = 1.10 x 6.0 = 6.6 mm/day. This means the maize crop uses 6.6 mm of water per day at mid-season; irrigation or rainfall must replace this daily loss; an irrigation event should supply enough water to refill the root zone when SMD reaches the management allowed deficit (typically 50 percent of AWC).
4. Climate (high temperature and low RH during harmattan increase ET0 to 6 to 9 mm/day in northern Nigeria). Soil water availability (AET falls below PET when soil moisture drops below 50 to 60 percent AWC). Crop type (C4 crops: maize, sorghum more water-use-efficient than C3 crops). Management (mulching reduces soil evaporation by 20 to 40 percent).
5. Mulching covers the bare soil surface between plants; it prevents direct evaporation from the soil, which accounts for a large fraction of total water loss from the field (especially early in the season before canopy closes and during the dry season when inter-row soil is hot and dry); reducing soil evaporation without reducing transpiration improves water productivity (more crop per drop).

Part 3.2

1. Infiltration capacity (fp) is the maximum rate at which a soil can absorb water at a given time. Initial rate (f0): very high when the soil is dry; both gravity and large matric suction pull water rapidly into the pores. Final rate (fc): equals the saturated hydraulic conductivity (Ks); only gravity drives flow; the soil is fully saturated and suction is exhausted; fc is always lower than f0.
2. Two concentric rings are driven into the soil (inner ring 30 cm diameter; outer ring 60 cm diameter). Water is poured into both rings to a constant shallow head (5 to 10 mm). The volume of water added to maintain the level in the inner ring is measured at regular time

intervals. The outer ring prevents lateral flow from the inner ring (buffer effect). Cumulative infiltration is plotted versus time; infiltration rate is calculated from the rate of water addition to the inner ring.

3. Texture (sandy soils have large pores and high Ks: 20 to 100 mm/hr; clay soils have small pores and low Ks: 0.1 to 5 mm/hr). Surface crusting (raindrop impact breaks aggregates and seals pores; reduces f from 30 mm/hr to below 2 mm/hr). Organic matter (higher OM improves aggregation and macroporosity; increases infiltration). Compaction (reduces pore size; bulk density above 1.6 g/cm3 severely restricts flow). Antecedent moisture (wet soils have partially satisfied matric suction; lower initial infiltration rate than dry soils).
4. Infiltration: entry of water at the soil surface; surface process; rate decreases from f0 to fc over time. Percolation: downward movement of water through the profile below the root zone; begins only after the soil above is wetted to FC; driven by gravity only. Role in groundwater recharge: percolated water reaches the water table; recharges shallow aquifers used by millions of rural Nigerians for drinking and irrigation; conservation structures (check dams, contour bunds) that slow runoff and increase infiltration also increase percolation and aquifer recharge.
5. Raindrop impact breaks down surface aggregates (dispersion); dispersed clay and silt particles migrate into and seal surface pores, forming a dense thin layer (crust) with very low permeability; a 2 to 5 mm crust can reduce infiltration from 20 to 30 mm/hr to below 2 mm/hr. Two preventive practices: mulching (covers the soil surface; absorbs raindrop impact; prevents aggregate breakdown); minimum tillage (preserves stable aggregates and macropores; reduces surface susceptibility to sealing).

Part 3.3

1. Horton (infiltration excess): rainfall intensity exceeds soil fp; excess water flows over surface; Nigerian example: intense convective storm on a bare, crusted Alfisol in south-western Nigeria at the start of the rainy season before crop establishment; crust limits fp to below 2 mm/hr while storm intensity exceeds 40 mm/hr. Dunne (saturation excess): soil becomes fully saturated; runoff from areas where water table is at or near the surface; Nigerian example: valley bottom fadama area in Kano State during peak of rainy season; shallow water table rises to soil surface making further infiltration impossible.
2. Rainfall intensity and duration (high intensity exceeds fp more; longer storms saturate more of the watershed). Antecedent moisture (wet soils in AMC III generate much more runoff than dry AMC I soils for the same storm). Soil infiltration and texture (low-fp clay and crusted soils generate more runoff than sandy or well-structured soils). Land use and

vegetation cover (forests: low runoff C 0.05 to 0.20; bare eroded soil: high runoff C 0.70 to 0.90). Slope (steeper slopes generate faster flow; shorter contact time for infiltration; higher runoff rates and erosive velocities).

3. Runoff coefficient C = runoff depth / rainfall depth for a given storm. Values: dense forest 0.05 to 0.20; grassland 0.15 to 0.40; bare eroded soil 0.70 to 0.90.
4. Q = CiA/360 = 0.45 x 60 x 50 / 360 = 1,350 / 360 = 3.75 m3/s.
5. Runoff plots are bounded field plots (metal or concrete borders; typically 2 m wide x 10 to 22 m long on a representative slope) with a collection trough and measurement device (flume or tipping bucket) at the downslope end; runoff water and eroded sediment are collected and measured after each storm. Importance: directly measure runoff and soil loss rates under different management treatments; calibrate erosion prediction models (USLE, RUSLE); evaluate effectiveness of conservation practices (mulching, minimum tillage, terracing); major research centres with plot facilities in Nigeria: IITA Ibadan and IAR Zaria.

Part 3.4

1. Irrigation scheduling determines when to irrigate and how much water to apply to maintain soil moisture in the favourable range for crop growth. Soil water balance method: SMD(t) = SMD(t-1) + ETc(t) - P(t) - I(t); SMD increases daily by ETc minus rainfall; irrigation is triggered when SMD reaches the MAD (50 to 60 percent of AWC); the amount applied equals GIR = SMD/Ea to restore the soil to FC.
2. GIR = SMD / Ea = 60 / 0.65 = 92.3 mm; approximately 92 mm must be applied at the field boundary to store 60 mm in the root zone (the remaining 32 mm is lost to non-uniformity and deep percolation).
3. Surface (Ea 0.45 to 0.65; lowest efficiency; lowest cost; dominant in Nigerian fadama; requires level fields; simple gravity operation). Sprinkler (Ea 0.70 to 0.85; suits undulating terrain without levelling; requires pressurised supply; moderate to high cost; wind affects uniformity). Drip (Ea 0.85 to 0.95; highest efficiency; reduces soil evaporation and foliar disease; high capital cost; growing adoption for high-value vegetable and fruit production in Nigeria).
4. EC_w is the electrical conductivity of irrigation water (dS/m), which measures total dissolved salt concentration. Below 0.7 dS/m: good quality; generally safe for all crops. Above 3.0 dS/m: severely saline; restricts water uptake osmotically and causes ionic toxicity; limits crop choice to salt-tolerant species. Nigerian river water is generally low in salinity (0.1 to 0.5 dS/m) but groundwater in semi-arid Sokoto and Borno may exceed safe limits.

5. SAR = Na / sqrt((Ca + Mg)/2) (mmol/L); measures the proportion of sodium relative to calcium and magnesium in irrigation water. SAR below 10: safe; soil structure not threatened. SAR 10 to 18: moderate hazard. SAR above 18: severe risk; sodium displaces Ca and Mg from soil exchange sites (sodification), collapsing aggregates, reducing infiltration and increasing surface crusting.

References and Attributions [Series 3]

Textual References (Books and External Sources)

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Figures, Plates, Tables, and Boxes

- Figure 3.1: Crop coefficient curve, infiltration rate curves, and irrigation scheduling graph. Attribution: AI generated. Suggested OER search string: “crop coefficient Kc infiltration rate irrigation scheduling soil moisture Nigeria OER⇓.

Series 4: Methods of Soil and Water Conservation

- **Part 4.1: Agronomic and Vegetative Conservation Measures**
    - Sub Part 4.1.1: Cover crops, mulching, and crop residue management
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    - Sub Part 4.1.3: Agroforestry and windbreaks as conservation measures
- **Part 4.2: Mechanical and Structural Conservation Measures**
    - Sub Part 4.2.1: Terraces: types, design, and construction
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- **Part 3.3: Water Harvesting and Conservation in Semi-Arid Nigeria**
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    - Sub Part 4.3.3: Rainwater collection and reuse
- **Part 4.4: Limitations and Selection of Conservation Methods**
    - Sub Part 4.4.1: Limitations of individual conservation methods
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    - Sub Part 4.4.3: Integrated watershed management in Nigeria

Introduction

Soil and water conservation involves a wide range of practices, structures, and systems designed to reduce soil erosion, improve water retention, maintain soil fertility, and sustain agricultural productivity across Nigeria's diverse ecological zones. Effective conservation rarely relies on a single measure; rather, successful conservation programmes combine agronomic and vegetative practices (which modify the land surface to reduce erosion) with mechanical and structural measures (which physically intercept and manage runoff) within an integrated watershed management framework.

This Series covers the main categories of conservation methods in systematic detail: agronomic and vegetative measures (cover crops, mulching, contour farming, strip cropping, agroforestry, and windbreaks); mechanical and structural measures (terraces, contour bunds, grass waterways, diversion channels, gully control structures); water harvesting and conservation for semi-arid Nigeria; and the limitations of individual methods and the criteria for selecting and combining them effectively. The Series concludes with a discussion of integrated watershed management, which provides the framework for applying these tools at catchment scale.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 4.1** describe the main agronomic and vegetative conservation measures (cover crops, mulching, contour farming, strip cropping, agroforestry, windbreaks) and explain how each reduces erosion and improves soil and water conservation (Linked to Part 4.1),
- **SLO 4.2** describe the types of terraces and their design principles, explain the purpose and construction of contour bunds, grass waterways, and diversion channels, and describe the structures used to control gully erosion (Linked to Part 4.2),
- **SLO 4.3** describe the main water harvesting techniques used in semi-arid Nigeria, explain the design principles for small farm dams and ponds, and describe rainwater collection and reuse systems (Linked to Part 4.3), and

- **SLO 4.4** explain the limitations of individual conservation methods, describe the criteria used to select appropriate conservation practices, and explain the integrated watershed management approach for Nigeria (Linked to Part 4.4).

4.1 Agronomic and Vegetative Conservation Measures

4.1.1 Cover crops, mulching, and crop residue management

Agronomic and vegetative conservation measures modify the land cover, crop management, and soil surface to reduce erosion without constructing permanent structures. They are generally lower in cost, accessible to smallholders, and reversible but require consistent management to sustain their effectiveness. Cover crops are fast-growing plants established primarily to protect the soil surface from erosion between main crop seasons or as living mulch under a main crop. Important cover crops in Nigeria: Mucuna pruriens (velvet bean; fast-growing legume; forms dense canopy that shades out weeds and protects soil; adds 80 to 200 kg N/ha through nitrogen fixation; widely used in the humid south as a fallow cover crop); Calopogonium mucunoides (calopo; creeping legume; used in oil palm and rubber plantations); Centrosema pubescens (centro; creeping legume; used in humid zones); Stylosanthes species (used in the savanna zone); Lablab purpureus (lablab; dual-purpose; human food and cover). Benefits of cover crops: reduce raindrop impact and surface runoff; improve infiltration; add organic matter and nitrogen; suppress weeds; maintain soil biological activity during fallow periods.

Mulching is the application of organic or inorganic material to the soil surface to protect it from raindrop impact, reduce evaporation, regulate soil temperature, and suppress weeds. Organic mulch materials in Nigeria: rice straw; maize stover; guinea grass; groundnut shells; wood chips; cocoa pod husks. Effects of mulching on erosion: at 70 to 80 percent soil cover, mulch reduces splash erosion by 90 to 95 percent; reduces runoff volume by 30 to 50 percent; reduces soil loss by 80 to 95 percent compared with bare soil; significantly reduces the C factor in the USLE. Recommended mulch application rates: 3 to 6 tonnes/ha for adequate surface cover. Crop residue management: leaving harvest residues (maize stover, sorghum stalks, cowpea haulms, groundnut shells) on the soil surface provides mulching benefits; the alternative practice of burning residues destroys organic matter, nutrients, and the protective mulch layer; burning also kills soil organisms and contributes to greenhouse gas emissions. No-till and minimum-till systems that retain crop residues are major conservation strategies but face adoption barriers in Nigeria (residues used for animal feed; insect pest concerns; equipment availability).

Fill in the blank: At 70 to 80 percent soil surface cover, organic ________ reduces splash erosion by 90 to 95 percent and soil loss by 80 to 95 percent compared with bare soil; it is one of the most cost-effective conservation measures accessible to Nigerian smallholder farmers.

4.1.2 Contour farming, strip cropping, and intercropping

Contour farming is the practice of performing all field operations (tillage, planting, weeding, harvesting) along contour lines (lines of equal elevation) rather than up and down the slope. Contour lines run perpendicular to the slope direction, so tillage furrows and crop rows act as small barriers to downslope water movement, reducing runoff velocity and increasing the time available for infiltration. Contour farming is effective on slopes of 2 to 8 percent; on steeper slopes it must be combined with structural measures (terraces, bunds). It is inexpensive (requires only a hand level or A-frame level to lay out contour lines) and accessible to all farmers. The P factor in the USLE for contour farming ranges from 0.25 to 0.60 depending on slope steepness (more effective on gentle slopes; less effective on steep slopes above 8 percent where runoff can accumulate and break through contour rows). Effectiveness: studies in Nigeria and other tropical countries show that contour farming reduces soil loss by 40 to 60 percent compared with up-and-down-slope tillage on the same soils and slopes.

Strip cropping is the alternating arrangement of strips of different crops (typically a close-growing protective crop like sorghum, millet, grass, or a legume, alternating with a more open row crop like maize or cassava) across the slope; the protective strips act as barriers to runoff flow and trap eroded sediment, while the productive strips provide income. Strip width is typically 20 to 40 m; strips are oriented on contour. Strip cropping combines the benefits of contour farming with additional sediment trapping and runoff retardation by the dense vegetative strips; it is particularly effective on slopes of 3 to 8 percent. Grass strips (vetiver grass, Napier grass, or Guinea grass planted in permanent strips on the contour) are among the most effective and durable forms of strip cropping; vetiver grass (Chrysopogon zizanioides) has very deep, strong roots, tolerates a wide range of soils and climates, and can be planted in dense strips that trap sediment and force overland flow to infiltrate or spread. Intercropping: growing two or more crops simultaneously on the same field; particularly relevant in Nigeria where the vast majority of smallholders practice intercropping; intercropping generally produces denser canopy cover than monoculture, reducing raindrop impact and improving erosion control; legume-cereal intercropping also improves soil fertility and reduces the farmer’s risk.

