Hornbill Classes

AGRICULTURAL ENGINEERING

TOOL KIT SERIES

UPSC

INDIAN FOREST SERVICE

2026 - 27

Linkage of Concepts with PYQs + Infused with Infographics & Maps

Paper - 1

Section - B

Quick Revision

MPPSC STATE FOREST SERVICE 2023



Shashank Jain
Comprehensive Forestry Course + CIGP



Jyoti Thakur
Comprehensive Forestry Course + CIGP



Shivam Gautam
Comprehensive Interview Guidance Programme



Nitin Patel
Comprehensive Forestry Course + CIGP



Ravi Kumar
Comprehensive Interview Guidance Programme + Test Series



Ankur Gupta
Comprehensive Forestry Course



Deependra Lodhi
Comprehensive Interview Guidance Programme



Kapil Chauhan
Comprehensive Forestry Course



Alok Kumar Jhariya
Comprehensive Forestry Course + CIGP



Tarun Chouhan
Comprehensive Interview Guidance Programme + Test Series



Raghvendra Thakur
Comprehensive Forestry Course + Test S. + CIGP

11 Out of 12 Total Selections in
Assistant Conservator of Forest (ACF) 2023

108 Out of 126 Total Selections in
Range Forest Officer (RFO) 2023



Arvind Ahirwar
Comprehensive Interview Guidance Programme + Test Series



Pushpendra Singh Ahirwar
Comprehensive Forestry Course + CIGP



Narendra Gunare
Comprehensive Interview Guidance Programme + Test Series



Jitendra Kumar Verma
Comprehensive Forestry Course + CIGP



Jaishrish Barethiya
Comprehensive Forestry Course + CIGP



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Comprehensive Forestry Course + CIGP



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Test Series



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Comprehensive Interview Guidance Programme



Golu Goyal
Comprehensive Interview Guidance Programme + Test Series



Pawan Raje
Comprehensive Interview Guidance Programme + Test Series

AGRICULTURE ENGINEERING

MODULE – 2

EDITION : 2026

+917223970423 **Hornbillclasses.com**

Gole ka mandir, Morar, Gwalior (MP) 474005

SYLLABUS

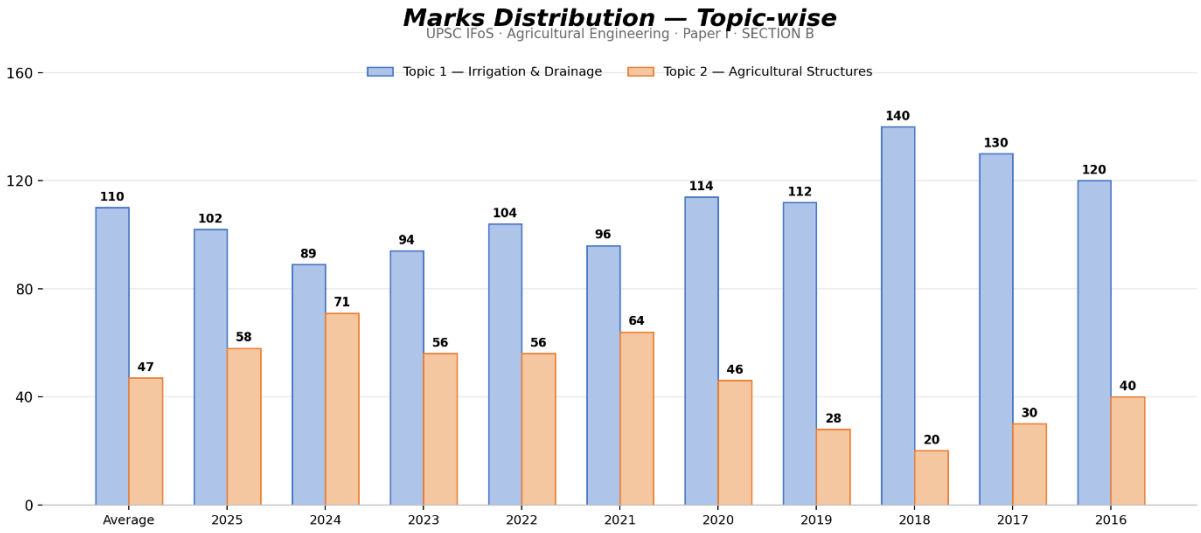
Indian Forest Service (IFoS) [Paper 1 | Section B]	***Irrigation and Drainage*** **:** Sources of water for irrigation. Planning and design of minor irrigation projects. Techniques of measuring soil moisture - laboratory and *in situ,* Soil-water plant relationships. Water requirement of crops. Planning conjunctive use of surface and ground water. Measurement of irrigation water, measuring devices - orifices, weirs and flumes. Methods of irrigation - surface, sprinkler and drip, fertigation. Irrigation efficiencies and their estimation. Design and construction of canals, field channels, underground pipelines, headgates, diversion boxes and structures for road crossing. Occurrence of ground water, hydraulics of wells, types of wells (tube wells and open wells) and their construction. Well development and testing. Pumps-types, selection and installation. Rehabilitation of sick and failed wells. Drainage causes of water logging and salt problem. Methods of drainage- drainage of irrigated and unirrigated lands, design of surface, sub-surface and vertical drainage systems. Improvement and utilization of poor-quality water. Reclamation of saline and alkali soils. Economics of irrigation and drainage systems. Use of waste water for irrigation - standards of waste water for sustained irrigation, feasibility and economics. ***Agricultural Structures :*** Site selection, design and construction of farmstead - farm house, cattle shed, dairy bam, poultry shed, hog housing, machinery and implement shed, storage structures for food grains, feed and forage. Design and construction of fences and farm roads. Structures for plant environment – green houses, poly houses and shade houses. Common building materials used in construction - timber, brick, stone, tiles, concrete etc and their properties. Water supply, drainage and sanitation system

Module - 2



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INDIAN FOREST SERVICE (IFoS) PYQs | 2016 – 2025

Soil-Water Relation

2025	• Discuss the important factors affecting planning and design of minor irrigation projects. [P1/5(a) | 8M] • Discuss the critical differences between crop water requirement and irrigation water requirement. [P1/5(c) | 8M] • Write short notes on the following : (i) Warabandi system of water allocation (ii) Conjunctive use of surface and groundwater (iii) Soil moisture characteristic curve (iv) Fertigation equipment (v) Reference evapotranspiration. [P1/6(c) | 10M]
2023	• Develop the relationship among delta, base period and duty of water. [P1/5(a) | 8M] • Distinguish between reservoir storage efficiency and water storage efficiency. [P1/5(b) | 8M] • An area of 25 hectares is to be irrigated by a pump working for 10 hours a day. The available moisture-holding capacity of the soil is 16 cm/m and the depth of root zone is 1 m. Irrigation is to be done when 50 percent of the available moisture in the root zone is depleted. The water application efficiency is 75 percent. The peak rate of moisture used by the crops is 5 mm/day (weighted average). The losses in water conveyance are negligible. Determine the irrigation period, net depth of water application, depth of water pumped per application, and the required capacity of irrigation system in hectare-cm/day and liters per second. [P1/6(a) | 20M]
2022	• Explain the different approaches for irrigation scheduling. [P1/6(a) | 15M] • How is conjunctive use of surface and groundwater vital in the integrated water resource development?. [P1/6(b) | 15M] • Distinguish between economic feasibility and financial feasibility of irrigation systems. [P1/7(c) | 10M] • (i) Describe the water conveyance efficiency, water application efficiency, water storage efficiency and water distribution efficiency. [10 M] (ii) A one-hectare farm needs to be irrigated with a depth of 100 mm, if the percolation losses are 30%. What will be the amount of water required for irrigation? [5 M]. [P1/7(a) | 15M]
2021	• Discuss the working procedure and application of pressure plate apparatus for determining Soil Matric Potential and Water Content with the help of a neat sketch. [P1/6(a) | 15M] • Enlist and discuss the principal methods for direct measurement of evapotranspiration. [P1/6(b) | 15M]
2020	• A tank has a water spread area of 40 hectares with an average depth of 3 m of water. Calculate the area of paddy crop of 120 days duration that can be irrigated if the duty is expressed as : (i) 960 hectare per m^3/sec (ii) 110 hectare cm and (iii) 90 hectare/million m^3 of water. [P1/6(a) | 15M] • A stream of 130 liters/second was diverted from a canal and 100 liters/sec were

	delivered to the field. An area of 1·8 hectares was irrigated in 8 hours. The runoff loss in the field was 432 m^3. Available moisture holding capacity of the soil is 20 cm per meter depth of soil. Determine the water conveyance, water application and water storage efficiency. Irrigation was started at a moisture level of 50 percent of the available moisture. [P1/7(a·i) | 12M] • Differentiate between the following : (i) Saline-alkali soil and Non-saline alkali soil (ii) Saturation capacity and Field capacity (iii) Permanent wilting point and Ultimate wilting point (iv) Soil texture and Soil structure. [P1/7(b) | 10M]
2019	• For a particular soil, moisture at field capacity is 29% (w/w) and irrigation is to be applied at a moisture content of 19% (w/w). The apparent specific gravity is 1·30 and depth of the soil to be wetted is 1 m. Determine - (i) hectare-cm of water per hectare of land; (ii) time required to irrigate 10 hectares of land with a 0·10 m^3/sec stream, if the efficiency of irrigation application is 75%. [P1/5(d) | 8M] • Explain in detail the direct and indirect methods of soil moisture measurement/determination. [P1/6(a) | 10M] • Explain irrigation efficiency and also explain its different types along with formulas to compute them. [P1/6(c) | 10M] • The following data were obtained in determining the soil moisture content at successive depths in the root zone prior to applying irrigation water: The bulk density of the soil in the root zone was 1·50 gm/cc. The available moisture-holding capacity of the soil was 17·8 cm/m depth. Determine - (i) moisture content at different depths in the root zone; (ii) moisture content in the root zone at the time of irrigation; (iii) net depth of water to be applied to bring the moisture content to field capacity; (iv) gross irrigation requirement at an estimated field irrigation efficiency of 70%. [P1/7(c) | 10M]
2018	• What are the different sources of irrigation in India? List different factors influencing planning and development of minor irrigation projects. What are the positive and negative impacts of irrigation on the ecosystem and environment?. [P1/5(a) | 8M] • Discuss various factors influencing irrigation water requirement. How can you estimate total irrigation water requirement incorporating different components for a given field and crop?. [P1/5(c) | 8M] • The soil moisture at Field Capacity (FC) is 25% (W/W) and the moisture content at the time of irrigating is 15% (W/W). The apparent specific gravity is 1·52 and depth of soil to be wetted is 90 cm. How much water in ha-cm per hectare must be applied?. [P1/5(d) | 8M] • Explain the concept of conjunctive use of surface and groundwater in canal command areas for efficient water use. What are the advantages and limitations of conjunctive use?. [P1/6(a) | 10M] • List different soil water coefficients. Explain the methodology to estimate maximum available soil water using these coefficients. [P1/7(a) | 10M] • What is crop coefficient and how is it estimated using crop evapotranspiration and reference evapotranspiration? Explain briefly the factors influencing crop coefficient.