Fill in the blank: Contour ________ alternates strips of protective close-growing crops with more open row crops across the slope; it traps eroded sediment in the vegetative strips, reduces runoff velocity, and is particularly effective on slopes of 3 to 8 percent; vetiver grass strips are among the most effective in Nigeria.

4.1.3 Agroforestry and windbreaks as conservation measures

Agroforestry systems integrate trees and shrubs with crops and/or livestock, providing multiple conservation benefits simultaneously: (1) Canopy cover: tree canopies intercept rainfall, reduce raindrop impact on the soil surface, and reduce the throughfall that reaches the ground (though stemflow may concentrate water at tree bases); deep-rooted trees improve soil structure and macroporosity, dramatically increasing infiltration rates. (2) Organic matter: leaf litter, dead roots, and pruning biomass add organic matter to the soil surface and subsurface, improving soil structure, water-holding capacity, and infiltration rates. (3) Nitrogen fixation: leguminous trees (Gliricidia sepium; Leucaena leucocephala; Acacia albida/Faidherbia albida; Albizia species) fix atmospheric nitrogen and supply it to associated crops through leaf litter and pruning. (4) Root binding: deep, extensive tree root systems bind the soil and resist erosion on steep slopes. (5) Wind erosion control: trees along field and property boundaries (alley cropping systems; boundary planting) reduce wind speed and protect crops and soil from wind erosion.

Windbreaks (shelterbelts) are rows of trees and shrubs planted perpendicular to the prevailing wind direction to reduce wind speed, protect crops from desiccation, and prevent wind erosion of soil. In semi-arid northern Nigeria (Sokoto, Kebbi, Katsina, Kano, Jigawa, Yobe, Borno states), windbreaks are critically important for reducing harmattan wind damage (November to March; wind speeds 5 to 10 m/s; RH 10 to 30 percent). Effective windbreaks reduce wind speed by 50 to 80 percent for a horizontal distance of 10 to 15 times the windbreak height on the leeward side; this reduces both wind erosion and evapotranspiration from crops, extending the effective growing season and improving crop yields. Tree species commonly used in Nigerian windbreaks: Eucalyptus camaldulensis (fast-growing; widely available; effective wind barrier); Casuarina equisetifolia (drought-tolerant; fixes nitrogen via Frankia bacteria; used across the Sahel); Azadirachta indica (neem; drought-tolerant; multipurpose: timber, medicine, biopesticide); Acacia species (thorny; provides good fence as well as windbreak; drought-tolerant). The Nigerian Great Green Wall project (part of the African Union Great Green Wall initiative) aims to restore 11.4 million ha of degraded land in Nigeria's northern states through tree planting, windbreaks, and agroforestry.

Fill in the blank: ________ (shelterbelts) planted perpendicular to the prevailing wind direction reduce wind speed by 50 to 80 percent on the leeward side for a distance of 10 to 15 times the windbreak height; they protect crops from desiccation and prevent wind erosion of soil in semi-arid northern Nigeria.

Pilot questions 4.1

1. Name four cover crops used in Nigeria and state one conservation benefit of each.
2. Explain how mulching reduces soil erosion and state the recommended mulch application rate for Nigerian conditions.
3. Define contour farming and explain how it reduces erosion; state its USLE P factor range.
4. Describe strip cropping and explain why vetiver grass strips are particularly effective in Nigeria.
5. Explain three conservation benefits of agroforestry systems in Nigerian agriculture.

4.2 Mechanical and Structural Conservation Measures

4.2.1 Terraces: types, design, and construction

Terraces are earthen embankments or channels constructed across a slope to reduce the effective slope length, slow runoff, and prevent erosion. They are among the most effective structural conservation measures for sloping agricultural land but also among the most expensive to construct and maintain. Types of terraces: (1) Bench terraces (level terraces): the slope is cut and filled to create a series of nearly level platforms (benches) separated by steep risers (vegetated or faced with stone or concrete); each bench is essentially a flat field on which any crop can be grown; very effective but require large amounts of earthmoving; most appropriate on slopes of 10 to 30 percent where they convert unusable steep land to productive agriculture; common in the terraced agricultural systems of Jos Plateau and Mambilla Plateau in Nigeria where farmers have maintained stone-walled terraces for centuries. (2) Broad-base terraces: low, wide ridges constructed on gentle slopes (1 to 8 percent); typically 1.5 to 3 m wide at the base and 0.3 to 0.5 m high; designed to slow and divert runoff to a safe outlet (grass waterway); the field between terraces remains cultivable and machinery can cross; most commonly used in the savanna zone of Nigeria for row crop production. (3) Narrow-based terraces: a narrow ridge on steep slopes (5 to 15 percent); not traversable by machinery; cultivation on one side only; suitable for perennial crops and orchards on steeper slopes.

Terrace design: the key design parameters are the vertical interval (VI; the elevation difference between adjacent terraces) and the horizontal interval (HI; the horizontal distance between adjacent terraces). The vertical interval is related to slope gradient (S; percent) by empirical formulae; a common West African recommendation is VI (m) = 0.3 + 0.03 x S (for S in percent). Horizontal interval HI = VI / (S/100) = VI x 100/S. Example: on a 10 percent slope; VI = 0.3 + 0.03 x 10 = 0.6 m; HI = 0.6 x 100/10 = 6 m. Channel grade: broad-based terrace channels are given a slight grade (0.1 to 0.5 percent) to lead water to a stable outlet without causing erosion in the channel; perfectly level terrace channels that fill with water (level terraces) are used where maximum water retention is the goal (drier areas). Terrace construction: marking terrace lines on the ground using surveying instruments (abney level, hand level, A-frame level, water tube level); earthmoving using manual labour (hoes and shovels for small-scale construction) or mechanical equipment (dozers, graders, tractors with blade or disc plough for large-scale); compacting and shaping the terrace ridge; establishing grass (Napier grass, Bahia grass, Guinea grass, vetiver) on the terrace ridge and channel to prevent erosion.

Fill in the blank: The vertical interval (VI) between terraces is estimated as VI = 0.3 + 0.03 x S (where S = slope percent); on a ________ percent slope, VI = 0.3 + 0.03 x 15 = 0.75 m and the horizontal interval HI = 0.75 x 100/15 = 5 m.

4.2.2 Contour bunds, waterways, and diversion channels

Contour bunds (earth bunds) are low earthen embankments constructed along the contour at intervals determined by the slope gradient and rainfall intensity; they are lower in cost and construction requirements than terraces and are the most widely used structural conservation measure in the savanna zones of Nigeria. Characteristics: height typically 0.3 to 0.6 m; base width 1.0 to 2.0 m; spaced at vertical intervals similar to terraces; constructed manually using hand tools or by a tractor-drawn ridger; the bund intercepts surface runoff, ponding it above the bund where it infiltrates or spreads; spaces between bunds remain cultivated. Contour bunds differ from terraces in that the space between bunds is not modified (retains original slope) and bunds are lower embankments; they are less effective than bench terraces but far less expensive. The FAO recommends the use of contour bunds as the primary conservation measure on slopes up to 15 percent in the West African savanna; above 15 percent, bench terraces become necessary. In Zambia, Ethiopia, Burkina Faso, and northern Nigeria, contour bunds (diguettes in French West Africa) have been shown to increase millet and sorghum yields by 30 to 60 percent in semi-arid areas through improved water retention and reduced erosion.

Grass waterways (grassed spillways) are natural or excavated channels, vegetated with permanent grass, that carry concentrated surface runoff (from terrace channels, diversion channels, or low-lying drainage areas) safely down the slope to a stable outlet (stream, pond, road culvert) without causing channel erosion. Design requirements: the channel must be large enough to convey the design peak discharge without overflowing; the grass cover must be dense enough (and the flow velocity low enough) to prevent scour; typical grass species for Nigerian waterways: Napier grass (Pennisetum purpureum), Bahia grass (Paspalum notatum), and Guinea grass (Panicum maximum). Diversion channels (diversions) are open channels excavated across a slope above vulnerable fields or structures to intercept runoff from upslope areas and divert it to a stable outlet before it can erode the protected land below; used to protect road cuts, building sites, and the upper edges of terrace systems; must be sized for the peak discharge from the contributing upslope area using the Rational Method and must include a stable outlet (grass waterway or drop structure) to prevent scour at the point of discharge.

Fill in the blank: Grass ________ are permanently vegetated channels that carry concentrated surface runoff safely down the slope from terrace outlets and diversion channel outlets to stable receiving points; they prevent channel erosion by maintaining a protective grass cover and limiting flow velocity.

4.2.3 Gully control structures: check dams and gully plugs

Gully erosion is the most dramatic and destructive form of soil erosion in Nigeria, particularly in south-eastern states where soft Cretaceous sedimentary soils combined with high-intensity rainfall and deforestation produce gullies of enormous size. Gully control involves: (1) Stabilising the gully head (headcut) to prevent upstream advance of the gully; (2) reducing the slope gradient in the gully channel to reduce scour velocity; (3) establishing vegetation to bind gully walls and bed; (4) managing the upslope watershed to reduce the volume and velocity of runoff entering the gully. Check dams are low barriers built across the gully channel to reduce flow velocity, trap sediment, and raise the bed level progressively; types: earth dams (compacted soil; temporary; simple to construct but vulnerable to overflow erosion; must be protected with a vegetated spillway); brush and timber dams (locally available materials; cheap; suitable for small gullies; biodegradable); gabion dams (wire mesh baskets filled with stones; durable; flexible; can accommodate channel movement; widely used in Nigerian gully rehabilitation projects; must be tightly constructed and anchored into the gully walls to prevent undercutting); concrete dams (permanent; expensive; used in large gullies or where stone is unavailable).

Design of check dams: the height of a check dam (H) determines the maximum depth of sediment it can trap and the reduction in channel slope; check dams are spaced so that the accumulated sediment behind each upstream dam begins at the crest of the next downstream dam (head-to-toe arrangement); for a series of check dams on a channel with original slope S, the reduced slope between dams equals zero (horizontal bed of sediment between dams). Spacing L between dams = H/tan(alpha), where alpha is the original gully slope angle; for a gully on a 10 percent slope and a check dam 1.0 m high, L = 1.0/0.10 = 10 m. Gully plugs (gully dams for water harvesting): in semi-arid northern Nigeria, large earthen check dams across seasonal gullies (called gully plugs or hafir dams) serve the dual purpose of controlling gully erosion and harvesting runoff water; the impounded water recharges groundwater and provides dry-season irrigation water; major gully plug programmes have been implemented in Kano, Jigawa, and Katsina states by state governments and NGOs. Vegetation establishment in gullies: pioneer plant species (Chrysopogon zizanioides/vetiver; Panicum maximum/Guinea grass; Brachiaria mutica; Pennisetum purpureum) are planted in the sediment accumulating behind check dams to progressively revegetate the gully floor and walls; revegetation reduces gully wall collapse and slumping and stabilises the fill.

Fill in the blank: Check dams are spaced so that the sediment accumulated behind each upstream dam reaches the ________ of the next downstream dam (head-to-toe arrangement); spacing L = H / tan(alpha) where H is dam height and alpha is the original gully slope angle.

Pilot questions 4.2

1. Distinguish between bench terraces and broad-base terraces in terms of slope suitability, cost, and cultivation method.
2. Calculate the vertical interval (VI) and horizontal interval (HI) between terraces on a 12 percent slope using the formula VI = 0.3 + 0.03S.
3. Define contour bunds and explain why they are preferred over bench terraces in the Nigerian savanna zone.
4. Describe the purpose and design requirements of a grass waterway.
5. Describe three types of check dam materials used in Nigerian gully control and state one advantage of each.

4.3 Water Harvesting and Conservation in Semi-Arid Nigeria

4.3.1 Water harvesting techniques

Water harvesting (rainwater harvesting) is the collection and concentration of runoff from a catchment area to a smaller target area (the cropped or harvested area) where it is used productively. In semi-arid and arid regions where rainfall is insufficient to produce reliable crops without supplementary water, water harvesting effectively concentrates limited rainfall into a smaller area to meet crop water requirements. The ratio of the catchment area to the cropped (target) area determines the concentration factor; typical concentration ratios range from 2:1 to 20:1 depending on rainfall, soil, and crop water requirement. Water harvesting techniques used in northern Nigeria: (1) Microcatchment water harvesting: small runoff-generating areas (0.1 to

0.5 ha) within or adjacent to the field; local surface runoff is directed to individual planting basins (zai pits; tassas) or planting strips; the zai pit (a traditional West African and Sahel technique; also used in northern Nigeria as tassa) is a planting pit of 20 to 30 cm diameter and 10 to 20 cm depth dug in hard degraded soil before the rains; it traps runoff and concentrates it around plant roots; combined with organic matter placement (compost, manure) in the pit, it allows crop production on severely degraded soils; transformational impact: farmers using zai pits in the Sahel have achieved millet yields of 500 to 1,000 kg/ha on soils that produced almost nothing without this technique.

(2) Negarim microcatchments: diamond-shaped or V-shaped bunds enclosing individual trees or tree planting positions; used for fruit trees, woodlots, and fodder trees in semi-arid areas; runoff from the upper part of the diamond is concentrated to the tree planting pit at the lower apex; commonly used in reforestation of degraded land in the Sahel countries and northern Nigeria. (3) Contour ridges and half-moon bunds: semi-circular earth bunds constructed on the contour to capture surface runoff and direct it to the centre of the half-moon where crops are planted; commonly used for pearl millet and sorghum in northern Nigeria and across the Sahel; simple to construct with hand tools; effective on flat to gently sloping land (below 2 percent). (4) Stone lines (aligned stone bunds): lines of stones placed on the contour at intervals of 15 to 30 m across the slope; slow runoff, promote infiltration, trap sediment, and gradually build up terrace-like ridges of deposited sediment; widely used in Burkina Faso (using local granite stones) and applicable in the basement complex terrain of northern Nigeria (Kano, Kaduna, Niger, Sokoto states where granite and gneiss outcrops provide abundant stone). (5) Macro-catchment water harvesting (wadi diversion): runoff from larger natural catchments (ephemeral streams, wadis) is diverted and spread over agricultural fields using earthen channels and diversion bunds; commonly used in floodplain areas of the Chad Basin and north-east Nigeria.

Fill in the blank: The zai pit (tassa) is a ________ water harvesting technique; the pit (20 to 30 cm diameter; 10 to 20 cm deep) traps runoff and concentrates it around plant roots; combined with compost, it enables crop production on severely degraded soils in the Sahel and northern Nigeria.

4.3.2 Small reservoirs, ponds, and farm dams

Small reservoirs (ponds and farm dams) are impoundments of water in natural depressions or across small valleys to store seasonal runoff for use during the dry season; they are the most important water storage infrastructure for smallholder irrigation and livestock watering in the Nigerian savanna and semi-arid zones. Types: (1) Dug ponds (excavated ponds): excavated in low-lying areas (clayey soils preferred for low seepage); filled by direct runoff, shallow groundwater, or pumped water; depths of 1.5 to 3 m; 0.1 to 1 ha in surface area; used for vegetable irrigation and fish culture; common in the fadama systems of northern Nigeria. (2) Small earth dams (earthen embankment dams): constructed across a valley or seasonal stream (gully) to impound runoff; the embankment (dam body) is constructed from compacted earth; must include a spillway to pass the design flood safely over or around the dam without eroding the embankment; the spillway is the most critical design element; dam heights of 2 to 6 m; storage capacity of 5,000 to 100,000 m3 typical for farm-scale dams in Nigeria. (3) Sand dams: a low weir constructed across a seasonal sandy riverbed to retain sand that traps and stores water in its pore spaces; the stored water is accessed from hand-dug wells or scoop holes in the sand downstream; very durable; low evaporation losses (water below sand surface); appropriate for basement complex terrain of central and northern Nigeria where seasonal stream beds have sandy bottoms.

Design principles for small earth dams: (1) Site selection: valley constriction (narrows the dam embankment; reduces earthfill volume); firm, impermeable foundation soils (avoid sand, gravel, and fractured rock that permit seepage); adequate catchment area to fill the reservoir; spillway site on firm rock or stable soil. (2) Embankment design: homogeneous compacted earth dam with 3:1 to 4:1 upstream slopes and 2:1 to 3:1 downstream slopes; freeboard (height above spillway crest) of 0.5 to 1.0 m to protect against wave action and overtopping; filter and toe drain on downstream face to control seepage and prevent piping failure. (3) Spillway design: sized to safely convey the design flood (typically 100-year return period; peak discharge from the Rational Method or SCS CN method); common types: side channel spillway (channel excavated in the valley side; lined with concrete or stone); pipe spillway (corrugated metal or concrete pipe through or around the dam; with energy dissipator at outlet). (4) Environmental and social considerations: community consultation and land allocation; downstream water rights; sedimentation management (silting of reservoirs is a major problem in Nigeria; estimated 50 to

80 percent loss of reservoir capacity over 50 to 100 years in high-sediment-yield watersheds without conservation upstream).

Fill in the blank: The ________ is the most critical design element of a small earth dam; it must safely convey the 100-year design flood over or around the embankment without eroding it; failure to provide an adequate spillway is the most common cause of small dam failure in Nigeria.

4.3.3 Rainwater collection and reuse

Rainwater collection (rooftop catchment) systems collect rainfall from impervious roof surfaces and store it in tanks or cisterns for household water supply, vegetable garden irrigation, and livestock watering. System components: (1) Catchment surface: corrugated iron (zinc) or asbestos cement roofing sheets are the most common catchment surfaces in Nigerian homes; they have runoff coefficients of 0.80 to 0.95 (80 to 95 percent of rainfall becomes runoff from the roof); tiles and clay roofing have lower runoff coefficients (0.60 to 0.75). (2) Gutters and downpipes: channels fixed to the roof eaves to collect water running off the roof; directed to downpipes that carry water to the storage tank; must be kept clear of leaves and debris. (3) First-flush diverter: a simple device that diverts the first 1 to 2 mm of rainfall away from the storage tank (the initial runoff carries dust, bird droppings, and pollutants from the roof surface) and directs subsequent cleaner water to storage; significantly improves stored water quality. (4) Storage tank: concrete or plastic tanks (0.5 to 10 m3 capacity for household systems; larger ferrocement tanks of 5 to 50 m3 for community systems); must be covered and darkened to prevent algal growth and mosquito breeding; fitted with a tap, overflow pipe, and inspection hatch.

Rainwater harvesting potential: monthly collection volume = rainfall (mm) x catchment area (m2) x runoff coefficient; example: for a 50 m2 roof in Kano with a monthly rainfall of 80 mm and runoff coefficient 0.85: monthly collection = 80 x 50 x 0.85 / 1,000 = 3.4 m3 (3,400 litres); seasonal collection over the 4-month rainy season (total approximately 700 mm): 700 x 50 x 0.85 / 1,000 = 29.75 m3 (approximately 30,000 litres). Limitations: variable and unreliable supply mirrors rainfall variability; limited storage capacity of most household tanks; roof materials (old zinc sheets) may leach contaminants; quality concerns without first-flush diversion and treatment. Water reuse in agriculture: collected rainwater is used for supplementary irrigation of household vegetable gardens during the rainy season and for watering small livestock; grey water (wastewater from household washing and cooking) can also be collected and reused for irrigating trees and fruit crops in home gardens (indirect use of water already treated once by the household).

Fill in the blank: Monthly rainwater collection from a roof = rainfall (mm) x catchment ________ (m2) x runoff coefficient / 1,000; for a 50 m2 roof in Kano receiving 80 mm monthly rainfall with runoff coefficient 0.85, monthly collection = 80 x 50 x 0.85 / 1,000 = 3.4 m3 (3,400 litres).

Pilot questions 4.3

1. Define water harvesting and explain why it is important in semi-arid northern Nigeria.
2. Describe the zai pit (tassa) technique and explain why it is effective for crop production on degraded soils.
3. Describe the three main types of small reservoirs used in northern Nigeria and state when each is most appropriate.
4. List the key design principles for a small earth dam and explain the importance of the spillway.
5. Calculate the monthly rainwater collection from a 60 m2 corrugated iron roof receiving 100 mm rainfall (runoff coefficient 0.85).

4.4 Limitations and Selection of Conservation Methods

4.4.1 Limitations of individual conservation methods

Every soil and water conservation method has inherent limitations that affect its applicability, effectiveness, and sustainability in specific contexts. Understanding these limitations is essential for selecting appropriate combinations of measures and setting realistic expectations. Limitations of agronomic measures: (1) Cover crops and mulching: cover crops may compete with main crops for water and nutrients if poorly managed; mulch may harbour pests (rodents; stem borers) or diseases; in semi-arid areas, adequate mulch biomass may be unavailable (insufficient crop residue due to low yields; competing demand for crop residues as animal feed); mulch application requires significant labour (collecting, transporting, and spreading 3 to 6 t/ha is labour-intensive for smallholders). (2) Contour farming and strip cropping: effectiveness declines sharply on slopes above 8 to 10 percent; contouring lines must be re-established after each season as they gradually become imprecise; strips must be maintained as permanent features to remain effective; farmers in land-scarce areas may resist devoting productive land to permanent grass strips.

Limitations of structural measures: (3) Terraces: very high construction cost (manual construction: N50,000 to N200,000 per hectare; mechanical construction: N200,000 to N500,000 per hectare); maintenance requirement (terrace ridges must be maintained annually; neglected terraces collapse and concentrate runoff, causing worse erosion than without terraces); may not suit all soil types (expansion clays like Vertisols crack and deform terrace ridges); reduce cultivable area by 5 to 15 percent at the terrace ridge itself. (4) Check dams: silt gradually fills the storage space behind each check dam (silting); check dams must be progressively raised or additional downstream dams constructed as siltation proceeds; improperly designed check dams can fail and release a catastrophic flush of previously trapped sediment; gabion check dams require continuous maintenance of wire mesh integrity. (5) Small dams: silting of reservoir storage (a major problem in Nigeria; reservoirs in high-sediment-yield watersheds lose 50 to 80 percent of capacity over 50 years without conservation upstream); potential for catastrophic failure if spillway is undersized or dam is improperly constructed; vector-borne disease risk (malaria, bilharzia/schistosomiasis) in dam impoundments.

Fill in the blank: Terraces have high construction costs (N50,000 to N500,000 per hectare) and require annual _________ to remain effective; neglected terraces collapse and concentrate runoff, potentially causing worse erosion than would occur without any conservation structure.

4.4.2 Selection criteria for conservation practices

Selecting appropriate conservation practices for a specific site and context requires evaluating multiple criteria: (1) Biophysical suitability: rainfall amount and intensity (higher rainfall requires more robust measures); slope gradient (gentle slopes: agronomic measures sufficient; moderate slopes: contour bunds and terraces needed; steep slopes: bench terraces essential); soil type (sandy soils with high infiltration: mulching and cover crops primary; clay soils prone to crusting: contour bunds and mechanical loosening needed); erosion type and severity (rill and sheet: agronomic measures sufficient; gully: structural gully control required). (2) Economic viability: benefit-cost ratio (the conservation practice must be economically justified by the value of soil, yield, or infrastructure protected); initial and maintenance costs relative to farmer income; payback period (how long before the farmer recovers the conservation investment from improved yields or reduced input costs). (3) Farmer acceptability and adoptability: practices that require minimal changes in existing farming practices are adopted more readily; labour requirements (labour-intensive practices adopted less when farm labour is scarce or expensive); land availability (practices requiring significant unproductive land allocation may be rejected in land-scarce communities); cultural fit (traditional practices such as contour ridging and zai pits are more readily adopted than unfamiliar technologies).

(4) Technical requirements: complexity of design and construction (simple measures like mulching require no technical expertise; terrace and dam design require engineering knowledge); availability of construction materials (gabion dams require suitable stones; concrete dams require cement, aggregates, and water); equipment availability (mechanical terrace construction requires tractors and implements). (5) Institutional and policy support: availability of extension services to promote and advise on conservation measures; government incentive programmes (subsidies for terrace construction; input vouchers for conservation farmers); community land tenure security (farmers invest in structural conservation only when land tenure is secure enough to recover the investment over many seasons). (6) Complementarity and integration: individual conservation measures are most effective when combined in an integrated system that addresses erosion at multiple scales; agronomic measures reduce the erosion load arriving at structural measures; structural measures manage the runoff that agronomic measures cannot absorb; water harvesting structures store runoff that structural measures divert.

Fill in the blank: Conservation measures are most effective when combined in an ________ system that addresses erosion at multiple scales; agronomic measures reduce the erosion load arriving at structural measures, which manage the runoff that agronomic measures cannot absorb.

4.4.3 Integrated watershed management in Nigeria

Integrated watershed management (IWM) is a holistic approach to the planning and management of an entire catchment (watershed) as a single unit, combining conservation measures, land use planning, institutional arrangements, and community participation to achieve sustainable land and water resource management. IWM recognises that erosion and water quality problems in lowland areas (sedimentation, flooding, reduced stream flow) originate from land misuse in upland areas; addressing these problems requires coordinated action across the watershed, not just at individual farm or field level. Components of IWM: (1) Watershed assessment and prioritisation: mapping land use, soil types, erosion hotspots, and hydrological characteristics; identifying the most critical upland areas for conservation investment. (2) Integrated land use planning: zoning the watershed for appropriate land uses (permanent forest protection on steep headwaters; agroforestry and terracing on intermediate slopes; intensive cropping on gentle lower slopes; water harvesting structures in valley bottoms); integrating these land uses into a coherent plan that reduces erosion across the entire watershed.

(3) Multi-measure integration: combining agronomic measures (cover crops, mulching, agroforestry) with mechanical measures (terraces, bunds, gully control) and water harvesting structures in a coherent design that addresses erosion at every scale from the raindrop to the watershed outlet. (4) Community participation and institutional development: engaging local communities in watershed planning, construction, and maintenance; establishing community-based water user associations and conservation groups; building local technical capacity for operation and maintenance of conservation structures. (5) Monitoring and evaluation: establishing a monitoring system (runoff plots, stream gauges, sediment measurement stations) to track the effectiveness of conservation measures and adapt the management plan accordingly. IWM programmes in Nigeria: the Integrated Water Resources Management (IWRM) programme; the World Bank-funded Fadama Development Projects (Fadama I, II, III); the Gully Erosion and Land Degradation Control Programme (GELDAP) for south-eastern Nigeria; the Great Green Wall Nigeria programme for the semi-arid north; the National Special Programme for Food Security (NSPFS); River Basin Development Authorities (RBDAs) watershed management programmes.

Fill in the blank: Integrated ________ management (IWM) is a holistic approach that plans and manages an entire catchment as a single unit, combining conservation measures, land use planning, and community participation to achieve sustainable land and water resource management.