	[P1/7(c) | 10M] • Irrigation scheduling involves determining "when to irrigate" and "how much to irrigate". Explain the factors to be considered in developing irrigation schedule, with an example. [P1/7(d) | 10M] • What are the priorities given to environmental issues in irrigated commands? Considering a holistic view of irrigated agriculture and socio-economic constraints, explain the issues in brief. [P1/8(b) | 10M] • In an exercise to develop design and operations plan for surface irrigation in wheat crop, an infiltration test was carried out. The following data were obtained from the test : Plot the infiltration rate vs time and find out basic infiltration rate. [P1/8(c) | 10M]
2017	• Differentiate between the following : (i) Water requirement and Irrigation requirement (ii) Crop water use efficiency and Field water use efficiency (iii) Evaporation and Consumptive use (iv) Confined and Unconfined aquifers. [P1/5(a) | 8M] • Discuss the procedure to develop soil moisture characteristic curve and its critical points. [P1/5(b) | 8M] • Discuss Darcy's law of soil water flow with a definition sketch. In what flow conditions is it applicable?. [P1/5(c) | 8M] • A field soil sample prior to being disturbed has a volume of 82 cm^3. The sample weighed 125 grams. After drying at 105°C for 24 hours, the dry soil sample weighs 100 grams. What is the soil moisture content on weight basis and volume basis? What depth of water must be applied to the volumetric water content of the top 1 m of soil to 0·40? Assume the density of water as 1·00 gm/cm^3. [P1/5(e) | 8M]
2016	• Write short notes on the following irrigation efficiencies : (i) Water conveyance efficiency (ii) Water application efficiency (iii) Water storage efficiency (iv) Water distribution efficiency. [P1/5(b) | 10M] • Tomato with 60 cm effective root zone depth is grown in a soil with field capacity and permanent wilting point of 22% and 8% respectively. Irrigation is applied after 40% depletion of the available moisture. Apparent specific gravity of soil = 1·6. Calculate the depth of irrigation required. If a pump delivers 10 l/s discharge, how much time will it take for the irrigation of 2 ha? Assume no loss of water. [P1/6(c) | 20M]

Surface Sprinkler, Drip Irrigation Methods

2025	• (i) Discuss the different types of drip irrigation systems based on installation method, emitter discharge rate and wetted soil surface area. [7 M] (ii) A sprinkler irrigation system is to be installed in an area of 20 hectares. The crop to be irrigated is wheat with gross application depth of 20 cm. The irrigation interval is 10 days with 12 operating hours per day. Determine the sprinkler irrigation system flow capacity in litres per second. [8 M]. [P1/6(b) | 15M]
2024	• Describe the main hydraulic principles involved in designing of sprinkler irrigation system.

	[P1/7(b) | 10M]
2023	• What are the limitations in the adoptability of check basin method?. [P1/5(c) | 8M]
2022	• Enlist the steps involved in design of drip irrigation system. [P1/5(a) | 8M]
2021	• Discuss the basic details of border method of irrigation with a neat sketch. [P1/5(a) | 8M] • Discuss about adaptability and limitations of sprinkler irrigation. [P1/5(b) | 8M] • Differentiate between Sand Media filter and Screen filter (used in drip / micro-irrigation systems). [P1/7(a·ii) | 5M] • Estimate the time, in hours, required to give a 4 cm irrigation to a border strip 100 metres long and 6 metres wide with a discharge of 12 litres per second from a tube-well. Assume the water conveyance efficiency to be 72%. [P1/7(b) | 10M]
2020	• Discuss the important hydraulic phenomenon involved in border irrigation method. [P1/5(e) | 8M] • Discuss the different types of sprinkler irrigation systems based on portability. [P1/6(c) | 15M]
2019	• What are the steps involved in the design of sprinkler irrigation system? Provide the formula, wherever required. [P1/8(b) | 10M] • Explain different filtration systems used in drip irrigation. [P1/8(c) | 10M]
2018	• A field of wheat crop of size 200 × 100 m with water source located at the lower left corner in the field is to be irrigated using sprinkler irrigation system. The prevailing land slope is south to north. Draw a layout of sprinkler mainline and lateral lines with brief explanation. [P1/6(c) | 10M] • What are the different methods for fertilizer injection (fertigation)? The location of fertigation systems is very important in drip irrigation systems. Discuss in brief. [P1/8(d) | 10M]
2017	• Draw a neat sketch showing the basic components of a drip irrigation system. Also describe the functions of each of them in brief. [P1/6(a) | 10M] • Discuss sprinkler irrigation uniformity and its measures and describe the procedure to estimate it in the field. [P1/6(c) | 10M] • Given : Climate Hot humid; Soil Fine sandy loam; Wind speed 7 km/h; Crop Wheat; Effective root zone depth 1·5 m; Water available in top soil (1·0 m) 167 mm/m; Water available in top soil (0·5 m) 183 mm/m; Irrigation application efficiency 80%; ECw 2·0 dS/m; ECe (for 10% yield reduction) 3·4 dS/m; Area 10 ha; Peak rate of water removal 7·6 mm/day; Management allowed deficit (MAD) 50%; Operating hours per day 12 hours. Find the Net and Gross depth of irrigation, Leaching requirement, Irrigation interval and Sprinkler system capacity. [P1/6(d) | 10M]
2016	• Discuss the major components of a drip irrigation system with necessary drawing. **[P1/6(b) | 10M]**

Water Measurement and conveyance

2025	• List the different methods of water flow measurement on an agricultural farm for an underground/overground pipeline and for open channel network. Also, briefly discuss their principles of measurement. [P1/6(a) | 15M]
2024	• Enlist the structures to be used in measuring irrigation water and also write their suitability. [P1/5(a) | 8M]
2023	• How do air vents and end plugs protect the underground pipeline from damage?. [P1/7(a) | 10M]
2021	• Differentiate between Cipoletti weir and Rectangular weir. [P1/7(a·i) | 5M]
2020	• Discuss the specialised structures used with underground pipeline system to control the water and protect the pipeline from damage. [P1/5(a) | 8M] • Discuss the coordinate method of measuring discharge from pipes discharging horizontally. [P1/5(b) | 8M]
2019	• Briefly explain various irrigation water measurement devices that can be installed in an irrigation channel. Use appropriate diagrams, wherever necessary. [P1/8(a) | 10M]
2018	• What is Parshall flume? Explain the working procedure of Parshall flume. How is it different from cut-throat flume?. [P1/5(e) | 8M]
2016	• Define a weir. Draw the neat sketch of a rectangular weir placed in a channel and label it. [P1/5(a) | 10M] • Write in brief on the following : (i) Venturi meter (ii) Parshall flume (iii) Cipolletti weir (iv) Tensiometer. [P1/6(a) | 10M]

Canal Design and fluid mechanics

2024	• Compute most efficient width for an open ditch/channel with flow depth of 2·40 metres in silt loam soil. What are the velocity and channel capacity, if channel gradient is 0·09 per cent and Manning's roughness coefficient is 0·04? The side slope of the channel for silt loam soil can be taken as 1·5 : 1. [P1/6(a) | 15M]
2023	• Discuss in detail about the hydraulic design of open drains. [P1/6(c) | 10M]
2019	• Explain the components of canal network in a large irrigation project using diagram. [P1/5(a) | 8M]

Groundwater, Wells Pump

2025	• Discuss the subsurface vertical distribution of groundwater with an emphasis on different types of subsurface water. [P1/5(b) | 8M]

2024	• What are the characteristics of the aquifer that influence yield of wells? Explain in brief. [P1/5(b) | 8M] • Discuss the effect of pump speed and impeller diameter on the performance of centrifugal pump. [P1/6(b) | 10M] • A well penetrating aquifer which is underlain and overlain by impermeable layers was tested with a uniform discharge of 1000 litres/min. The steady state drawdowns measured in two observation wells which were at 1·0 m and 10·0 m radial distances from the centre of the pumped well were 13·40 m and 4·20 m, respectively. Determine the hydraulic properties of the aquifer, if its saturated thickness is 10·0 m. [P1/7(a) | 15M]
2023	• What is cavitation? How does it affect the performance of pumping system?. [P1/6(b) | 10M] • What are the parameters to be considered in designing of tube wells? Explain. [P1/7(b) | 10M]
2022	• Discuss the different types of aquifers. [P1/5(b) | 8M]
2021	• Discuss the effect of speed and impeller diameter on pump performance. [P1/6(c) | 10M]
2020	• Differentiate between the following : (I) Semi confined aquifer and Perched water table, (II) Transmissibility and Storage coefficient, (III) Piezometric surface and Pumping water level, (IV) Single acting pump and Double acting pump. [P1/7(a·ii) | 8M] • Discuss the basic requirements for any well screen. [P1/7(c) | 10M]
2019	• ¶Write short notes on (with sketches/diagrams, wherever required) : (i) Cavity tube wells (ii) Dug-cum-bore wells (iii) Driven wells (iv) Filter points. [P1/5(b) | 8M] • Write in brief about different types of centrifugal pumps based on various criteria. [P1/6(b) | 10M] • A pump lifts 95000 litres of water per hour against a total head of 20 m. Compute the water hp. If the pump has an efficiency of 75%, what size of prime mover is required to operate the pump? If a direct drive electric motor having an efficiency of 85% is used to operate the pump, compute the cost of electrical energy in a month of 30 days. The pump is operated for 12 hours per day for 30 days. The cost of electrical energy is ₹ 5 per unit. [P1/8(d) | 10M]
2018	• Differentiate between the following : (i) Specific capacity of well and Specific yield of aquifer (ii) Open wells and Tubewells (iii) Pumping test and Recuperation test of a well (iv) Confined and Unconfined aquifers. [P1/5(b) | 8M] • A tubewell is established in an artesian aquifer. Find its yield in litres per hour for a drawdown of 3 m when the diameter of the well is 20 cm and the thickness of the aquifer is 30 m. Assume the coefficient of permeability to be 35 m/day. If the diameter of the well is doubled, find the increase in the yield, the other conditions remaining the same. Assume the radius of influence as 300 m in both cases. [P1/7(b) | 10M]
2017	• What is Cavitation? How does it affect the performance of a pumping system? How is it prevented in a centrifugal pump?. [P1/5(d) | 8M] • Discuss the important aquifer characteristics influencing yields of wells. [P1/6(b) | 10M]

	• A 25 cm diameter well is pumped at a uniform rate of 50 l/s. The drawdown observed at 1 m and 100 m distances from the centre of the well are 8 m and 40 m respectively. Determine the hydraulic conductivity of the water bearing strata. Assume the thickness of the saturated part of the aquifer as 25 m. [P1/7(b) | 10M] • Discuss the Pumping Test of wells. Explain the step-by-step procedure adopted for conducting pumping tests of wells. [P1/7(c) | 10M] • What are submersible pumps? Explain the complete procedure to install a submersible pump in a borewell including initial preparations, installation and testing. [P1/7(d) | 10M]
2016	• Define a centrifugal pump. Discuss the probable reasons when the centrifugal pump may fail to operate. [P1/5(c) | 10M] • An engine-driven centrifugal pump is to be installed in an open well. The yield of the well is sufficient to deliver 16000 litres of water per hour. The static water level is 15 m and the pumping water level is 18 m from ground level. Total losses due to friction in pipe and accessories may be assumed 15% of the total static head. If the pump efficiency is 55% and drive efficiency is 70%, calculate the BHP of the engine required to drive the pump. [P1/5(d) | 10M]

Drainage Engineering, Soil Reclamation

2025	• An agricultural area of 1 hectare needs to be drained of excess water. The soil contains 47% pore space and the soil moisture content after gravitational drainage is 39% (by volume). Find the void ratio, drainable porosity and drainable water volume from the area. The effective root zone depth of the area is 0·9 m. [P1/5(d) | 8M] • Discuss the advantages and limitations of surface drain and subsurface drain. Explain and discuss the information required to design and for the installation of subsurface drainage systems. [P1/7(a) | 15M] • Discuss the characteristics of saline, sodic and saline-sodic soils. Explain the principles and approaches of saline soil management. [P1/7(b) | 15M]
2024	• How does waterlogging and salt accumulation affect the agricultural land adversely? Explain in brief. [P1/5(c) | 8M] • What are the supplemental structures used in tile drainage system for their successful functioning and long life?. [P1/6(c) | 15M]
2023	• (i) Compute the velocity of flow of water to be drained and discharge capacity of 150 mm diameter corrugated plastic pipe flowing full if the slope is 0·4 percent. Manning's roughness coefficient is 0·016. (ii) How will you reclaim and manage the saline soils? Explain. [P1/7(c) | 10M]
2022	• In a tile drainage system, drains are to be installed at impervious layer at the depth of 2·0 m below the ground surface. The hydraulic conductivity of the soil is 1·8 m/day. The average rate of recharge is 0·2 cm/day. Calculate the required spacing of the drains if water table is to be kept at 1·0 m from the ground surface. [P1/5(c) | 8M]

	• Discuss mole drainage. [P1/6(c) | 10M] • Describe in brief the reclamation of salt affected soils. [P1/7(b) | 15M]
2021	• Differentiate between Interceptor drainage and Relief drainage. [P1/7(a·iii) | 5M] • (i) Define leaching requirement. How is leaching requirement estimated for the design of subsurface drainage? [5 M] (ii) Estimate the leaching requirement when the EC of the saturation extract of the soil is 11 mmho/cm at 25 percent reduction in the yield of cotton. The EC of irrigation water is 1·4 mmho/cm. [10 M]. [P1/7(c) | 15M]
2020	• Discuss about the pipe drain and pipless drains (mole) used in subsurface drainage system. [P1/6(b) | 10M] • What is sanitary drainage system? What are the different types of drainage systems? What is the difference between sewage and drainage? How can drainage systems be improved?. [P1/8(b) | 10M]
2019	• What are the causes of waterlogging and soil salinity in an irrigated agriculture/agricultural field?. [P1/5(c) | 8M]
2018	• What is the importance of drainage network in canal command and large irrigation projects? List all the information required for design and installation of subsurface drainage systems. [P1/6(b) | 10M]
2017	• Differentiate between ESP and SAR. Derive the relationship between these two indices. What are salt affected soils? Explain different reclamation measures to manage salt affected soils. [P1/7(a) | 10M] • Discuss the purpose, benefits and types of subsurface drainage systems. Explain the design of pipe drainage systems used for large irrigation projects. [P1/8(c) | 10M]
2016	• Define agricultural drainage. What are the sources and ill effects of drainage?. [P1/7(a) | 10M] • Runoff water from a watershed enters into a drainage area for 8 hours at the rate of 3 m^3/s. The total rainfall during 24-hour period is 12 cm and the total infiltration during the period is 4 cm. If the total drainage area is 200 ha and the crop can tolerate a ponding of 10 cm, calculate the drainage coefficient of the land. [P1/7(b) | 20M] • Discuss the following in brief : (i) Mole drain (ii) Interceptor drain (iii) Bio-drainage (iv) Channel lining. [P1/7(c) | 10M]

Farmstead, Storage and Building

2025	• With a neat drawing, explain the stanchion barn for housing of dairy animals. Mention its specific advantages. [P1/5(e) | 8M] • What are the requirements of good water supply distribution system for farmstead? Briefly discuss about the different water distribution systems commonly adopted in farmstead. [P1/7(c) | 10M] • What are the advantages of deep litter poultry housing? Draw a neat sketch to

	accommodate 1000 birds. Take floor area of 0·36 sq. m per bird. [P1/8(c) | 10M] • Write short notes on the following : (i) Electric farm fencing (ii) PUSA storage bin (iii) Advantages of greenhouse cultivation (iv) Requirements of good storage structures (v) Classification of lime used in farm housing. [P1/8(a) | 15M]
2024	• What is hermetic storage? List the advantages of using hermetic storage structures. [P1/5(d) | 8M] • Write in brief about : (i) Woven Mesh type of farm fence (ii) Seasoning of Timber. [P1/5(e) | 8M] • Write short notes on the following : (i) Functions of Septic Tank (ii) Brooder Houses (iii) Surkhi (iv) Slump Test on Concrete (v) CAP Storage System. [P1/7(c) | 15M] • Discuss the importance of location selection for establishment of a farmstead. What are the facilities to be kept in mind while designing a good farm house?. [P1/8(a) | 15M] • What are the different components of silo storage system? Mention specific advantages of metallic silos over concrete silos. [P1/8(b) | 15M]
2023	• Design a bag storage structure for storing 300 tonnes of wheat with a stack of 10 bags in length, 10 bags in width and 10 bags in height. Each bag is of 100 cm × 60 cm × 30 cm dimension having capacity of 100 kg. Take a clear distance between the walls and the end of the stack as 0·8 m and between the stacks as 2·0 m. Give the complete floor plan of the structure with dimension and draw layout. [P1/5(d) | 8M] • Discuss various factors to be taken care in designing a storage structure for grains. What measures can be adopted to improve the performance of traditional storage structure?. [P1/8(a) | 10M] • Discuss how you plan to construct a new dairy barn. Discuss various dairy barn equipments. Compare between stall barn and loose housing barn. [P1/8(c) | 20M] • How are bricks (the common building material) prepared in India? Classify bricks and briefly discuss about each type of brick. [P1/8(b) | 10M]
2022	✎ What would be the storage structure for grains?. [P1/5(d) | 8M] ✎ How can you take care of drainage and sewage management?. [P1/5(e) | 8M] ✎ Explain the causes by which losses of grain occur during storage. Discuss about humidity to be maintained in the storage system. How can you control the losses?. [P1/8(a) | 15M] ✎ In your view, how should the design and construction of farm roadways be done?. [P1/8(c) | 10M] • Write short notes on the properties of the common building materials used in construction : (i) Timber (ii) Brick (iii) Stone (iv) Tiles (v) Concrete. [P1/8(b) | 15M]
2021	• Work out the economical diameter and depth of silo/siloes to store sufficient quantity of silage for a herd of 650 dairy cows having average weight of 400 kg each. Number of days for which silage has to be fed = 240 days; Weight of 1 cu·m of silo = 675 kg; Thickness of silage to be fed each day = 10 cm; Quantity of silage to be fed per 100 kg of body mass = 4 kg; Maximum diameter of silo permitted = 6 m; Allowable loss of

	handling = 10%. [P1/5(c) | 8M] ✎ Write in brief about different types of poultry housing systems. List out the important equipment being used in poultry system. [P1/5(d) | 8M] ✎ What are different types of farm fencing based on method of construction and material used? Briefly describe the principle used for electric fencing of farm. [P1/5(e) | 8M] ✎ Differentiate between Deep and Shallow bins. Give the merits and demerits of Bag and Bulk storage system. [P1/8(a) | 15M] • Give a comparative analysis between Loose housing barn and Stall barn. [P1/8(c) | 10M]
2020	✎ Describe the importance and significance of selection of a suitable site for a nuclear power plant. [P1/5(c) | 8M] ✎ Discuss safe disposal of all human sewage and domestic wastes in farmstead planning, illustrating suitable layout. How is it different from homestead planning?. [P1/8(a) | 20M] ✎ What are the considerations to frame water supply system in rural areas? Illustrate with examples. [P1/8(c) | 10M]
2019	• A cylindrical silo of 2·5 m diameter and 20 m in height is filled with wheat. Calculate the load on the bottom only. The silo is made of steel with smooth walls. The characteristics of stored wheat are as follows : (i) The minimum bulk density = 720 kg/m³ (ii) The maximum bulk density = 830 kg/m³ (iii) The minimum angle of internal friction = 25° (iv) The maximum angle of internal friction = 30° (v) The minimum angle of friction on smooth sheeting = 18°. [P1/5(e) | 8M] • Calculate the cost of fencing a square farm of 25 ha fenced by barbed wire using cement concrete posts. Take the following values : (i) Posts ₹335 per post of cement (ii) Corner posts ₹500 per post (iii) Cost of barbed wire is ₹1,000 per 100 m (iv) Cost of earthwork @ ₹50 per pit (v) Cost of cement concrete @ ₹100 per pit (vi) Labour charges for fixing wire are ₹3,000 (vii) Cost of gate is ₹15,000. Assume 1·80 m high angle iron posts spaced 3 m apart with 6 lines of barbed wires are used. [P1/6(d) | 10M]
2018	• It is very important for a farmstead to be properly arranged. List and explain in brief, the factors to be considered for best arrangement of farmstead. [P1/6(d) | 10M]
2017	• Discuss dairy barns, their types and their components. Draw a model layout of a dairy farm for a 20 cow/buffalo unit. [P1/8(b) | 10M] • What is a Farmstead? What factors govern the location of the farmstead on the farm?. [P1/8(d) | 10M]
2016	• Classify silos. Describe constructional features and use of pit silos. [P1/8(b) | 12M] • A rectangular farm of 10 ha (500 m × 200 m) is to be fenced by barbed wires with concrete poles. Estimate the cost of fencing with six rows of barbed wires. Assume suitable values for spacing of posts and appropriate prices for posts and wires. [P1/8(c) | 16M]

Plant Environment, Greenhouse Protected Cultivation

2025	✎ (i) Write briefly about the various aspects of selection and design of greenhouse. [10 M] (ii) Briefly describe the different types of silos which can be used to store animal feed/forage. [5 M]. [P1/8(b) | 15M]
2024	✎ What is the necessity of controlling environment inside the greenhouse? Briefly mention different methods to control greenhouse environment. [P1/8(c) | 10M]
2023	✎ Classify various types of greenhouse and briefly discuss each of them. [P1/5(e) | 8M]
2021	✎ What are the classifications of greenhouses based on shape? List the different covering materials used for greenhouses. [P1/8(b) | 15M]
2020	✎ What do you mean by Greenhouse Effect? How does it affect the climate? How can you build a low cost greenhouse?. [P1/5(d) | 8M]
2019	✎ Give the details of different greenhouse construction materials and covering materials. [P1/7(b) | 10M]
2018	✎ What are the main components of Polyhouse? Discuss various factors influencing the design and installation of Polyhouses in India for surface covered cultivation. [P1/8(a) | 10M]
2017	✎ Discuss various types of poly houses (low to high cost) used for cultivation of high value crops. Explain the working principle of fan and pad evaporative cooling systems. [P1/8(a) | 10M]
2016	✎ What is polyhouse? Describe the working of fan and pad cooling system with a neat sketch. [P1/8(a) | 12M]