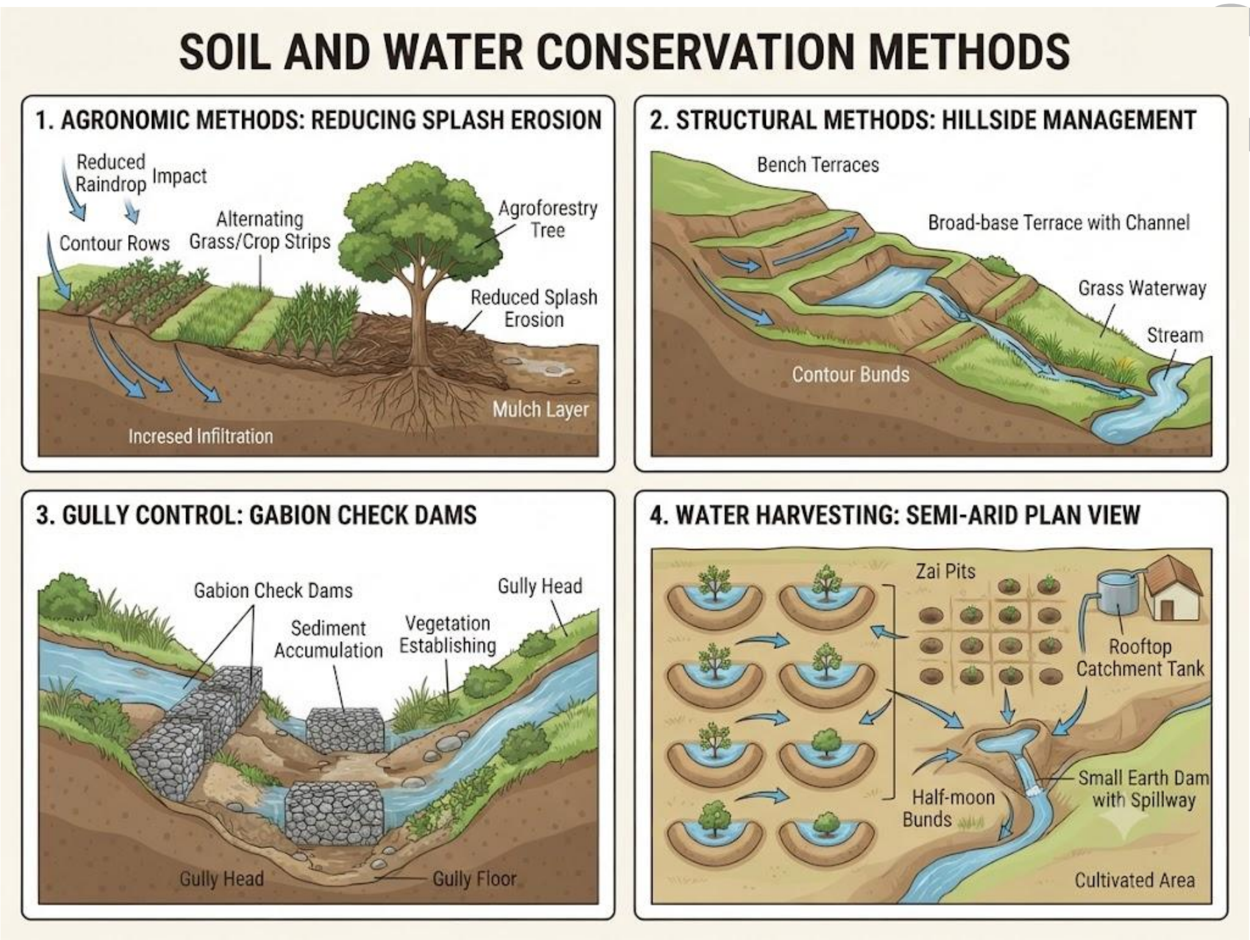

Figure 4.1: Soil and water conservation measures: agronomic (top left), structural/terrace (top right), gully control (bottom left), and water harvesting (bottom right)

Pilot questions 4.4

1. State three limitations of structural conservation measures (terraces, check dams, small dams).
2. State five criteria used to select appropriate conservation practices for a Nigerian farming community.
3. Explain why integrated watershed management is more effective than individual farm-level conservation measures.
4. Name four IWM programmes or projects implemented in Nigeria and state the primary focus of each.

5. Explain why labour requirements and competing demand for crop residues are barriers to conservation adoption by Nigerian smallholders.

Series Summary

This Series examined **agronomic, vegetative, and structural soil and water conservation measures used to reduce erosion, conserve moisture, and restore degraded land**. Agronomic practices include cover cropping, mulching, contour farming, strip cropping, agroforestry, and windbreaks. Cover crops protect the soil and may add nitrogen, while adequate mulch can greatly reduce splash erosion and soil loss. Contour farming and strip cropping slow runoff on gentle slopes, agroforestry improves soil structure and root binding, and windbreaks reduce wind speed and erosion, especially in northern Nigeria. Structural measures include bench and broad-base terraces, contour bunds, grass waterways, diversion channels, check dams, and gully plugs. Terrace spacing may be determined using $\mathbf{VI = 0.3 + 0.03S}$ and $\mathbf{HI = VI \times 100/S}$, while check-dam spacing is estimated as $\mathbf{L = H/\tan\alpha}$.

The Series also covered **water harvesting, small reservoirs, measure selection, and integrated watershed management**. Water-harvesting methods include zai pits, negarim microcatchments, half-moon bunds, stone lines, and wadi diversion, while storage options include dug ponds, earth dams, sand dams, and rooftop collection systems. Monthly rooftop water collection is estimated as $\mathbf{P \times A \times Rc / 1{,}000}$. Earth dams require a suitable valley site, firm foundation, stable embankment slopes, adequate freeboard, and a properly designed spillway. Each conservation measure has limitations relating to cost, labour, maintenance, land loss, siltation, pests, or failure risk. Selection should therefore consider rainfall, slope, soil, erosion type, economic viability, farmer acceptance, technical capacity, institutional support, and compatibility with other measures. Integrated watershed management combines land-use planning, community participation, several complementary practices, and continuous monitoring at catchment scale.

Glossary of Terms

- **Bench terrace:** a terrace that cuts and fills the slope to create nearly level planting platforms separated by steep risers; appropriate for slopes of 10 to 30 percent; very effective but high construction cost.

- **Check dam:** a low barrier constructed across a gully channel to reduce flow velocity, trap sediment, and raise the gully bed level; types: earth, brush/timber, gabion, concrete; spaced head-to-toe (L = H/tan(alpha)).
- **Contour bund:** a low earthen embankment (0.3 to 0.6 m high) constructed along the contour to intercept surface runoff and promote infiltration; lower cost than terraces; increases millet and sorghum yields by 30 to 60 percent in semi-arid areas.
- **Contour farming:** performing all field operations along lines of equal elevation (contours) rather than up and down the slope; crop rows act as barriers to downslope water movement; reduces erosion by 40 to 60 percent; P factor 0.25 to 0.60.
- **Cover crop:** a fast-growing plant established to protect the soil surface from erosion between main crop seasons; examples in Nigeria: Mucuna pruriens (velvet bean), Stylosanthes species, Lablab purpureus; leguminous cover crops also fix nitrogen.
- **Diversion channel:** an open channel excavated across a slope above a vulnerable area to intercept upslope runoff and divert it to a stable outlet before it can erode the land below; must be sized using the Rational Method.
- **Grass waterway:** a natural or excavated channel permanently vegetated with grass (Napier, Guinea, vetiver) that carries concentrated runoff safely down the slope from terrace and diversion outlets to a stable receiving point.
- **Integrated watershed management (IWM):** holistic management of an entire catchment as a single unit, combining conservation measures, land use planning, institutional arrangements, and community participation to achieve sustainable soil and water resource management.
- **Mulching:** application of organic material (rice straw, maize stover, guinea grass) to the soil surface; at 70 to 80 percent cover reduces splash erosion by 90 to 95 percent and soil loss by 80 to 95 percent; recommended rate 3 to 6 t/ha.
- **Sand dam:** a low weir across a seasonal sandy riverbed that retains sand in which water is stored in pore spaces; accessed from hand-dug wells in the sand; low evaporation losses; appropriate for basement complex terrain of northern Nigeria.
- **Strip cropping:** alternating strips of protective crops (grass, legume) and productive row crops across the slope; protective strips trap sediment and reduce runoff velocity; effective on slopes of 3 to 8 percent; vetiver grass strips are particularly durable.

- **Vertical interval (VI):** the elevation difference between adjacent terraces or contour bunds; estimated as VI = 0.3 + 0.03S (S = slope percent); determines spacing of structural measures on a slope.
- **Water harvesting:** collection and concentration of runoff from a catchment area to a smaller target area for productive use; techniques: zai pits, negarim microcatchments, half-moon bunds, stone lines, small earth dams; critical for crop production in semi-arid northern Nigeria.
- **Windbreak (shelterbelt):** rows of trees and shrubs planted perpendicular to the prevailing wind to reduce wind speed by 50 to 80 percent on the leeward side for a distance of 10 to 15 times the windbreak height; protects crops and soil from wind erosion in semi-arid northern Nigeria.
- **Zai pit (tassa):** a planting pit of 20 to 30 cm diameter and 10 to 20 cm depth dug in degraded soil before the rains; traps runoff and concentrates water and nutrients around plant roots; combined with compost, enables millet yields of 500 to 1,000 kg/ha on severely degraded soils.

Concept Check Questions [Series 4]

Objective Questions

1. At 70 to 80 percent soil surface cover, organic ________ reduces splash erosion by 90 to 95 percent and soil loss by 80 to 95 percent compared with bare soil. (Linked to SLO 4.1)
2. Contour farming reduces erosion by 40 to 60 percent and has a USLE P factor of 0.25 to 0.60; it is most effective on slopes of 2 to ________ percent. (Linked to SLO 4.1)
3. The vertical interval between terraces is estimated by the formula VI = 0.3 + 0.03 x S, where S is the ________ gradient in percent. (Linked to SLO 4.2)
4. Check dams are spaced so that the sediment accumulated behind each dam reaches the ________ of the next downstream dam (head-to-toe arrangement); spacing L = H / tan(alpha). (Linked to SLO 4.2)
5. The ________ pit (tassa) is a traditional water harvesting technique in which planting pits of 20 to 30 cm diameter trap runoff and concentrate it around plant roots; combined with compost, millet yields of 500 to 1,000 kg/ha are achieved on degraded Sahel soils. (Linked to SLO 4.3)

Short-Answer Questions

1. Name three cover crops used in Nigeria and state one conservation benefit of each. (Linked to SLO 4.1)
2. Distinguish between bench terraces and broad-base terraces and state the slope range suitable for each. (Linked to SLO 4.2)
3. Calculate VI and HI for terraces on a 15 percent slope using VI = 0.3 + 0.03S. (Linked to SLO 4.2)
4. Describe three water harvesting techniques used in semi-arid northern Nigeria. (Linked to SLO 4.3)
5. State five criteria used to select appropriate conservation practices for a Nigerian farming community. (Linked to SLO 4.4)

Long-Answer Questions

1. Describe the agronomic and vegetative conservation measures (cover crops, mulching, contour farming, strip cropping, agroforestry, windbreaks) and explain how each reduces erosion in Nigerian conditions. (Linked to SLO 4.1)
2. Describe the mechanical conservation measures (terraces, contour bunds, grass waterways, diversion channels, check dams) and the water harvesting techniques used in Nigeria. Explain

the limitations of conservation methods and describe the integrated watershed management approach. (Linked to SLOs 4.2, 4.3, 4.4)

Answers to Concept Check Questions [Series 4]

Objective Questions

1. Mulch.
2. 8.
3. Slope.
4. Crest.
5. Zai.

Short-Answer Questions

1. Mucuna pruriens (velvet bean: forms dense canopy; reduces raindrop impact; fixes 80 to 200 kg N/ha). Stylosanthes species (savanna zone cover; reduces wind and water erosion; improves soil organic matter). Calopogonium mucunoides (calopo: creeping legume; used under oil palm and rubber; protects soil between tree rows).
2. Bench terraces: slope cut and filled to create nearly level platforms; steep risers; for slopes 10 to 30 percent; very effective but high cost. Broad-base terraces: low wide ridges with channel; traversable by machinery; for slopes 1 to 8 percent; less effective but less expensive.
3. VI = 0.3 + 0.03 x 15 = 0.75 m. HI = VI x 100/S = 0.75 x 100/15 = 5.0 m.
4. Zai pits/tassa (planting pits 20 to 30 cm diameter; 10 to 20 cm deep; trap runoff around plant roots; combined with compost enable crops on degraded soils). Half-moon bunds (semi-circular earthen bunds on contour; capture runoff to centre where sorghum or millet are planted; flat to gentle slopes below 2 percent). Stone lines (stones placed on contour at 15 to 30 m intervals; slow runoff; promote infiltration; trap sediment; used on basement complex soils of northern Nigeria).
5. Biophysical suitability (rainfall intensity, slope, soil type, erosion type and severity). Economic viability (benefit-cost ratio; cost relative to farmer income; payback period). Farmer acceptability (labour requirement; land availability; cultural fit). Technical requirements (complexity of design; material availability). Institutional support (extension services; government incentives; land tenure security).