Rference resources

Irrigation and drainage

- "***Irrigation: Theory and Practice***" — *A.M. Michael (the standard, most comprehensive reference; covers water requirement of crops, irrigation methods, efficiencies, canal design)*
- "***Irrigation Engineering and Hydraulic Structures***" — *S.K. Garg (strong on canal design, diversion structures, measuring devices — weirs/flumes/orifices)*
- "***Groundwater Hydrology***" — *David Keith Todd (for well hydraulics, aquifer types, tube well design/testing)*
- "***Drainage Engineering***" — *Michael & Ojha / or the drainage sections within Michael's Irrigation text (waterlogging, salinity, sub-surface drainage design)*
- "***Soil and Water Conservation Engineering***" — *Suresh R. Suresh (useful for soil-water-plant relationships, moisture measurement)*

- **"Fundamentals of Irrigation and On-farm Water Management"** — Vol. 1 — *Prabhakar Pathak & M.L. Kherde (ICAR/NAIP publication, good for fertigation, sprinkler/drip specifics)*
- ***Government/Institutional sources:***
- ICAR — ***Water Technology Centre (WTC), IARI*** *publications and technical bulletins*
- *Central Water Commission (CWC) — guidelines on minor irrigation project planning*
- *Bureau of Indian Standards (BIS) codes on canal lining, drainage design (IS codes are occasionally referenced in higher-level answers)*
- *FAO Irrigation & Drainage Papers (e.g., FAO-24, FAO-56 on crop water requirements) — internationally recognized and safe to cite*

Agricultural structures

- **"Elements of Agricultural Engineering"** — *Jagdishwar Sahay (has a solid farm structures section — farmstead planning, storage structures, farm roads)*
- **"Farm Structures"** — *J.C. Nagpal / or Sahay's structures chapters (site selection, cattle sheds, poultry housing, grain storage)*
- ICAR ***Handbook of Agriculture*** — *has a dedicated farm structures/rural engineering chapter, useful for exam-oriented factual content*
- *ASAE (American Society of Agricultural Engineers) Standards — for greenhouse/poly house/shade house design parameters (used carefully, only for factual specs, not reproduced verbatim)*
- ***Supplementary:***
- *CIAE (Central Institute of Agricultural Engineering), Bhopal — technical reports on storage structures and farm building materials*
- *State Agricultural University (SAU) lecture notes/practical manuals (PAU Ludhiana, GBPUAT Pantnagar) — often have concise farm structures modules useful for cross-checking*

CHAPTER

1

SOIL-WATER RELATIONS & IRRIGATION WATER REQUIREMENTS

Soil moisture · Potential & retention · ET & crop water · Duty–Delta · Efficiencies · Scheduling · Conjunctive use

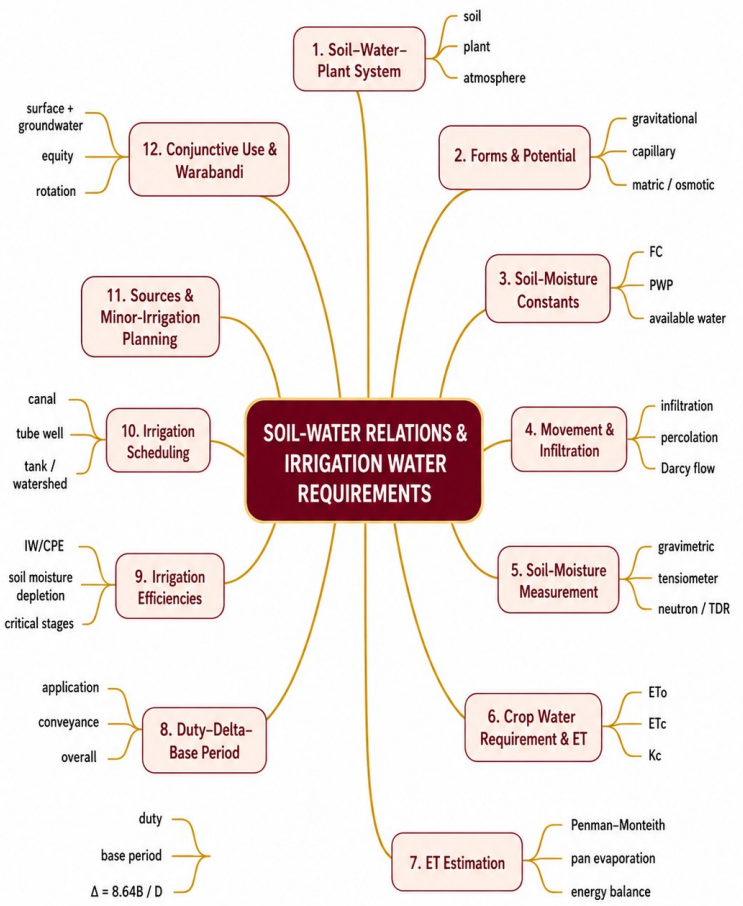
SYLLABUS (Paper I · Soil & Water Conservation): Soil-water-plant relationship — field capacity, permanent wilting point, available water, soil-moisture coefficients, matric potential, soil-moisture characteristic curve, Darcy's law of soil-water flow, infiltration. Methods of soil-moisture measurement (direct & indirect — gravimetric, tensiometer, pressure plate, neutron probe). Crop water requirement, irrigation water requirement, consumptive use, evapotranspiration (ETo, ETc, crop coefficient). Duty, delta and base period. Irrigation efficiencies. Irrigation scheduling and management-allowed deficit. Conjunctive use of surface and groundwater. Sources of irrigation and planning of minor-irrigation projects. Warabandi.

Chapter Outline

1. **Scope & the Soil–Water–Plant System**
2. **Soil Water: Forms & Energy Concept**
3. **Soil-Moisture Constants**
4. **Soil-Water Movement & Infiltration**
5. **Measurement of Soil Moisture**
6. **Crop Water Requirement, Consumptive Use & ET**
7. **Estimation of Evapotranspiration**
8. **Duty, Delta & Base Period**
9. **Irrigation Efficiencies**
10. **Irrigation Scheduling**
11. **Sources of Irrigation & Minor-Irrigation Planning**
12. **Conjunctive Use & Warabandi**

1 SCOPE & THE SOIL–WATER–PLANT SYSTEM

Soil-water relations answer the two questions at the heart of irrigation water management — ***when*** and ***how much*** to irrigate. Between two irrigations the soil is the reservoir from which the crop draws water, so the way water is received, stored, transmitted and released by the soil fixes the ***crop water requirement***, the ***irrigation interval*** and the ***efficiency*** of every application.



Soil–water–plant relationship — *the study of the soil's capacity to receive, store, transmit and release water, together with the way plant roots extract that water to meet transpiration demand.*

Soil is a ***three-phase system***: a ***solid*** mineral-and-organic matrix, a ***liquid*** phase (the soil solution) filling part of the pore space, and a ***gaseous*** phase (soil air) filling the rest. Water and air share the pore volume, so as soil water rises soil air falls — the balance that governs both water supply and root aeration.

- ***Solid phase*** : mineral particles (sand, silt, clay) and organic matter; forms the matrix and provides the adsorptive surfaces that hold water.
- ***Liquid phase*** : the soil solution held in the pores; the immediate source of water and dissolved nutrients for the plant.
- ***Gaseous phase*** : soil air in the larger pores; supplies the oxygen needed for root and microbial respiration.

Water moves through the continuous ***soil–plant–atmosphere continuum* (SPAC)** along a gradient of falling water potential from wet soil (high potential) through the plant to the drier atmosphere (low potential). Every concept in this chapter is one link in that chain.

SOIL AS A THREE-PHASE SYSTEM

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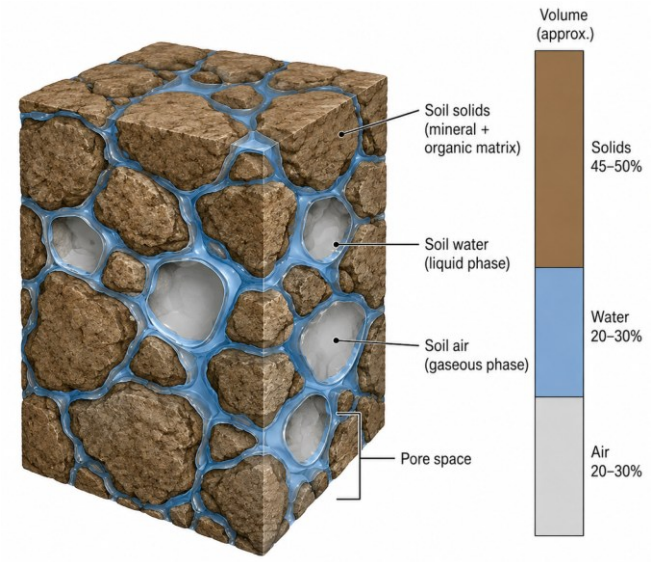


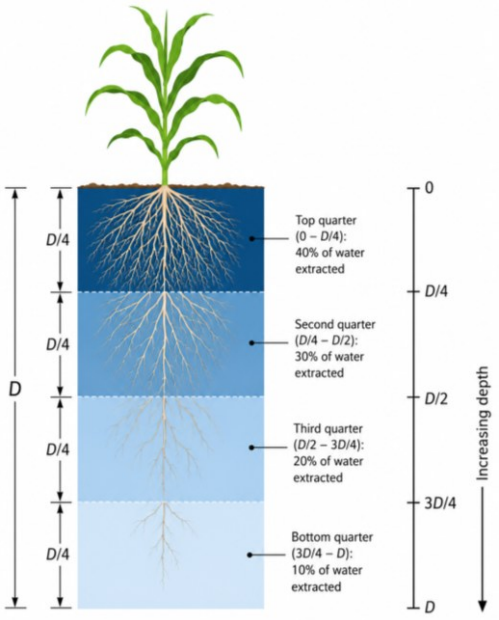
Fig. 1.1 The soil as a three-phase system: water and air jointly occupy the pore

1.1 Moisture-Extraction Pattern of the Root Zone

In a deep, uniform soil with adequate moisture, a crop draws most of its water from the upper root zone. The classical extraction pattern is **40 : 30 : 20 : 10** — about 40% of the water used comes from the top quarter of the root zone, 30% from the second quarter, 20% from the third and only 10% from the deepest quarter, because root density is greatest near the surface. This pattern explains why the upper root zone is monitored for scheduling irrigation.

2 SOIL WATER — FORMS, ENERGY & RETENTION

Soil water is retained by ***adsorption and capillarity***, exists at a definite ***energy state*** (its potential), and the way its amount changes with that energy is captured by the ***retention curve***. These three ideas define field capacity, wilting point, availability, movement and every measurement in this chapter.