Long-Answer Questions

1. Cover crops: Mucuna pruriens, Stylosanthes, Calopogonium; protect soil surface; fix nitrogen; improve organic matter. Mulching: 3 to 6 t/ha of organic material; 70 to 80 percent cover reduces splash erosion by 90 to 95 percent; soil loss reduced by 80 to 95 percent; crop residue burning destroys this benefit. Contour farming: operations along contour lines; P factor 0.25 to 0.60; reduces erosion 40 to 60 percent; effective on 2 to 8 percent slopes; requires A-frame level for layout. Strip cropping: alternating protective (grass, legume) and productive (maize, cassava) strips on contour; traps sediment; effective 3 to 8 percent slopes; vetiver grass particularly durable (deep roots, wide climate tolerance). Agroforestry: tree canopy reduces raindrop impact; leaf litter adds organic matter; leguminous trees (Gliricidia, Leucaena, Faidherbia) fix nitrogen; deep roots improve infiltration; boundary trees reduce wind erosion. Windbreaks: perpendicular to prevailing wind; reduce wind speed 50 to 80 percent for 10 to 15 x windbreak height leeward; species: Eucalyptus, Casuarina, neem; critical in semi-arid north (harmattan November to March; 5 to 10 m/s; RH 10 to 30 percent); Great Green Wall Nigeria programme.
2. Mechanical measures: Bench terraces (level platforms; steep risers; 10 to 30 percent slopes; Jos and Mambilla Plateaus; high cost); broad-base terraces (1 to 8 percent; traversable; savanna zone); VI = 0.3 + 0.03S; HI = VI x 100/S. Contour bunds (0.3 to 0.6 m high; lower cost than terraces; 30 to 60 percent yield increase in Sahel). Grass waterways (vegetated channels; Napier, vetiver, Guinea grass; safe conveyance of concentrated runoff). Diversion channels (intercept upslope runoff; Rational Method sizing; stable outlet required). Check dams (across gully; earth, brush/timber, gabion, concrete; head-to-toe spacing L = H/tan(alpha); gabion most used in Nigeria). Water harvesting: zai pits (20 to 30 cm diameter; 10 to 20 cm deep; trap runoff + compost; 500 to 1,000 kg/ha millet on degraded soils). Negarim microcatchments (diamond bunds for tree planting). Half-moon bunds (semi-circular; sorghum/millet; flat land). Stone lines (contour; basement complex soils). Earth dams (embankment across valley; spillway critical; 100-year design storm; 2 to 6 m height; silting problem). Rainwater: P x A x Rc / 1,000. Limitations: mulch (labour; biomass shortage; pest); terraces (cost; maintenance; area reduction); check dams (siltation; failure); dams (silting; disease). Selection criteria: biophysical suitability; economic viability (BCR); farmer acceptability; technical requirements; institutional support; complementarity. IWM: catchment-scale; watershed assessment; integrated land use planning; multi-measure integration; community participation; monitoring; Nigerian programmes: Fadama I/II/III, GELDAP, Great Green Wall, IWRM.

Answers to Pilot Questions [Series 4]

Part 4.1

1. Mucuna pruriens (velvet bean: dense canopy; reduces raindrop impact; fixes 80 to 200 kg N/ha). Stylosanthes species (savanna zone cover; improves soil organic matter; reduces wind and water erosion). Centrosema pubescens (centro; creeping legume; used in humid zones under plantation crops). Lablab purpureus (lablab; dual-purpose; food and soil cover; rapidly spreads to protect bare soil).
2. Mulch absorbs raindrop energy before it can detach soil particles (reducing splash erosion); mulch also slows overland flow, increasing infiltration time and reducing runoff volume and velocity. Recommended rate: 3 to 6 tonnes per hectare to achieve 70 to 80 percent ground cover; at this cover, splash erosion is reduced by 90 to 95 percent and total soil loss by 80 to 95 percent.
3. Contour farming means performing all field operations (tillage, planting, weeding, harvesting) along lines of equal elevation (contour lines) perpendicular to the slope. Tillage furrows and crop rows act as small ridges that obstruct downslope water flow, slowing runoff, increasing infiltration time, and reducing erosive velocity. USLE P factor: 0.25 to 0.60 depending on slope (lower value = more effective on gentle slopes).
4. Strip cropping alternates strips of protective close-growing crops (grass, legumes) with productive row crops (maize, cassava) across the slope; protective strips slow runoff and trap eroded sediment. Vetiver grass (Chrysopogon zizanioides) strips are particularly effective because vetiver has very deep, strong roots that anchor the strip firmly; it is drought-tolerant; it survives trampling and temporary inundation; and it tolerates a very wide range of soil types and climates found in Nigeria.
5. Canopy cover (tree canopies intercept rainfall and reduce raindrop impact on the soil surface). Organic matter addition (leaf litter and pruning biomass increase soil organic matter, improving aggregate stability, infiltration, and water-holding capacity). Nitrogen fixation (leguminous trees such as Gliricidia, Leucaena, and Faidherbia albida fix atmospheric nitrogen and supply it to associated crops through leaf litter and prunings, reducing fertiliser requirements while improving soil fertility).

Part 4.2

1. Bench terraces: slope is cut and filled to create nearly level platforms (benches) with steep risers; suitable for 10 to 30 percent slopes; very effective but high construction cost; requires significant earthmoving; reduces usable area slightly at risers; used on Jos and Mambilla

Plateaus and for terraced vegetable gardens. Broad-base terraces: low wide ridges (0.3 to 0.5 m high, 1.5 to 3 m wide base) with a channel; slope between terraces remains unchanged; traversable by machinery; suitable for 1 to 8 percent slopes; lower cost; most common in the Nigerian savanna zone for row crops.

2. VI = 0.3 + 0.03 x 12 = 0.3 + 0.36 = 0.66 m. HI = VI x 100/S = 0.66 x 100/12 = 5.5 m.
3. Contour bunds are low earthen embankments (0.3 to 0.6 m high; 1 to 2 m base width) constructed along the contour at regular intervals. They are preferred in the Nigerian savanna because: construction is much simpler and cheaper than bench terraces (can be done with hand tools or a tractor-drawn ridger); they are effective on the gentle to moderate slopes (2 to 15 percent) typical of the savanna zone; they significantly increase crop yields (30 to 60 percent improvement in millet and sorghum yields in semi-arid areas) through improved water retention.
4. A grass waterway is a natural or excavated channel permanently vegetated with dense grass that carries concentrated runoff (from terrace outlets, diversion channel outlets, or low drainage areas) safely down the slope to a stable receiving point. Design requirements: channel cross-section must be large enough to convey the design peak discharge without overtopping; grass cover must be dense enough (species: Napier, vetiver, Guinea grass) to resist scour at the design flow velocity; side slopes gentle enough to allow machinery to cross.
5. Earth dams (compacted soil; cheapest; simple to construct from locally available material; disadvantage: vulnerable to overflow erosion at the spillway if improperly designed; must have vegetated spillway). Brush and timber dams (locally available materials; cheap and quick to construct; disadvantage: biodegradable; short lifespan; suitable only for small gullies). Gabion dams (wire mesh baskets filled with stones; durable and flexible; can absorb channel movement without cracking; most widely used in Nigerian gully rehabilitation projects; disadvantage: wire mesh requires maintenance against corrosion and mechanical damage).

Part 4.3

1. Water harvesting is the collection and concentration of runoff from a larger catchment area to a smaller target area where it is used productively for crops, trees, or livestock. It is important in semi-arid northern Nigeria because annual rainfall (400 to 800 mm) is insufficient for reliable cropping without supplementary water; water harvesting concentrates the limited rainfall arriving during the brief rainy season (3 to 5 months) to support crop production on otherwise unproductive degraded land.

2. A zai pit (tassa) is a planting pit of 20 to 30 cm diameter and 10 to 20 cm depth dug in hard, degraded soil before the rains. It is effective because: the pit creates a micro-depression that traps and concentrates surface runoff (water from the surrounding crust is funnelled into the pit where crops are planted); when combined with compost or manure placed in the pit, it provides a localised improved soil environment for germination and root growth; this combination of concentrated water and improved nutrition allows millet and sorghum to establish and produce on soils too degraded for conventional cropping.
3. Dug ponds (excavated 1.5 to 3 m deep in clay soils; filled by runoff or shallow groundwater; used for vegetable irrigation and fish culture in fadama areas). Earth dams (compacted embankment across a valley or gully; store 5,000 to 100,000 m3; dry-season irrigation and livestock watering; spillway critical). Sand dams (low weir across sandy streambed; water stored in sand pore spaces; accessed from hand-dug wells; low evaporation; appropriate for basement complex stream beds in northern Nigeria).
4. Key design principles: site at a valley constriction with firm impermeable foundation; design embankment with 3:1 to 4:1 upstream and 2:1 to 3:1 downstream slopes; provide 0.5 to 1.0 m freeboard above spillway crest; include filter and toe drain for seepage control; size spillway for the 100-year design flood. The spillway is critical because if the design flood overtops the embankment, erosion of the unprotected earthfill rapidly destroys the dam; inadequate spillway capacity is the most common cause of small dam failure in Nigeria.
5. Monthly collection = P x A x Rc / 1,000 = 100 x 60 x 0.85 / 1,000 = 5,100 / 1,000 = 5.1 m3 (5,100 litres).

Part 4.4

6. High construction cost (bench terraces: N50,000 to N500,000 per hectare; beyond reach of most smallholders). Maintenance requirement (terraces collapse if not maintained annually; check dams silt up progressively; neglected structures may cause more damage than having none). Risk of catastrophic failure (check dams can release trapped sediment in a destructive flush if improperly designed or maintained; earth dams fail if the spillway is undersized).
7. Biophysical suitability (rainfall, slope, soil type, and erosion type and severity must match the method’s design parameters). Economic viability (benefit-cost ratio must justify the investment; payback period must be within the farmer’s planning horizon). Farmer acceptability (labour requirement and competing demands for crop residues limit adoption; cultural fit improves uptake). Technical requirements (complexity of design and material availability must match local

capacity). Institutional support (extension services, government incentives, and secure land tenure are necessary for farmer investment in structural conservation).

8. Individual farm-level conservation only controls erosion on that farm; runoff and sediment from neighbouring and upslope farms can negate on-farm efforts. IWM coordinates conservation actions across the entire watershed: upland vegetation protects headwaters; conservation structures on middle slopes manage runoff; water harvesting in valley bottoms stores runoff for productive use; this integrated approach prevents erosion at source, manages it in transit, and uses water productively at the outlet, providing benefits that individual farm conservation cannot achieve alone.
9. Fadama Development Projects I/II/III (World Bank-funded; develops smallholder irrigation and farm productivity in fadama (floodplain) areas of all zones). GELDAP (Gully Erosion and Land Degradation Control Programme; specifically addresses severe gully erosion in south-eastern Nigeria: Anambra, Enugu, Imo, Cross River). Great Green Wall Nigeria (part of African Union initiative; tree planting, windbreaks, and agroforestry in semi-arid northern states; aims to restore 11.4 million ha). Fadama Development Projects (address watershed management through community-level water resource development and conservation).
10. Labour: collecting, transporting, and spreading 3 to 6 t/ha of mulch requires 10 to 20 person-days per hectare; smallholders with limited household labour and no hired labour capacity cannot afford this additional workload during the planting season when labour is already scarce. Competing demand for crop residues: in many parts of Nigeria, crop residues (maize stover, sorghum stalks, groundnut haulms) are essential livestock feed during the dry season; farmers who need their residues for cattle or goats cannot afford to leave them on the soil as mulch; this directly conflicts with the conservation benefit of residue retention.

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Figures, Plates, Tables, and Boxes

- Figure 4.1: Soil and water conservation measures: agronomic, structural/terrace, gully control, and water harvesting. Attribution: AI generated. Suggested OER search string: “soil water conservation methods terraces contour bunds check dams water harvesting Nigeria diagram OER⇓.

Series 5: Groundwater and Fluid Flow Dynamics

- **Part 5.1: Characteristics of Groundwater**
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    - Sub Part 5.1.2: Groundwater movement: Darcy's Law
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Introduction

Water in motion, whether moving slowly through the pores of an aquifer, flowing steadily through an irrigation pipe network, or rushing over a spillway, obeys the fundamental laws of fluid mechanics: conservation of mass, energy, and momentum. These laws, applied to the specific geometry and boundary conditions of soil pores, pipe conduits, and open channel cross-sections, yield the equations that engineers and hydrologists use to design water supply and drainage systems, size conservation structures, and assess the forces acting on hydraulic structures.

This Series covers the characteristics of groundwater and the Darcy's Law that governs its movement; the soil water zones, capillarity, and unsaturated flow principles that connect the surface water and groundwater domains; the hydraulics of pipe flow and open channel flow, including the key design equations (Darcy-Weisbach, Hazen-Williams, and Manning's); and the principles of hydrostatic pressure and the forces acting on plane and curved submerged surfaces. These topics complete the student's quantitative toolkit for water and land conservation engineering.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 5.1** describe the types of aquifers and their occurrence in Nigeria, apply Darcy's Law to calculate groundwater flow velocity and discharge, and explain groundwater quality and contamination (Linked to Part 5.1),
- **SLO 5.2** describe the soil water zones and the water table, explain capillarity and soil water potential, and describe the principles of unsaturated flow (Linked to Part 5.2),
- **SLO 5.3** distinguish between laminar and turbulent flow and apply the Reynolds number criterion, apply the Darcy-Weisbach and Hazen-Williams equations to pipe flow problems, and apply Manning's equation to open channel flow design (Linked to Part 5.3), and

- **SLO 5.4** calculate hydrostatic pressure at any depth, determine the total force on a plane submerged surface and its point of application, and explain the concept of buoyancy and its application in hydraulic engineering (Linked to Part 5.4).

5.1 Characteristics of Groundwater

5.1.1 Occurrence and types of aquifers

Groundwater occupies the pore spaces, fractures, and voids below the water table in the saturated zone of the earth's crust. It constitutes approximately 30 percent of the world's freshwater resources (excluding polar ice) and is the primary dry-season water source for rural communities and irrigation across Nigeria. An aquifer is a geological formation sufficiently permeable to yield economically significant quantities of water to wells and springs. Types: (1) Unconfined aquifer (water table aquifer): the uppermost aquifer; the water table is free to rise and fall with recharge and discharge; water in a penetrating well rises only to the water table level; most shallow boreholes in Nigeria access unconfined aquifers in the regolith overlying the basement complex. (2) Confined aquifer (artesian aquifer): overlain by a low-permeability confining layer (clay or shale) that isolates the aquifer from atmospheric pressure; water in a penetrating well rises above the top of the aquifer (artesian head); if the artesian head exceeds the land surface, the well flows without pumping.

(3) Perched aquifer: a localised saturation zone above the main water table, separated from it by an unsaturated zone; occurs above a clay lens or hardpan; seasonal and limited in extent; common in the basement complex regolith of central and northern Nigeria. (4) Fractured rock aquifer: water stored and transmitted in fractures, joints, and faults in hard rock (granite, gneiss); primary aquifer type in the basement complex; yield depends on fracture density and connectivity; highly variable between boreholes; electromagnetic surveys locate productive fracture zones before drilling. (5) Sedimentary aquifer: water in the pore spaces of sedimentary rocks (sandstone, limestone); more uniform porosity and permeability; primary aquifer type in the Anambra Basin (south-east), Chad Basin (north-east), and coastal sedimentary basins; generally higher and more reliable borehole yields.