2.1 Forms / Types of Soil Water

Soil water is classified by the ***force with which it is held*** and by its ***availability to plants***:

Form	Where & how held	Tension	Availability
Gravitational (free)	macro-pores; moves under gravity	0 – ⅓ bar	unavailable — drains in 1–3 d; impairs aeration
Capillary	micro-pores; surface tension (films/wedges)	⅓ – 31 bar	the principal available water (FC → PWP)
Hygroscopic	adsorbed film on particle surfaces	31 – 10 000 bar	unavailable — removed only by oven-drying
Chemically-combined	in the mineral crystal lattice	—	unavailable; not removed by ordinary drying

Gravitational water fills the large pores after rain/irrigation and drains under gravity within 1–3 days; while present it starves roots of oxygen — short-lived and unavailable. ***Capillary water*** is held in the micro-pores by surface tension between FC (≈⅓ bar) and the hygroscopic coefficient (≈31 bar); it is the reservoir the crop draws on, its readily-available part (≈75%) taken without stress. ***Hygroscopic water*** is the tightly-adsorbed film (31–10 000 bar), removed only by oven-drying at 105°C; ***chemically-combined water*** is locked in the clay lattice. Only capillary water between FC and PWP is available.

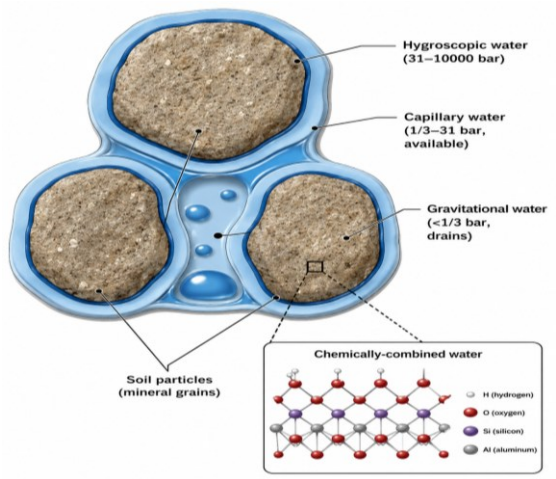


Fig : 2.1. Forms of soil water around soil particles

PREVIOUS YEAR QUESTIONS

- What are the different types of soil water? [OPSC·CSE (Main) 2023–24 · Paper-I Q.5(a) · 15M]
- Define soil water. Describe the different forms of soil water. [OPSC·CSE (Main) 2018–19 · Paper-I Q.1(b)(i) · 8M]

2.2 Soil-Water Potential & Its Components

Water in the soil carries ***potential energy*** (kinetic energy negligible - flow is slow) and moves spontaneously from higher to lower total potential, at a rate set by the potential gradient. The ***total soil-water potential*** Ψt is the sum of four components:

Total soil-water potential (Ψt) : *the work done per unit quantity of water in transferring it reversibly and isothermally from a reference pool of pure free water (at a stated elevation, atmospheric pressure) to the soil water at the point considered.*

$$\Psi t = \Psi g + \Psi m + \Psi p + \Psi o$$

gravitational + matric + pressure + osmotic

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THE COMPONENTS, IN DETAIL

- ***Gravitational (Ψg)*** : from elevation z relative to a datum; Ψg = z (head) or ρ_w g z (volume basis); always present; drives drainage.
- ***Matric (Ψm)*** : the ***negative*** potential from adsorption + capillarity; zero at saturation, more negative as soil dries; ***dominant in unsaturated soil***; measured by tensiometer; basis of the retention curve.
- ***Pressure/submergence (Ψp)*** : the ***positive*** hydrostatic potential below a water table; Ψp = h (depth below the free surface); only in saturated soil; measured by piezometer. Ψm and Ψp are mutually exclusive.
- ***Osmotic/solute (Ψo)*** : the ***negative*** potential from dissolved salts; roots must overcome it; important in ***saline/alkali soils***; does not drive liquid flow — acts on uptake and vapour.

UNITS & HYDRAULIC HEAD

Expressed per unit mass (J kg^{-1}), volume (pressure — Pa/bar/atm) or weight (head — m of water). 1 bar ≈ 100 kPa ≈ 10.2 m water ≈ 0.987 atm. For saturated flow $H = \Psi g + \Psi p$, and Darcy flow follows the gradient of H.

COMPONENTS OF SOIL-WATER POTENTIAL

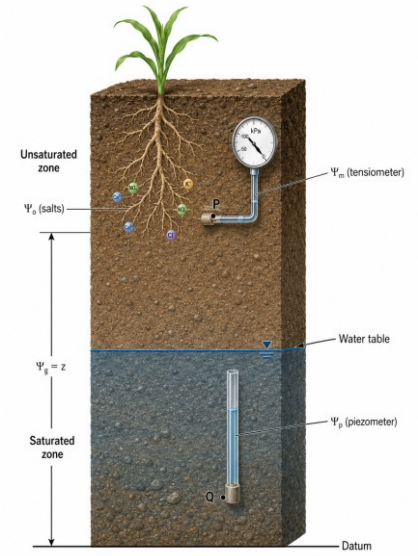


Fig. 2.2 The four components of total soil-water potential and how each is sensed.

PREVIOUS YEAR QUESTIONS

- Define soil water potential. Discuss in detail the various components of soil water potential.
  [UK·PSC ACF/RFO (Mains) 2025 · Q.2(i) · 15M]
- What are the components of total soil water potential? Explain.
  [OPSC·CSE (Main) 2023–24 · Paper-I Q.6(a) · 15M]

2.3 Soil-Moisture Characteristic (Retention) Curve & pF

Soil-moisture characteristic curve — *the relationship between the soil's water content (θ) and the matric suction (or matric potential / pF) at which that water is held; the soil-water retention curve.*

As suction rises (soil dries), water leaves the ***large pores first*** and small pores last, so the curve is steep near saturation and flattens at high suction. Clay retains more at every suction; sand drains abruptly past its air-entry value.

PROCEDURE TO DEVELOP THE CURVE

1. Take an initially saturated, undisturbed sample in good hydraulic contact with a saturated porous plate/membrane.
2. Apply a known suction — hanging water column / tension table for low suctions (0–1 bar); pressure-plate / pressure-membrane (Richards) apparatus for high suctions (1–15 bar+) via known air pressure.
3. Let the sample drain to equilibrium at that suction (outflow ceases).
4. Measure the equilibrium water content for that suction (weigh, or from outflow collected).
5. Increase suction in steps; repeat from saturation to ~15 bar (or higher) — the drying (desorption) curve.
6. Optionally re-wet in steps for the wetting (sorption) curve — the two differ (hysteresis).
7. Plot water content vs suction (log scale, or pF) — the characteristic curve.

pF SCALE & CRITICAL POINTS

$$pF = \log_{10}(h)$$

h = suction as cm of water column (Schofield, 1935)

- ***Air-entry value*** : suction at which the largest pores begin to drain (curve's first break).
- ***Saturation → FC → PWP → Hygroscopic*** : pF 0 → ≈⅓ bar (pF 2.5) → 15 bar (pF 4.2) → 31 bar (pF 4.5); available water = θ(FC)−θ(PWP).

Hysteresis (ink-bottle effect, contact-angle, entrapped air) makes θ higher on the drying than the wetting curve — the relation is not unique. Uses: read FC, PWP, available water; derive unsaturated conductivity; calibrate tensiometers.

PLOT SPEC (YOU GENERATE):

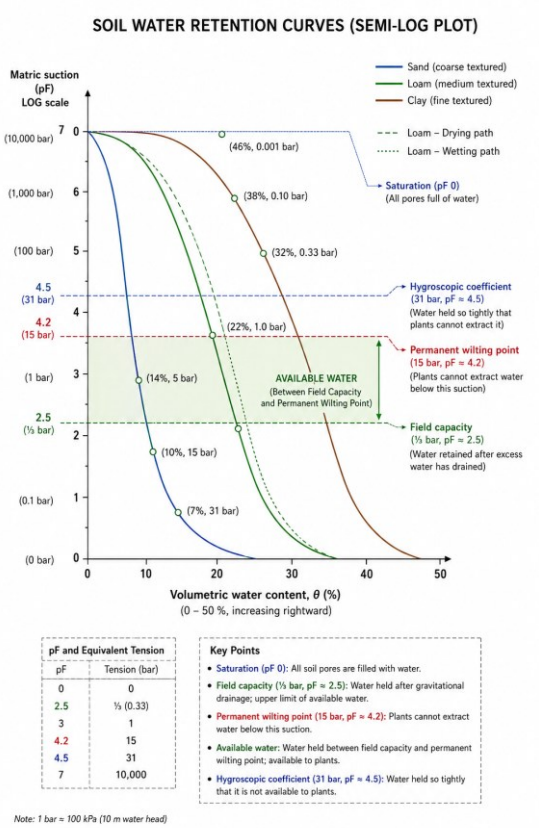


Fig. 2.3 Retention curves for sand, loam and clay with air-entry, FC, PWP, available-water band and hysteresis.

PREVIOUS YEAR QUESTIONS

Discuss the procedure to develop soil moisture characteristic curve and its critical points.

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[IFoS 2017 · P1/5(b) · 8M]

Write short notes on: Soil moisture characteristic curve. [IFoS 2025 · P1/6(c)(iii) · part of 10M]

3 SOIL-MOISTURE CONSTANTS

Soil-moisture constants are reference water contents, each tied to a definite tension, that fix the ***limits of usable water*** and drive every scheduling and depth-of-irrigation calculation.

Constant	Tension	Meaning / significance
Saturation capacity	≈ 0	all pores full; temporary, poor aeration
Field capacity (FC)	⅓ bar	water held after gravity drainage (1–3 d); upper limit of available water
Moisture equivalent	≈ ⅓ bar	≈ FC for medium soils (centrifuge at 1000 g)
Permanent wilting point (PWP)	15 bar	plant wilts irreversibly; lower limit of available water
Ultimate wilting point	≈ 60 bar	plant dead; = hygroscopic coefficient region
Hygroscopic coefficient	≈ 31 bar	air-dry moisture; wholly unavailable
Available water (AW)	FC – PWP	the reservoir the crop uses
Readily available water	≈ 75% of AW	taken without stress

Field capacity is determined in the field by ponding water on a 2–5 m² plot, covering it to stop evaporation, and sampling gravimetrically after 2–3 days when drainage has nearly ceased (or in the lab on a pressure plate at ⅓ bar). It ***rises with fineness of texture, organic matter, good structure and an impeding sub-layer***. ***Permanent wilting point*** is found with the sunflower method or a pressure-membrane at 15 bar.

Temporary wilting is recovered overnight without added water; ***permanent wilting*** needs irrigation; ***ultimate wilting*** is irreversible (plant dies).

SOIL-WATER COEFFICIENTS & MAXIMUM AVAILABLE SOIL MOISTURE

The ***soil-water (moisture) coefficients*** are the characteristic moisture percentages — saturation, field capacity, moisture equivalent, wilting coefficient (PWP) and hygroscopic coefficient. The ***maximum available soil moisture*** (also the maximum soil-moisture deficiency that may be created) is the depth of water between FC and PWP:

$$\text{Max. available water} = A_s \cdot D \cdot [\theta(FC) - \theta(PWP)]$$

A_s = apparent specific gravity (bulk density); D = root-zone depth; θ as fractions

Methodology: determine FC and PWP for the soil, take their difference, and multiply by the bulk density and the root-zone depth; the readily-available fraction is ≈75% of this. This maximum deficiency is what irrigation may deplete before refilling to FC — the link to ***scheduling*** (irrigate when available water falls to the management-allowed deficit, then refill to FC; the consumptive-use rate fixes the interval).