Fill in the blank: An ________ aquifer is overlain by an impermeable confining layer; water is under pressure; wells penetrating it rise above the top of the aquifer and may flow at the surface if the artesian head exceeds land surface elevation.

5.1.2 Groundwater movement: Darcy's Law

Groundwater moves through porous media under a hydraulic gradient. Darcy's Law (1856):

$Q = K \times A \times (dh/dl)$

where Q = discharge (m^3/s); K = hydraulic conductivity (m/s); A = cross-sectional area perpendicular to flow (m^2); dh/dl = hydraulic gradient (dimensionless). Specific discharge (Darcy velocity):

$q = Q/A = K \times (dh/dl)$

Pore velocity:

$v_p = q / n_e$ where n_e = effective porosity (typically 0.15 to 0.35)

Darcy's Law is valid for laminar flow ($Re < 1$ to 10 for porous media). Key hydraulic parameters:

K values (m/s): gravel 10^{-2} to 10^{-1}; coarse sand 10^{-4} to 10^{-2}; fine sand 10^{-6} to 10^{-4}; silt 10^{-8} to 10^{-6}; clay 10^{-11} to 10^{-8} m/s

Transmissivity:

$T = K \times b$ (m^2/s);   where b = saturated aquifer thickness (m)

Storage coefficient S: for unconfined aquifers S ≈ specific yield (0.10 to 0.30); for confined aquifers S = 10

S (confined) = 10^{-5} to 10^{-3}

Worked example: $K = 5 \times 10^{-4}$ m/s; width = 100 m; saturated thickness = 20 m; hydraulic gradient = 0.005:

$Q = 5 \times 10^{-4} \times (100 \times 20) \times 0.005 = 5 \times 10^{-4} \times 2{,}000 \times 0.005 = 0.005\ m^3/s = 5\ L/s$

Fill in the blank: Darcy's Law: Q = K × A × (dh/dl); K = hydraulic ________ (m/s); pore velocity v_p; valid only for laminar flow (Re < 1 to 10).

5.1.3 Groundwater quality and contamination

Natural groundwater chemistry reflects geochemical reactions between water and aquifer minerals. Major dissolved ions:

Ca^{2+} Mg^{2+} Na^+ K^+ HCO_3^- $SO_4 2^-$ Cl^-

Total dissolved solids (TDS): WHO guideline below 500 mg/L acceptable; above 1,500 mg/L unacceptable. Groundwater contamination in Nigeria: (1) Point source: septic tanks and pit latrines (most widespread source; coliform bacteria and

NO_3^- (nitrate) contamination of shallow wells; major public health risk in peri-urban and rural communities); industrial effluents (petroleum refinery wastewater in the Niger Delta; tannery effluents in Kano). (2) Diffuse: nitrate (NO_3^-) from excessive fertiliser or animal manure leaching. (3) Geological: naturally occurring high fluoride (F^-) from fluorite-bearing basement complex rocks in Ogun, Ondo, Kwara, Niger, and Kano states; above 1.5 mg/L causes dental fluorosis; above 4 mg/L causes skeletal fluorosis; high iron (Fe^{2+} from pyrite weathering; above 0.3 mg/L causes staining and taste problems.

Fill in the blank: The most widespread groundwater contamination in Nigerian rural areas is from ________ tanks and pit latrines; they introduce coliform bacteria and NO_3^- (nitrate) into the shallow unconfined aquifer used for drinking water.

Pilot questions 5.1

1. Define an aquifer and distinguish between confined and unconfined aquifers.
2. State Darcy's Law and define each term in the equation.

3. Calculate Q if $K = 2 \times 10^{-4}$ m/s, $A = 500\ m^2$, and hydraulic gradient = 0.008.
4. Name three sources of groundwater contamination in Nigeria and the primary health risk of each.
5. Explain why borehole yields are more variable in basement complex aquifers than in sedimentary aquifers.

5.2 Principles of Infiltration and Percolation

5.2.1 Soil water zones and the water table

The subsurface is divided into two major zones: (1) Unsaturated zone (vadose zone): extends from the soil surface to the water table; pore spaces are partly filled with water and partly with air; three sub-zones: soil water zone (root zone; water content varies with rainfall and ET; plants extract water here); intermediate vadose zone (stable water content; percolation pathway between root zone and capillary fringe after rainfall); capillary fringe (nearly saturated zone immediately above the water table; thickness from centimetres in coarse sand to over 1 m in fine silt). (2) Saturated zone (phreatic zone): all pore spaces filled with water under positive pressure; the water table is its upper boundary; it rises during recharge and falls during dry periods. The water table is the surface at which water pressure equals atmospheric pressure. Piezometric head:

$$\mathbf{h = z + P / (\rho\, g)}$$

where z = elevation above datum (m); P = water pressure (Pa); $\rho = 1{,}000\ kg/m^3$; $g = 9.81\ m/s^2$. At the water table P = 0, so h = z. In a confined aquifer the piezometric surface lies above the top of the aquifer (artesian head).

Fill in the blank: The ________ table is the upper boundary of the saturated zone where water pressure equals atmospheric pressure; water in an unconfined well rises to the water table level; it rises during recharge and falls during dry periods.

5.2.2 Capillarity and soil water potential

Capillarity is the rise of water in narrow soil pores above a free water surface, driven by surface tension and adhesion to pore walls. Capillary rise height:

h_c **= 2T cosθ / (ρ g r)**

where T = surface tension (0.073 N/m at 20°C); $\theta \approx 0°$ for most soil minerals ($\cos\theta \approx 1$); ρ = 1,000 kg/m³; g = 9.81 m/s²; r = pore radius (m). Example for $r = 10^{-4}$ m:

$h_c = (2 \times 0.073 \times 1) / (1{,}000 \times 9.81 \times 10^{-4}) = 0.146 / 0.981 = 0.149$ m (≈15 cm)

Capillary rise supplements root zone water from the water table; in semi-arid areas it brings dissolved salts upward, contributing to soil salinisation. Soil water potential (matric potential ψ; suction): the energy status of soil water expressed as pressure (kPa); negative in unsaturated soil. Total water potential:

$\psi_{total} = \psi_m + \psi_g$ where $\psi_g = \rho g z$

Key reference points on the soil water retention (pF) curve:

Field capacity: $\psi_m \approx -10$ to -33 kPa (pF 2.0 to 2.5)

Permanent wilting point: $\psi_m \approx -1{,}500$ kPa (pF 4.2)

Water moves from high potential (wetter; less negative) to low potential (drier; more negative).

Fill in the blank: Capillary rise $h_c = 2T\cos\theta / (\rho g r)$; h_c ________ as pore radius r increases; fine-pored silt soils can have capillary rise exceeding 1 to 2 m above the water table.

5.2.3 Unsaturated flow and Richards' equation

Unsaturated flow is more complex than saturated Darcy flow because: (1) the hydraulic conductivity K is not constant but depends on volumetric water content θ; as soil dries, air replaces water in larger pores and K decreases by several orders of magnitude from its saturated value K_s; (2) the driving force includes both the gravitational gradient and the matric potential gradient. Richards' equation (1931):

$$\partial\theta/\partial t = \partial/\partial z\ [K(\theta) \times (\partial\psi/\partial z + 1)]$$

where θ = volumetric water content (m^3/m^3); $K(\theta)$ = unsaturated hydraulic conductivity (m/s); ψ = matric potential head (m; negative); z = vertical coordinate (positive upward); the +1 term represents the unit gravitational gradient. Richards' equation explains wetting front propagation after rainfall or irrigation. Field monitoring methods: tensiometers (measure ψ directly; 0 to −80 kPa; ceramic porous cup; widely used in Nigerian irrigated vegetable production); capacitance probes (measure θ through dielectric constant; automated continuous monitoring); gravimetric sampling (oven-drying at 105°C; accurate reference method; slow and destructive).

Fill in the blank: Richards' ________ describes unsaturated flow; $K(\theta)$ decreases by several orders of magnitude as the soil dries because air replaces water in the larger pores, making the water-filled pore network more tortuous and disconnected.

Pilot questions 5.2

1. Describe the three sub-zones of the vadose zone and state the agricultural significance of each.
2. Calculate the capillary rise height for $r = 5 \times 10^{-5}$ m ($T = 0.073$ N/m; $\rho = 1{,}000$ kg/m³; $g = 9.81$ m/s²; contact angle = 0°).
3. Explain soil water potential and state the matric potential values at field capacity and permanent wilting point.
4. State Richards' equation and explain why unsaturated hydraulic conductivity $K(\theta)$ is not constant.
5. Name three field methods of measuring soil water status and state one advantage of each.

5.3 Fluid Flow in Pipes and Open Channels

5.3.1 Types of fluid flow: laminar and turbulent

Fluid flow is classified as laminar or turbulent based on the pattern of particle motion and the relative importance of viscous and inertial forces. Laminar flow: particles move in parallel streamlines; parabolic velocity profile in a pipe; Re < 2,000; dominant in groundwater. Turbulent flow: chaotic mixing pattern; flat velocity profile; Re > 4,000; dominant in irrigation pipes, drainage channels, and rivers. Reynolds number:

$$\mathbf{Re = \rho V D / \mu = V D / \nu}$$

where ρ = 1,000 kg/m³ (water); V = mean velocity (m/s); D = pipe diameter (m); μ = dynamic viscosity = 0.001 Pa·s at 20°C; ν = kinematic viscosity = μ/ρ =

$\nu = 1.0 \times 10^{-6}$ m²/s at 20°C

Critical values: Re < 2,000 = laminar; Re 2,000–4,000 = transitional; Re > 4,000 = turbulent

Example: D = 0.15 m; V = 2.0 m/s:

$Re = 2.0 \times 0.15 / (1.0 \times 10^{-6}) = 300{,}000 \Rightarrow$ turbulent

Fill in the blank: Re = V D / ν; Re < 2,000 = ________ flow; Re > 4,000 = turbulent; most irrigation pipes operate at Re >> 4,000.

5.3.2 Flow in pipes: Darcy-Weisbach and Hazen-Williams equations

Darcy-Weisbach equation (fundamental pipe friction formula):

$h_f = f \times (L/D) \times V^2 / \mathbf{2g}$

where h^f = friction head loss (m); f = Darcy-Weisbach friction factor (from Moody chart; dimensionless); L = pipe length (m); D = internal pipe diameter (m); V = mean velocity (m/s); g = 9.81 m/s². Worked example: L = 500 m; D = 0.1 m; Q = 0.01 m³/s; f = 0.02:

$V = 4Q / (\pi D^2) = 4 \times 0.01 / (\pi \times 0.01) = 1.27$ m/s

$h_f = 0.02 \times (500 / 0.1) \times (1.27^2 / (2 \times 9.81)) = 0.02 \times 5{,}000 \times 0.082 = 8.2$ m

Hazen-Williams equation (empirical; no Moody chart needed):

$V = 0.8492 \times C_{HW} \times R_h^{0.63} \times S^{0.54}$

where C_h^W = Hazen-Williams roughness coefficient (new PVC = 150; smooth concrete = 130 to 140; average cast iron = 100; old corroded iron = 60 to 80); R_h = hydraulic radius (= D/4 for a full circular pipe); S = hydraulic slope = h^f/L. Discharge form:

$$Q = 0.2785 \times C_{HW} \times D^{2.63} \times S^{0.54}$$

Minor losses at fittings:

$$h_m = K_m \times V^2 / 2g$$

K_m values: 90° elbow ≈0.5 to 1.5; gate valve (fully open) ≈0.1; sudden expansion up to 1.0.

Fill in the blank: The Hazen-Williams coefficient C_{HW} = _________ for new PVC pipe; C_{HW} = 100 for average cast iron; lower C_{HW} indicates a rougher pipe with greater friction losses.

5.3.3 Flow in open channels: Manning's equation

Open channel flow occurs where the flow surface is exposed to atmospheric pressure: rivers, irrigation canals, drainage channels, grass waterways. Manning's equation (1891) for uniform flow:

$$V = (1/n) \times R_h^{2/3} \times S^{1/2}$$

$$Q = A \times V = (A/n) \times R_h^{2/3} \times S^{1/2}$$

where V = mean flow velocity (m/s); n = Manning's roughness coefficient; R_h = A/P (m); S = channel bed slope (m/m); A = cross-sectional area (m²); P = wetted perimeter (m). Manning's n values: concrete-lined canal 0.012 to 0.014; earthen canal (clean) 0.022 to 0.026; grass-lined waterway 0.030 to 0.040; natural river (clean) 0.025 to 0.035. Trapezoidal channel geometry (bottom width b; side slope z:1; depth y):

$$A = (b + z\,y)\,y; \quad P = b + 2y\sqrt{(1 + z^2)}$$

$$R_h = A / P$$

Worked example: $b = 1.0$ m; $z = 1.5$; $y = 0.6$ m; $S = 0.001$; $n = 0.025$:

$A = (1.0 + 1.5 \times 0.6) \times 0.6 = 1.9 \times 0.6 = 1.14\ m^2$

$P = 1.0 + 2 \times 0.6 \times \sqrt{(1 + 1.5^2)} = 1.0 + 1.2 \times 1.803 = 3.164$ m

$R_h = 1.14 / 3.164 = 0.360$ m

$V = (1/0.025) \times 0.360^{2/3} \times 0.001^{1/2} = 40 \times 0.503 \times 0.0316 = 0.636$ m/s

$Q = 1.14 \times 0.636 = 0.725\ m^3/s$

Fill in the blank: Manning's n = 0.012 to 0.014 for concrete-lined canals; n = 0.025 for clean earthen ________ canals; n = 0.030 to 0.040 for grass waterways; higher n = rougher boundary = lower velocity for the same R_h and S.

Pilot questions 5.3

6. Define laminar and turbulent flow and state the Reynolds number criterion for each.
7. Water flows through a 200 mm pipe at 1.5 m/s. Calculate Re ($\nu = 1.0 \times 10^{-6}\ m^2/s$) and state the flow regime.
8. State the Darcy-Weisbach equation, define all terms, and calculate h^f for L = 300 m; D = 0.1 m; V = 1.0 m/s; f = 0.025.
9. State Manning's equation and calculate Q for a rectangular concrete channel: b = 0.8 m; y = 0.5 m; S = 0.002; n = 0.013.
10. Define hydraulic radius R_h and state its value for a full circular pipe of diameter D.

5.4 Forces on Submerged Surfaces

5.4.1 Hydrostatic pressure and pressure distribution

Hydrostatic pressure is the pressure exerted by a static fluid on any surface in contact with it. For an incompressible fluid under gravity:

$$\mathbf{P = \rho\ g\ h}$$

where P = hydrostatic gauge pressure (Pa); ρ = 1,000 kg/m³; g = 9.81 m/s²; h = depth below the free water surface (m). At h = 1 m:

$P = 1{,}000 \times 9.81 \times 1 = 9{,}810 \text{ Pa} \approx 10 \text{ kPa}$

Hydrostatic pressure acts perpendicular to any surface it contacts (Pascal's law: pressure in a static fluid acts equally in all directions at any point). Pressure distribution over a vertical submerged surface varies linearly with depth (triangular distribution for a surface with one edge at the free surface). For a vertical rectangular surface of width b and height H with its top edge at the free surface:

$F = \rho g b H^2 / 2$;   point of application at H/3 from base

Pascal's principle: pressure applied to a confined static fluid is transmitted undiminished throughout the fluid; the basis of hydraulic jacks and presses used in agricultural machinery and construction equipment.

Fill in the blank: Hydrostatic pressure P = ρ g h increases ________ with depth h; at 1 m depth P = 9,810 Pa; it acts perpendicular to any surface; pressure distribution over a vertical surface is triangular (zero at water surface; ρgH at greatest depth).

5.4.2 Forces on plane submerged surfaces

Total hydrostatic force on any plane submerged surface:

$\mathbf{F = \rho g \bar{h} A}$

where $\bar{h}$ = depth of the centroid of the surface below the free surface (m); A = total area (m²). This formula applies regardless of surface orientation. Centre of pressure (point of application of F):

$h_{cp} = \bar{h} + I_G / (A \times \bar{h})$

where I^G = second moment of area about the centroidal axis (m⁴):

Rectangle (b × H): $I_G = b\,H^3 / 12$

Circle (diameter D): $I_G = \pi\,D^4 / 64$

The centre of pressure always lies below the centroid (except for horizontal surfaces). Worked example: rectangular floodgate b = 2 m; H = 3 m; top edge 1 m below the free surface:

$\bar{h} = 1 + 3/2 = 2.5$ m; $A = 2 \times 3 = 6\ m^2$

$F = 1{,}000 \times 9.81 \times 2.5 \times 6 = 147{,}150$ N = 147.15 kN

$I_G = 2 \times 3^3 / 12 = 4.5\ m^4$

$h_{cp} = 2.5 + 4.5 / (6 \times 2.5) = 2.5 + 0.3 = 2.8$ m below the free surface

Fill in the blank: Total hydrostatic force: $F = \rho\,g\,\bar{h}\,A$; $\bar{h}$ is the depth to the ________ of the surface; centre of pressure $h_{cp} = \bar{h} + I_G / (A \times \bar{h})$; h_{cp} always lies deeper than the centroid.

5.4.3 Forces on curved submerged surfaces and buoyancy

For curved surfaces, pressure acts perpendicular to the surface in different directions at each point, so forces are resolved into horizontal and vertical components. Horizontal component:

$F_H = \rho\,g\,\bar{h}_{proj} \times A_{proj}$

where $A_{pro}{}^{J}$ is the projected vertical area of the curved surface and $\bar{h}_{pro}{}^{J}$ is the centroid depth of that projected area; the line of action is at the centre of pressure of the projected area. Vertical component:

$F_V = \rho\,g \times$ Volume of fluid (real or imaginary) above the curved surface

Fƀ acts upward for a concave-upward surface (buoyancy-like) and downward for a convex-upward surface. Buoyancy (Archimedes' principle): any object fully or partially submerged experiences an upward buoyant force equal to the weight of fluid displaced:

$F_B = \rho_{fluid} \times g \times V_{displaced}$

An object floats when $F^B \geq$ its weight; sinks when its weight exceeds F^B. Worked example: empty concrete pipe; outer diameter 600 mm; wall thickness 75 mm; length 1 m; concrete density 2,400 kg/m³:

Outer volume = $\pi \times 0.6^2 / 4 \times 1 = 0.2827\ m^3$

Inner volume = $\pi \times 0.45^2 / 4 \times 1 = 0.1590\ m^3$

Volume of concrete = $0.2827 - 0.1590 = 0.1237\ m^3$

Weight = $0.1237 \times 2{,}400 \times 9.81 = 2{,}910$ N; $F_B = 1{,}000 \times 9.81 \times 0.2827 = 2{,}773$ N

Weight (2,910 N) > F^B (2,773 N) $\Rightarrow$ the pipe sinks.

Fill in the blank: Archimedes' principle: $F_B = \rho_{fluid} \times g \times V_{displaced}$; an object floats if $F_B \geq$ its weight; the vertical component of force on a curved surface equals the ________ of the real or imaginary fluid column above it.

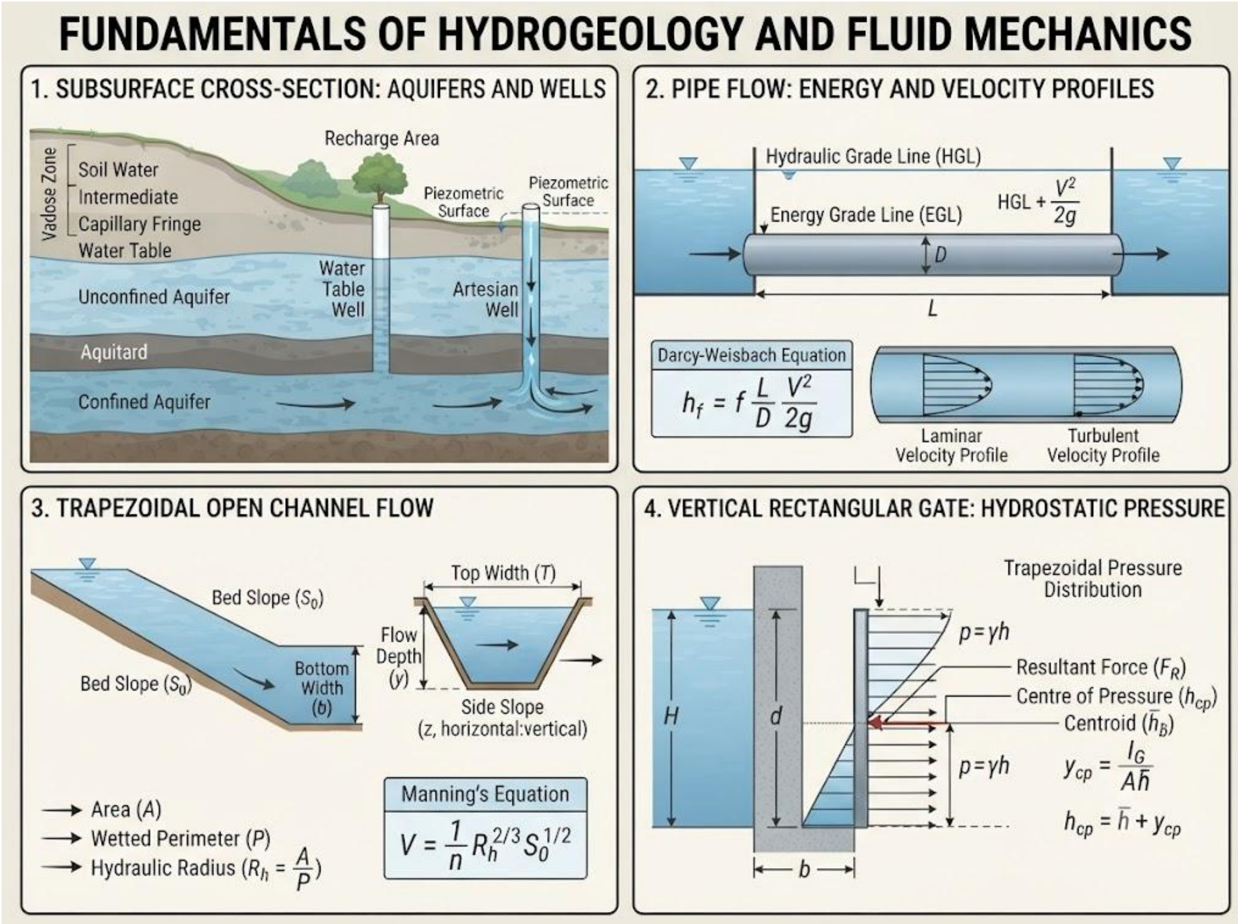

Figure 5.1: Aquifer types and soil water zones (top left); pipe flow and velocity profiles (top right); open channel Manning's parameters (bottom left); hydrostatic pressure on a submerged gate (bottom right)

Pilot questions 5.4

1. State Pascal's principle and explain how hydrostatic pressure varies with depth.
2. A vertical rectangular gate (b = 1.5 m; H = 2 m) has its top edge 0.5 m below the free surface. Calculate F and hc_p.
3. Explain the difference between centroid and centre of pressure for a submerged surface.
4. Explain how the horizontal and vertical force components on a curved submerged surface are calculated.
5. State Archimedes' principle and determine whether a hollow steel cylinder (weight 5,000 N; external volume 0.8 m³) will float or sink.

Series Summary

This Series examined **groundwater systems, soil water movement, and the basic principles of fluid mechanics used in soil and water engineering**. Aquifers may be unconfined, confined, perched, fractured-rock, or sedimentary, with groundwater flow described by **Darcy's Law: $Q = K \times A \times (dh/dl)$**. Hydraulic conductivity varies greatly with soil and rock type, while transmissivity is **$T = K \times b$**. Groundwater quality is assessed through dissolved ions, total dissolved solids, and possible contamination from latrines, industrial waste, or naturally occurring substances such as fluoride and iron. Soil water occurs in the vadose, capillary, and saturated zones, and moves from higher to lower water potential. Field capacity is about −33 kPa, permanent wilting point about −1,500 kPa, and unsaturated flow is described by the Richards equation. Tensiometers and capacitance probes are used to monitor soil moisture.

The Series also covered **pipe flow, open-channel flow, hydrostatics, and buoyancy**. Flow may be laminar or turbulent depending on the Reynolds number, with **$Re < 2{,}000$** indicating laminar flow and **$Re > 4{,}000$** turbulent flow. Pipe head loss may be estimated using the Darcy–Weisbach or Hazen–Williams equations, while minor losses are calculated as **$h_m = K_m V^2/2g$**. Open-channel velocity is commonly estimated using Manning's equation, **$V = (1/n)R_h^{2/3}S^{1/2}$**, with discharge given by **$Q = AV$**. Hydrostatic pressure is **$P = \rho g h$**, and the total force on a submerged surface is **$F = \rho g \bar{h} A$**. For curved surfaces, horizontal force equals the force on the vertical projection, while vertical force equals the weight of fluid above the surface. Buoyancy is determined by **$F^B = \rho g V$**, and an object floats or sinks depending on whether the buoyant force is greater or less than its weight.

Glossary of Terms

- **Aquifer:** a geological formation sufficiently permeable to yield economically significant quantities of water to wells and springs; types: unconfined, confined (artesian), perched, fractured rock, sedimentary.
- **Artesian (confined) aquifer:** an aquifer overlain by an impermeable confining layer; water is under pressure; well water rises above the aquifer top; may flow freely at the surface.

- **Buoyancy (Archimedes' principle):** the upward force on a submerged object equal to the weight of fluid displaced; $F^B = \rho\ g\ V^{DIsml}$; object floats if $F^B \geq$ weight.
- **Capillary fringe:** the nearly saturated zone immediately above the water table where pores are filled by capillary forces; thickness from centimetres in coarse sand to over 1 m in fine silt.
- **Capillary rise:** rise of water in a narrow pore above the free water surface; $hc = 2T \cos\theta/(\rho gr)$; decreases as pore radius increases.
- **Centre of pressure (hc_p):** the point at which the resultant hydrostatic force acts on a submerged surface; lies deeper than the centroid by $I^G/(A\underline{\bar{h}})$.
- **Darcy's Law:** $Q = K \times A \times (dh/dl)$; describes laminar groundwater flow through porous media; K = hydraulic conductivity (m/s); dh/dl = hydraulic gradient.
- **Darcy-Weisbach equation:** $h^f = f(L/D)(V^2/2g)$; calculates friction head loss in pipe flow; f = Moody friction factor from the Moody chart.
- **Hazen-Williams equation:** $V = 0.8492\ C_h^W\ R_h\text{^}0.63\ S\text{^}0.54$; empirical pipe flow formula; C_h^W = 150 for new PVC; 100 for cast iron; no Moody chart needed.
- **Hydraulic conductivity (K):** constant of proportionality in Darcy's Law (m/s); gravel 10^{-2} to 10^{-1}; clay 10^{-11} to 10^{-8} m/s.
- **Hydrostatic pressure:** $P = \rho gh$; pressure exerted by a static fluid at depth h; increases linearly with depth; acts perpendicular to any surface.
- **Laminar flow:** flow in which particles move in parallel streamlines; $Re < 2{,}000$; parabolic velocity profile; dominant in groundwater.
- **Manning's equation:** $V = (1/n)\ R_h\text{^}(2/3)\ S\text{^}(1/2)$; $Q = AV$; standard equation for uniform open channel flow; n = roughness coefficient.
- **Matric potential (ψ_m):** energy status of soil water (kPa); negative in unsaturated soil; field capacity ≈ −33 kPa; permanent wilting point ≈ −1,500 kPa.
- **Reynolds number (Re):** $Re = VD/\nu$; ratio of inertial to viscous forces; $Re < 2{,}000$ = laminar; $Re > 4{,}000$ = turbulent.
- **Richards' equation:** $\partial\theta/\partial t = \partial/\partial z[K(\theta)(\partial\psi/\partial z + 1)]$; governing equation for unsaturated flow; $K(\theta)$ decreases with decreasing water content.
- **Transmissivity (T):** $T = K \times b$ (m^2/s); product of hydraulic conductivity and saturated aquifer thickness; capacity of the full aquifer to transmit water horizontally.
- **Turbulent flow:** flow in which particles move chaotically with lateral mixing; $Re > 4{,}000$; flat velocity profile; dominant in irrigation pipes and open channels.