KEY DIFFERENTIATIONS (FREQUENTLY ASKED)

Basis	Saturation capacity	Field capacity
Pores filled	all (macro + micro)	only micro (macro air-filled)
Tension	≈ 0	≈ ⅓ bar
Duration	temporary — drains	stable after 1–3 d
Aeration	poor	good

Basis	Saline-alkali soil	Non-saline alkali (sodic) soil
Soluble salts (EC_e)	high, > 4 dS/m	low, < 4 dS/m
Exchangeable sodium (ESP)	high, > 15	high, > 15
pH	≤ 8.5	> 8.5 (often 8.5–10)
Structure	flocculated (salts mask sodium)	dispersed, poor tilth

Basis	Soil texture	Soil structure
Definition	proportions of sand, silt, clay	arrangement of particles into peds
Nature	inherent, stable	modifiable by management
Classes	sand, loam, clay …	granular, blocky, platy, prismatic
Controls	water retention, plasticity	porosity, infiltration, aeration

TYPICAL VALUES (% OF DRY WEIGHT)

Soil	FC %	PWP %	AW %
Sand	5	2	3
Sandy loam	12	5	7
Loam	18	10	8
Silt loam	24	15	9
Clay loam	30	19	11
Clay	40	24	16

PREVIOUS YEAR QUESTIONS

- Define and describe field capacity and permanent wilting point. What do you understand by available water capacity and readily available water? Why are these important?
  [OPSC·CSE (Main) 2024–25 · Paper-I Q.3 · 15M]
- List different soil water coefficients. Explain the methodology to estimate maximum available soil water using these coefficients.
  [IFoS 2025 · P1/6(c)(iii) · part of 10M]
- How can the field capacity moisture content of a soil be determined? Briefly explain the factors that influence it.
  [OPSC·CSE (Main) 2020–21 · Paper-I Q.2(a)(i) · 8M]
- Differentiate between: (i) Saline-alkali soil and Non-saline alkali soil (ii) Saturation capacity and Field capacity (iii) Permanent wilting point and Ultimate wilting point (iv) Soil texture and Soil structure.
  [IFoS 2020 · P1/7(b) · 10M]
- Define field capacity, wilting point, available soil moisture, consumptive use. How are these terms relevant in scheduling irrigation?
  [OPSC·CSE (Main) 2017–18 · Paper-I Q.4(a) · 15M]

◆ **WORKED NUMERICAL — Depth of irrigation & time to irrigate** [IFoS 2019 · P1/5(d) · 8M]

Problem. *FC = 29% (w/w), irrigation applied at 19% (w/w); apparent specific gravity 1.30; depth wetted 1 m. Find (i) ha-cm/ha; (ii) time to irrigate 10 ha with a 0.10 m^3/s stream at 75% application efficiency.*

Formula. $d = A_s \cdot D \cdot (FC - MC)$

Substitution. $d = 1.30 \times 100 \times (0.29 - 0.19) = 1.30 \times 100 \times 0.10$.

(i) Net depth = 13 cm = 13 ha-cm/ha.

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(ii) Gross = 13/0.75 = 17.33 cm; volume(10 ha) = 100000 × 0.1733 = 17 333 m³; t = 17 333/0.10 = 173 333 s = **48.2 h.**

◆ **WORKED NUMERICAL — Depth of water applied** [IFoS 2018 · P1/5(d) · 8M]

Problem. *FC = 25% (w/w), MC = 15% (w/w), apparent specific gravity 1.52, depth wetted 90 cm. Water in ha-cm/ha?*

d = A_s·D·(FC−MC) = 1.52 × 90 × 0.10 = **13.68 ha-cm/ha.**

◆ **WORKED NUMERICAL — Irrigation depth & time (tomato)** [IFoS 2016 · P1/6(c) · 20M]

Problem. *Tomato, 60 cm root depth; FC 22%, PWP 8%; irrigate after 40% depletion; A_s = 1.6. Depth of irrigation; time to irrigate 2 ha at 10 L/s (no loss)?*

AW = 22 − 8 = 14%; allowed depletion = 0.40 × 0.14 = 0.056.

Depth d = 1.6 × 60 × 0.056 = **5.38 cm.**

V = 2 ha × 5.376 cm = 1075.2 m³; t = 1075.2/0.010 = 107 520 s = **29.9 h.**

SOIL-MOISTURE CONTINUUM & CONSTANTS

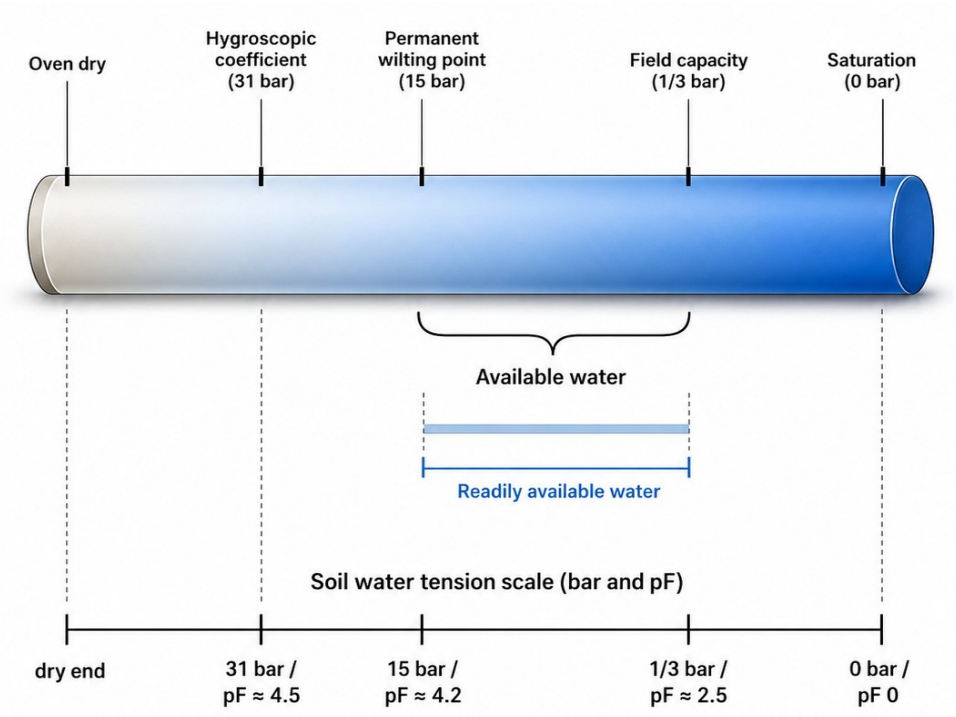


Fig. 3.1 The soil-moisture continuum and the available-water reservoir between FC and PWP.

4 SOIL-WATER MOVEMENT & INFILTRATION

4.1 Darcy's Law of Soil-Water Flow

In saturated soil the flux is proportional to the ***hydraulic gradient***:

$$q = -K\,(dH/dx) \qquad Q = K \cdot i \cdot A$$

q = flux (velocity); K = hydraulic conductivity; i = dH/dx; A = area

Darcy's law holds for ***laminar, saturated*** flow (low Reynolds number, Re < 1). It fails for turbulent flow (coarse gravel, high gradients) and, strictly, for very fine clays at very low gradients. In ***unsaturated*** soil the conductivity K(θ) falls steeply as the larger pores empty, so flow is much slower and matric-potential-driven.

PREVIOUS YEAR QUESTIONS

Discuss Darcy's law of soil water flow with a definition sketch. In what flow conditions is it applicable?
[IFoS 2017 · P1/5(c) · 8M]

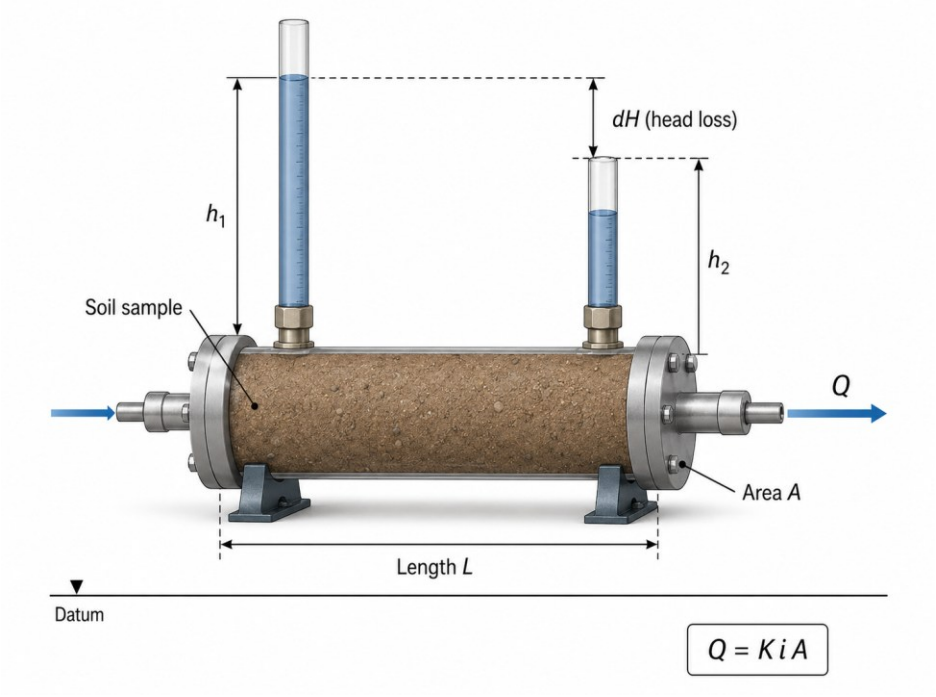


Fig. 4.1 Definition sketch for Darcy's law.

4.2 Infiltration

Infiltration is the entry of water through the soil surface. The ***infiltration rate*** starts high and decays to a steady ***basic (final) rate*** as surface pores fill, clays swell and a surface seal forms; the running total is the ***cumulative infiltration***. Common models:

Horton: $f = f_c + (f_o - f_c)e^{(-kt)}$ Kostiakov: $f = a \cdot t^{(-n)}$ Philip: $f = \tfrac{1}{2}\, s \cdot t^{(-1/2)} + A$

f_o initial, f_c basic rate; a,n,k,s,A = soil constants

FACTORS AFFECTING INFILTRATION RATE

- initial soil moisture (drier → faster), texture and structure (coarse/well-aggregated → faster), surface sealing/crusting and compaction (slower), organic matter and vegetal cover (faster), depth to a restricting layer or water table, and slope. Measured with a ***double-ring infiltrometer***.

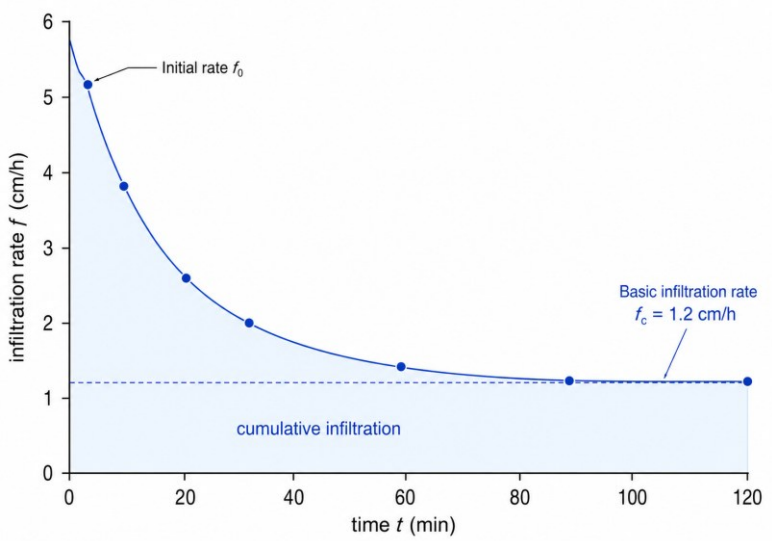
◆ WORKED NUMERICAL — Basic infiltration rate from field data [IFoS 2018 · P1/8(c) · 10M (method)]

Problem. *Double-ring readings (representative): t = 5,10,20,30,60,90,120 min; f = 5.2,3.8,2.6,2.0,1.4,1.2,1.2 cm/h. Plot f vs t and find the basic infiltration rate.*

Plot f (cm/h) vs t (min); the curve decays and flattens.

The tail is constant at 90–120 min, so **basic infiltration rate $f_c \approx 1.2$ cm/h** (Horton $f = 1.2 + 4.0\, e^{(-kt)}$).

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AQUIFERS (CONFINED VS UNCONFINED) — ASKED HERE, DETAILED IN THE GROUNDWATER CHAPTER

Basis	Unconfined (water-table) aquifer	Confined (artesian) aquifer
Upper boundary	the water table (atmospheric)	an overlying impermeable layer
Pressure	water table at atmospheric pressure	water under pressure > atmospheric
Recharge	direct, from above	from a distant exposed edge
Well water level	rises to the water table	rises above the aquifer top (may flow)

PREVIOUS YEAR QUESTIONS

- What are the factors which affect the infiltration rate of water into soil? [AP·PSC RFO (Mains) 2012 · Q.1(E) · 4M]
- Differentiate between Confined and Unconfined aquifers. [IFoS 2017 · P1/5(a)(iv) · part of 8M]

5 MEASUREMENT OF SOIL MOISTURE

5.1 Direct Method — Gravimetric & Moisture Representation

The ***gravimetric method*** is the standard against which all others are calibrated: a sample is weighed moist, oven-dried at **105 °C for 24 h** and re-weighed. Moisture is expressed three ways:

$$\theta_m = (M_{moist} - M_{dry})/M_{dry} \qquad \theta_v = \theta_m \cdot \rho_b \qquad \text{depth } d = \theta_v \cdot D$$

θ_m = weight basis (w/w); θ_v = volume basis (v/v); ρ_b = bulk density; D = soil depth

5.2 Indirect Methods (with working)

- ***Tensiometer*** — a water-filled porous ceramic cup connected to a vacuum gauge; soil suction draws water out, and the vacuum registered = ***matric potential*** (useful to ≈ 0.85 bar). Water content is read off the characteristic curve.
- ***Gypsum / electrical-resistance block*** — two electrodes in a porous block equilibrate with soil water; resistance falls as moisture rises (calibration curve). Cheap, wide range, coarse near saturation.
- ***Neutron moisture meter*** — fast neutrons from an Am–Be source are thermalized (slowed) by hydrogen in soil water; the slow-neutron count, read by a scaler, is proportional to volumetric water content; measures a sphere of influence around an access tube.
- ***TDR*** — the transit time of an electrical pulse along buried probes depends on the soil's dielectric constant (water ≈ 80, solids 2–5); accurate, continuous, needs little calibration.

PRESSURE-PLATE / MEMBRANE APPARATUS — WORKING PROCEDURE

Apparatus: a sealed ***pressure chamber (extractor)*** holding a saturated porous ceramic plate whose fine pores stay water-filled up to a high air-entry value; soil samples rest on the plate; an outflow tube from beneath the plate leaves the chamber to atmosphere.

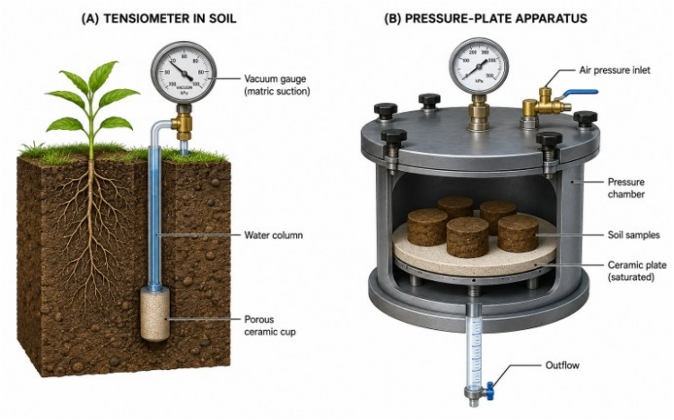


Fig. 5.1 Tensiometer (field matric potential) and pressure-plate

1. Saturate the soil samples and the ceramic plate; place the samples on the plate in the chamber and seal it.
2. Apply a known air pressure inside the chamber (e.g. ⅓ bar for field capacity, 15 bar for the wilting point) using compressed air.
3. Water is forced out of the soil, through the water-filled plate and out of the chamber, until outflow stops (equilibrium); the applied air pressure then equals the soil-water matric suction.
4. Remove the samples and determine their moisture gravimetrically — this is the water content held at that suction.
5. Repeat at successive pressures to obtain points of the soil-moisture characteristic curve (and directly FC at ⅓ bar, PWP at 15 bar).

PREVIOUS YEAR QUESTIONS

- Discuss the working procedure and application of pressure plate apparatus for determining soil matric potential and water content with the help of a neat sketch.
  [IFoS 2021 · P1/6(a) · 15M]
- Explain in detail the direct and indirect methods of soil moisture measurement/determination.
  [IFoS 2019 · P1/6(a) · 10M]
- What are the indirect methods of determination of soil moisture content?
  [OPSC·CSE (Main) 2023–24 · Paper-I Q.6(b) · 15M]

◆ **WORKED NUMERICAL — Gravimetric & volumetric water content** [IFoS 2017 · P1/5(e) · 8M]

Problem. *A soil sample of volume 82 cm³ weighs 125 g; after drying at 105 °C it weighs 100 g. Find w/w and v/v moisture; what depth of water raises the volumetric content of the top 1 m to 0.40? (ρ_w = 1.)*

Water = 125 − 100 = 25 g → 25 cm³. θ_m = 25/100 = **25%.**

ρ_b = 100/82 = 1.22 g/cm³; θ_v = 0.25 × 1.22 = **30.5% (= 25/82).**

Δθ_v = 0.40 − 0.305 = 0.0951 over 1 m → depth = **95.1 mm ≈ 9.51 cm.**

◆ **WORKED NUMERICAL — Moisture at successive depths & gross requirement** [IFoS 2019 P1/7(c) / OPSC-Forest · 10–20M]

Problem. *Depth samples 0–25,25–50,50–75,75–100 cm give moist/dry weights 135.60/127.82, 137.28/128.95, 123.95/116.32, 111.92/103.64 g; bulk density 1.65; field-capacity storage 18 cm over 1 m. Find root-zone moisture, net and gross requirement at 70% field efficiency.*

Layer depth = w/w × ρ_b × 25 cm: 6.08%→2.51; 6.46%→2.66; 6.56%→2.71; 7.99%→3.29 cm.

Present moisture = 2.51+2.66+2.71+3.29 = **11.17 cm.**

NIR = 18 − 11.17 = 6.83 cm; Gross = 6.83/0.70 = **9.76 cm.**

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6 CROP WATER REQUIREMENT, CONSUMPTIVE USE & ET

Crop water requirement is the total water a crop needs from sowing to harvest; it is met almost entirely by ***evapotranspiration***. The terms below build the requirement chain.

Term	Meaning
Evapotranspiration (ET)	soil evaporation + crop transpiration
Potential ET (PET)	ET of a short green crop, never short of water
Reference ET (ETo)	ET of a standard reference grass — the climatic demand
Crop ET (ETc)	ET of the actual crop = Kc · ETo
Consumptive use (Cu)	ET + water built into plant tissue (≈ ET)
Crop coefficient (Kc)	ETc/ETo; varies with growth stage

The requirement chain: $CIR = ETc - R_e$ (consumptive irrigation requirement, after effective rainfall); $NIR = CIR + LR + PSR + NWR$ (adds leaching, presowing, nursery); $FIR = NIR/\eta_a$ (field, after application losses); $GIR = FIR/\eta_c$ (gross, after conveyance losses).

$ETc = Kc \cdot ETo$ $\quad CIR = ETc - R_e$ $\quad NIR = CIR + LR + PSR + NWR$ $\quad GIR = NIR/(\eta_a \cdot \eta_c)$

R_e = effective rainfall; LR leaching; PSR presowing; NWR nursery

CROP COEFFICIENT (KC) — ESTIMATION & FACTORS

$Kc = ETc/ETo$ is found by measuring ETc (lysimeter / soil-moisture balance) and dividing by ETo (from a climatic method or pan). It follows a four-stage curve — low at ***initial*** (≈0.3), rising through ***development***, a plateau at ***mid-season*** (≈1.15) and falling at ***late season*** (≈0.6). It depends on crop type and variety, growth stage and canopy cover, planting date, climate, and wetting frequency of the surface.

FACTORS AFFECTING WATER / IRRIGATION REQUIREMENT

- crop (type, variety, growth stage, root depth), climate (temperature, humidity, wind, sunshine), soil (texture, water-holding capacity), effective rainfall and stored soil moisture, irrigation method and efficiency, and cultural practices (mulching, weed control).

KEY DIFFERENTIATIONS

Basis	Water requirement (WR)	Irrigation requirement (IR)
Meaning	total field demand incl. losses	only the part supplied by irrigation
Sources counted	ET + losses + special needs	WR − effective rainfall − stored soil moisture
Always	≥ IR	≤ WR

Basis	Evaporation	Consumptive use
What	water lost from soil/water surface	ET + tissue water of the crop
Includes plant?	no	yes (transpiration)
Magnitude	a component	the total crop use

Basis	Crop water-use efficiency (CWUE)	Field water-use efficiency (FWUE)
Definition	yield per unit water consumed (ET)	yield per unit water delivered to the field
Water base	consumptive use	water applied at field
Reflects	crop physiology	crop + application losses

Fertigation equipment (short note): applies fertiliser with irrigation water — a ***venturi injector***, a ***fertiliser (bypass) tank***, or a ***injection/dosing pump***; best suited to drip and sprinkler systems for precise, split nutrient application.