- **Unconfined aquifer:** aquifer with a free water table as its upper boundary; water in a penetrating well rises to the water table level; most shallow Nigerian boreholes.
- **Water table:** upper boundary of the saturated zone where P = atmospheric; level to which water rises in an unconfined aquifer well.

Concept Check Questions [Series 5]

Objective Questions

1. A confined ________ aquifer is overlain by a clay or shale confining layer; water under pressure rises above the aquifer top in a penetrating well and may flow at the surface without pumping. (Linked to SLO 5.1)
2. Darcy's Law: $Q = K \times A \times (dh/dl)$; K is hydraulic ________ (m/s); the law is valid for laminar flow with $Re < 1$ to 10. (Linked to SLO 5.1)
3. Capillary rise $hc = 2T \cos\theta/(\rho g r)$; hc ________ as pore radius r increases; fine-pored silt soils can have capillary rise exceeding 1 to 2 m. (Linked to SLO 5.2)
4. $Re = VD/\nu$; $Re < 2{,}000$ = ________ flow; $Re > 4{,}000$ = turbulent; most irrigation pipes carry turbulent flow. (Linked to SLO 5.3)
5. Manning's $n = 0.012$ to 0.014 for ________ canals; $n = 0.025$ for earthen canals; $n = 0.030$ to 0.040 for grass waterways. (Linked to SLO 5.3)

Short-Answer Questions

1. Distinguish between unconfined and confined aquifers with one Nigerian example of each. (Linked to SLO 5.1)
2. State Darcy's Law and calculate Q for $K = 3 \times 10^{-4}$ m/s, $A = 200\ m^2$, hydraulic gradient = 0.006. (Linked to SLO 5.1)
3. State the matric potential values at field capacity and permanent wilting point and explain what each represents. (Linked to SLO 5.2)
4. State the Darcy-Weisbach and Manning's equations, defining all terms in each. (Linked to SLO 5.3)
5. A vertical rectangular gate ($b = 1$ m; $H = 2$ m) has its top edge at the water surface. Calculate F and hc_p. (Linked to SLO 5.4)

Long-Answer Questions

1. Describe aquifer types in Nigeria, apply Darcy's Law with a worked example, describe groundwater contamination, explain soil water zones, capillarity and soil water potential, and Richards' equation. (Linked to SLOs 5.1, 5.2)
2. Explain laminar and turbulent flow (Re criterion). Apply Darcy-Weisbach and Manning's equations with worked examples. Explain hydrostatic pressure, calculate forces on a plane submerged surface with a worked example, and state Archimedes' principle. (Linked to SLOs 5.3, 5.4)

Answers to Concept Check Questions [Series 5]

Objective Questions

1. Artesian.
2. Conductivity.
3. Decreases.
4. Laminar.
5. Concrete.

Short-Answer Questions

1. Unconfined: water table is free to rise and fall; well water rises to water table level; Nigerian example: shallow regolith borehole in Plateau State basement complex. Confined (artesian): overlain by clay confining layer; artesian head above aquifer top; Nigerian example: deep sandstone aquifer in the Anambra Basin.
2. $Q = K \times A \times (dh/dl) = 3 \times 10^{-4} \times 200 \times 0.006 = 0.036\ m^3/s = 36\ L/s$.
3. Field capacity: $\psi_m \approx -10$ to -33 kPa; the water content retained after free drainage ceases; upper limit of plant-available water. Permanent wilting point: $\psi_m \approx -1{,}500$ kPa; the water content at which plants wilt permanently; lower limit of plant-available water.
4. Darcy-Weisbach: $h^f = f(L/D)(V^2/2g)$; h^f = friction head loss (m); f = friction factor; L = pipe length (m); D = pipe diameter (m); V = mean velocity (m/s); g = 9.81 m/s². Manning's: $V = (1/n)R_h\text{^}(2/3)\ S\text{^}(1/2)$; Q = AV; n = roughness coefficient; R_h = A/P (m); S = bed slope (m/m).
5. $\bar{h} = H/2 = 1.0$ m (top edge at water surface). $A = 1 \times 2 = 2\ m^2$. $F = 1{,}000 \times 9.81 \times 1.0 \times 2 = 19{,}620\ N = 19.62\ kN$. $I^G = 1 \times 2^3/12 = 0.667\ m^4$. $hc_p = 1.0 + 0.667/(2 \times 1.0) = 1.333$ m below the free surface.

Long-Answer Questions

1. Aquifer types: unconfined (free water table; Nigerian basement complex regolith); confined artesian (clay confining; Anambra Basin, Chad Basin sandstones); perched (above impermeable lens; seasonal); fractured rock (basement complex; variable; EM survey needed); sedimentary (uniform porosity; higher yields). Darcy's Law: $Q = K \times A \times (dh/dl)$; K values: gravel 10^{-2} to 10^{-1} m/s; clay 10^{-11} to 10^{-8} m/s; worked example: $K = 5 \times 10^{-4}$; A = 2,000 m²; gradient = 0.005; Q = 0.005 m³/s. Contamination: septic tanks/latrines (coliform and NO_3^-; most widespread); industrial effluents; geological F^- (fluorosis), Fe^{2+} (staining). Soil water zones: soil water zone (root zone; variable); intermediate vadose (percolation path); capillary fringe (nearly saturated above water table). Saturated zone: positive pressure;

water table = upper boundary. Capillary rise: $hc = 2T\cos\theta/(\rho gr)$; silt 1 to 2 m; supplements root zone; causes salinisation. Soil water potential: ψ_m (negative); FC ≈ −33 kPa; PWP ≈ −1,500 kPa. Richards': $\partial\theta/\partial t = \partial/\partial z[K(\theta)(\partial\psi/\partial z + 1)]$; $K(\theta)$ decreases with drying.

2. Laminar vs turbulent: $Re = VD/\nu$; $Re < 2{,}000$ = laminar; $Re > 4{,}000$ = turbulent; example: D = 0.15 m; V = 2.0 m/s; Re = 300,000; turbulent. Darcy-Weisbach: $h^f = f(L/D)(V^2/2g)$; example: L = 500 m; D = 0.1 m; f = 0.02; V = 1.27 m/s; h^f = 8.2 m. Hazen-Williams: $V = 0.8492\ C_h^W\ R_h$^0.63 S^0.54; C_h^W: PVC 150; cast iron 100. Manning's: $V = (1/n)\ R_h$^(2/3) S^(1/2); Q = AV; example: b = 1.0 m; z = 1.5; y = 0.6 m; n = 0.025; S = 0.001; Q = 0.725 m³/s. Hydrostatic pressure: $P = \rho gh$; linear; perpendicular. Force: $F = \rho g\bar{\underline{h}}A$; $hc_p = \bar{\underline{h}} + I^G/(A\bar{\underline{h}})$; example: F = 147.15 kN; hc_p = 2.8 m. Buoyancy: $F^B = \rho\ g\ V^{DIsml}$; pipe: weight 2,910 N > F^B 2,773 N; sinks.

Answers to Pilot Questions [Series 5]

Part 5.1

1. An aquifer is a geological formation sufficiently permeable to yield economically significant quantities of water to wells and springs. Unconfined: water table is the upper boundary; free to rise and fall; well water rises to water table level. Confined (artesian): overlain by an impermeable clay or shale layer; water under pressure; well water rises above the aquifer top; may flow freely at the surface.
2. Q = K × A × (dh/dl); K = hydraulic conductivity (m/s); A = cross-sectional area perpendicular to flow (m^2); dh/dl = hydraulic gradient (change in hydraulic head per unit length; dimensionless).
3. $Q = 2 \times 10^{-4} \times 500 \times 0.008 = 0.08\ m^3/s = 80$ L/s.
4. Septic tanks and pit latrines (coliform bacteria and NO_3^- in shallow wells; most widespread in rural Nigeria). Industrial effluents such as petroleum wastewater in the Niger Delta (hydrocarbons and heavy metals). Geological fluoride F^- from basement complex rocks (above 1.5 mg/L causes dental fluorosis; above 4 mg/L causes skeletal fluorosis).
5. Basement complex aquifers store water in fractures and joints whose density and connectivity vary greatly over short distances, making yields highly variable. Sedimentary aquifers have uniform intergranular porosity throughout the formation, giving more predictable and generally higher yields.

Part 5.2

1. Soil water zone (root zone; water content varies with rainfall and ET; plants extract water here). Intermediate vadose zone (stable water content; percolation pathway between root zone and capillary fringe). Capillary fringe (nearly saturated above water table; supplements root zone water; thickness from centimetres in sand to over 1 m in silt).
2. $hc = 2T \cos\theta/(\rho g r) = (2 \times 0.073 \times 1)/(1{,}000 \times 9.81 \times 5 \times 10^{-5}) = 0.146/0.4905 = 0.298$ m (≈30 cm).
3. Soil water potential (ψ_m) is the energy status of soil water (kPa); negative because water is held under suction in unsaturated soil. Field capacity: $\psi_m \approx -10$ to -33 kPa (upper limit of plant-available water). Permanent wilting point: $\psi_m \approx -1{,}500$ kPa (lower limit; plants wilt permanently).
4. $\partial\theta/\partial t = \partial/\partial z[K(\theta)(\partial\psi/\partial z + 1)]$. K(θ) is not constant because as soil dries, air replaces water in larger pores; the remaining water-filled pore network becomes more tortuous and disconnected, reducing K by several orders of magnitude from K_s.

5. Tensiometers (measure ψ_m directly; 0 to −80 kPa; simple and robust; widely used in Nigerian irrigated vegetable production). Capacitance probes (measure volumetric water content θ via dielectric constant; automated continuous monitoring). Gravimetric sampling (oven-drying at 105°C; accurate reference method; slow and destructive).

Part 5.3

1. Laminar: Re < 2,000; parallel streamlines; parabolic velocity profile; viscous forces dominate; dominant in groundwater. Turbulent: Re > 4,000; chaotic mixing; flat velocity profile; inertial forces dominate; dominant in irrigation pipes and open channels.
2. $Re = VD/\nu = 1.5 \times 0.2 / (1.0 \times 10^{-6}) = 300{,}000$; flow is turbulent (Re >> 4,000).
3. $h^f = f(L/D)(V^2/2g)$; f = friction factor; L = pipe length; D = pipe diameter; V = mean velocity; $g = 9.81\ m/s^2$. $h^f = 0.025 \times (300/0.1) \times (1.0^2/(2 \times 9.81)) = 0.025 \times 3{,}000 \times 0.051 = 3.83$ m.
4. $V = (1/n) R_h$^(2/3) S^(1/2); Q = AV. $A = 0.8 \times 0.5 = 0.4\ m^2$; $P = 0.8 + 2 \times 0.5 = 1.8$ m; $R_h = 0.4/1.8 = 0.222$ m. $V = (1/0.013) \times 0.222$^(2/3) × 0.002^(1/2) = 76.92 × 0.369 × 0.0447 = 1.27 m/s. $Q = 0.4 \times 1.27 = 0.508\ m^3/s$.
5. $R_h = A/P$ (cross-sectional flow area divided by wetted perimeter); accounts for channel shape. For a full circular pipe: $A = \pi D^2/4$; $P = \pi D$; $R_h = D/4$.

Part 5.4

Pascal's principle: pressure in a confined static fluid is transmitted undiminished in all directions. Hydrostatic pressure: $P = \rho g h$; increases linearly with depth; at h = 1 m, P = 9,810 Pa; acts perpendicular to any surface.

$\bar{h} = 0.5 + 2/2 = 1.5$ m. $A = 1.5 \times 2 = 3.0\ m^2$. $F = 1{,}000 \times 9.81 \times 1.5 \times 3.0 = 44{,}145$ N = 44.15 kN. $I^G = 1.5 \times 2^3/12 = 1.0\ m^4$. $hc_p = 1.5 + 1.0/(3.0 \times 1.5) = 1.5 + 0.222 = 1.722$ m below the free surface.

The centroid is the geometric centre of the surface (depends only on shape). The centre of pressure is where the resultant hydrostatic force acts; it lies deeper than the centroid by $I^G/(A\bar{h})$ because pressure increases with depth, giving the lower part of the surface more force.

F^H: equals the force on the projected vertical area of the curved surface; $F^H = \rho g \bar{h}_{pro}{}^J \times A_{pro}{}^J$; applied at the centre of pressure of the projected area. F^b: equals the weight of the real or imaginary fluid column above the curved surface to the free surface level; acts upward for concave-upward; downward for convex-upward.

Archimedes': $F^B = \rho \times g \times V^{DIsml} = 1{,}000 \times 9.81 \times 0.8 = 7{,}848$ N. Weight = 5,000 N. Since F^B (7,848 N) > weight (5,000 N), the hollow steel cylinder will float.

References and Attributions [Series 5]

Textual References (Books and External Sources)

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Figures, Plates, Tables, and Boxes

- Figure 5.1: Aquifer types, pipe flow, Manning's channel, and hydrostatic forces. Attribution: AI generated. Suggested OER search string: "aquifer types Manning equation hydrostatic pressure submerged gate pipe flow diagram OER".