PREVIOUS YEAR QUESTIONS

- Discuss the critical differences between crop water requirement and irrigation water requirement. [IFoS 2025 · P1/5(c) · 8M]
- Discuss various factors influencing irrigation water requirement. How can you estimate total irrigation water requirement incorporating different components for a given field and crop? [IFoS 2018 · P1/5(c) · 8M]
- What is crop coefficient and how is it estimated using crop and reference evapotranspiration? Explain the factors influencing crop coefficient. [IFoS 2018 · P1/7(c) · 10M]
- Explain the terms evapotranspiration, potential evapotranspiration, reference crop ET and consumptive use. [OPSC·CSE (Main) 2023–24 · Paper-I Q.7(a) · 15M]
- Differentiate between: (i) Water requirement and Irrigation requirement (ii) Crop water use efficiency and Field water use efficiency (iii) Evaporation and Consumptive use. [IFoS 2017 · P1/5(a) · 8M]

CROP-COEFFICIENT (KC) CURVE

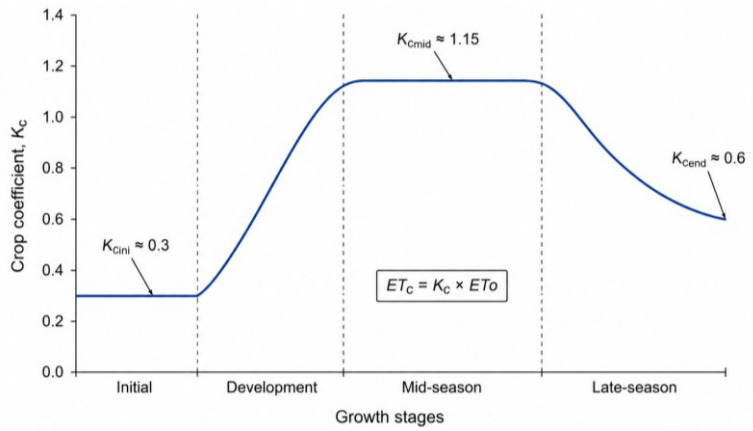


Fig. 6.1 Generalised crop-coefficient curve across the four growth stages.

7 ESTIMATIONS OF EVAPOTRANSPIRATION

7.1 Direct Methods

Lysimeter — a large tank holding an undisturbed soil monolith growing the crop, installed flush with the field so conditions match the surroundings. Its ***working principle*** is a water balance: **ET = (irrigation + rainfall) − drainage ± change in soil-water storage.** In a ***weighing lysimeter*** the storage change is got by weighing the tank; in a ***drainage (non-weighing) lysimeter*** it is got from measured percolate. It is the most direct measurement of ET.

- ***Soil-moisture depletion studies*** : sample moisture between irrigations; ET = moisture depleted over the period.
- ***Field experimental plots / water balance*** : ET from the field water balance over a season.

7.2 Climatological (Empirical) Methods

- ***Blaney–Criddle*** : temperature and % daytime hours; simple, seasonal.

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- ***Penman / Penman–Monteith (FAO-56)*** : combines an energy balance with an aerodynamic term; the ***most accurate*** and the FAO standard for ETo.
- ***Hargreaves, Thornthwaite*** : temperature-based; used where data are scarce.
- ***Pan evaporation*** : ETo = K_p·E_pan from a USWB Class-A pan; K_p ≈ 0.7–0.85.

Blaney–Criddle: $f = p\,(0.46\,T + 8.13)$ Pan: $ETo = K_p \cdot E_{pan}$

T = mean temp (°C); p = mean daily % of annual daytime hours; ETc = Kc·ETo

PREVIOUS YEAR QUESTIONS

- Enlist and discuss the principal methods for direct measurement of evapotranspiration. [IFoS 2021 · P1/6(b) · 15M]
- Explain the most popular method of estimating the evapotranspiration of crop and list out the others. [OPSC·CSE (Main) 2017–18 · Paper-I Q.3(a) · 15M]
- Explain the evapotranspiration estimation methods based on climatological approach and in-situ measurement. [OPSC·Forest (Main) 2023–24 · Paper-I Q.6(a) · 20M]
- How is evapotranspiration measured in field using lysimeter? [AP·PSC RFO (Mains) 2012 · Q.3(B) · 8M]
- Differentiate between: (i) Water requirement and Irrigation requirement (ii) Crop water use efficiency and Field water use efficiency (iii) Evaporation and Consumptive use. [IFoS 2017 · P1/5(a) · 8M]

LYSIMETER & USWB CLASS-A PAN



Fig. 7.1 Lysimeter (direct ET by water balance) and the USWB Class-A pan (ETo = K_p·E_pan).

8 DUTY, DELTA & BASE PERIOD

Term	Definition	Unit
Duty (D)	area irrigated by a continuous 1-cumec supply through the base period	ha/cumec
Delta (Δ)	total depth of water needed by the crop over the base period	cm (m)
Base period (B)	time between the first and last watering of the crop	days

8.1 Relationship Δ = 8.64 B / D (derivation)

◆ **WORKED NUMERICAL — Derivation of Δ = 8.64 B/D** [IFoS 2023 · P1/5(a) · 8M]

Problem. *Develop the relationship among delta, base period and duty of water.*

Volume supplied by 1 cumec in B days = $1\ m^3/s \times (B \times 24 \times 3600)\ s$ = **$86\,400\ B\ m^3$.**

This covers the duty area D ha = $D \times 10^4\ m^2$.

Depth Δ = Volume/Area = $86\,400\ B / (D \times 10^4)$ = **8.64 B/D metres,** i.e. Δ(cm) = 864 B/D.

8.2 Factors Affecting Duty & How to Improve It

- ***Factors*** : soil (permeable soils lower the duty), climate and rainfall (more rain raises it), base period (longer lowers it), crop (water-loving crops lower it), method of irrigation, and canal condition (seepage lowers it).
- ***Improving duty*** : line the canals (cut seepage), adopt rotational supply (Warabandi), use efficient irrigation methods, level the land, and reduce conveyance and field losses.

◆ **WORKED NUMERICAL — Area irrigable from a tank (three duty units)** [IFoS 2020 · P1/6(a) · 15M]

Problem. *A tank of water-spread 40 ha, average depth 3 m. Area of a 120-day paddy crop irrigable if the duty is (i) 960 ha per m³/s, (ii) 110 ha-cm, (iii) 90 ha per million m³.*

Total water = 40 × 300 = **12 000 ha-cm (= 1.2 × 10^6 m^3).**

(i) Δ = 8.64 × 120/960 = 1.08 m = 108 cm → 12 000/108 = **111 ha.**

(ii) Δ = 110 cm → 12000/110 = **109 ha.**

(iii) 90 × 1.2 = **108 ha.**

◆ **WORKED NUMERICAL — Delta of potato** [OPSC·CSE (Main) 2020–21 · P1 Q.4(b)(ii) · 12M]

Problem. *Base period 90 days; irrigation applied every 10 days, 5 cm each time. Find the delta.*

Number of waterings = base/interval = 90/10 = 9.

Δ = 9 × 5 = **45 cm.**

PREVIOUS YEAR QUESTIONS

What is meant by Duty and Delta of canal water? Derive the relationship between duty and delta for a given base period.

[OPSC·Forest (Main) 2015–16 · Paper-I Q.7(a) · 10M]

DUTY–DELTA–BASE PERIOD

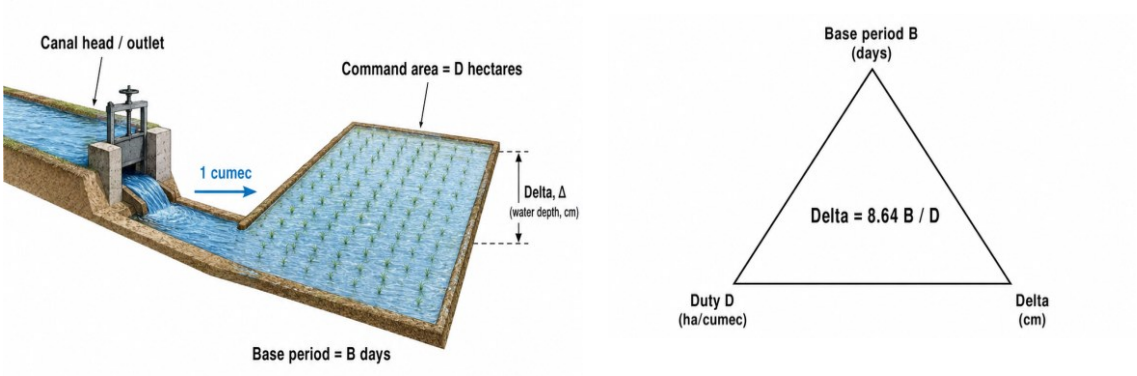


Fig. 8.1 The inverse duty–delta relationship for a fixed base period.

9 IRRIGATION EFFICIENCIES

Efficiencies track how much water survives each stage from source to crop; all are expressed as percentages.

Efficiency	Definition	Formula
Conveyance η_c	delivered to field / diverted at source	W_f / W_r
Application η_a	stored in root zone / delivered to field	W_s / W_f

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Storage η_s	stored in root zone / needed in root zone	W_s / W_n
Distribution η_d	uniformity of wetting down the root zone	1 − y/d
Water-use efficiency (WUE)	crop yield per unit water used	Y / WR
Field water-use efficiency	yield per unit water delivered to field	Y / W_f

Here y is the average numerical deviation of the stored depth from the mean depth d. ***Water productivity*** (crop per drop) generalises WUE to economic output per unit water.

RESERVOIR STORAGE VS WATER STORAGE EFFICIENCY (DISTINGUISH)

Basis	Reservoir storage efficiency	Water storage efficiency
What it compares	water stored in the reservoir / inflow	water stored in root zone / water needed
Losses reflected	reservoir evaporation, seepage, spill	under-irrigation of the root zone
Scale	reservoir	field / soil

◆ **WORKED NUMERICAL — Four irrigation efficiencies** [OPSC·CSE 2020–21 (cf. IFoS 2020) · 12M]

Problem. *Stream 135 L/s diverted, 100 L/s delivered to a 1.6 ha field, irrigated in 8 h. Root depth 1.8 m; runoff loss 432 m³; penetration varies 1.8 m (head) to 1.2 m (tail); available moisture 20 cm/m; started at 50% depletion. Find the four efficiencies.*

η_c = 100/135 × 100 = **74.1%.**

Delivered = 100 L/s × 8 h = 2880 m³. Deficit = 0.50 × 20 × 1.8 = 18 cm → need = 0.18 × 16000 = 2880 m³.

Infiltrated (stored) = 2880 − 432 = 2448 m³ (< 2880 → no deep percolation).

η_a = 2448/2880 = **85%;** η_s = 2448/2880 = **85%.**

Mean d = (1.8+1.2)/2 = 1.5 m; y = 0.15 m → η_d = (1 − 0.15/1.5)×100 = **90%.**

◆ **WORKED NUMERICAL — Water required with percolation loss** [IFoS 2022 · P1/7(a)(ii) · 5M]

Problem. *One hectare irrigated to a depth of 100 mm; percolation losses 30%. Water required?*

η_a = 70% → gross = 100/0.70 = 142.9 mm → V = 10000 × 0.1429 = **1428.6 m³.**

PREVIOUS YEAR QUESTIONS

- Describe the water conveyance efficiency, water application efficiency, water storage efficiency and water distribution efficiency.

  [IFoS 2022 · P1/7(a)(i) · 10M]

- Distinguish between reservoir storage efficiency and water storage efficiency.

  [IFoS 2023 · P1/5(b) · 8M]

- Explain various forms/types of irrigation efficiency including water use efficiency and relate it with water productivity.

  [OPSC·CSE (Main) 2017–18 · Paper-I Q.2(b) · 15M]

WATER LOSSES FROM SOURCE TO ROOT ZONE

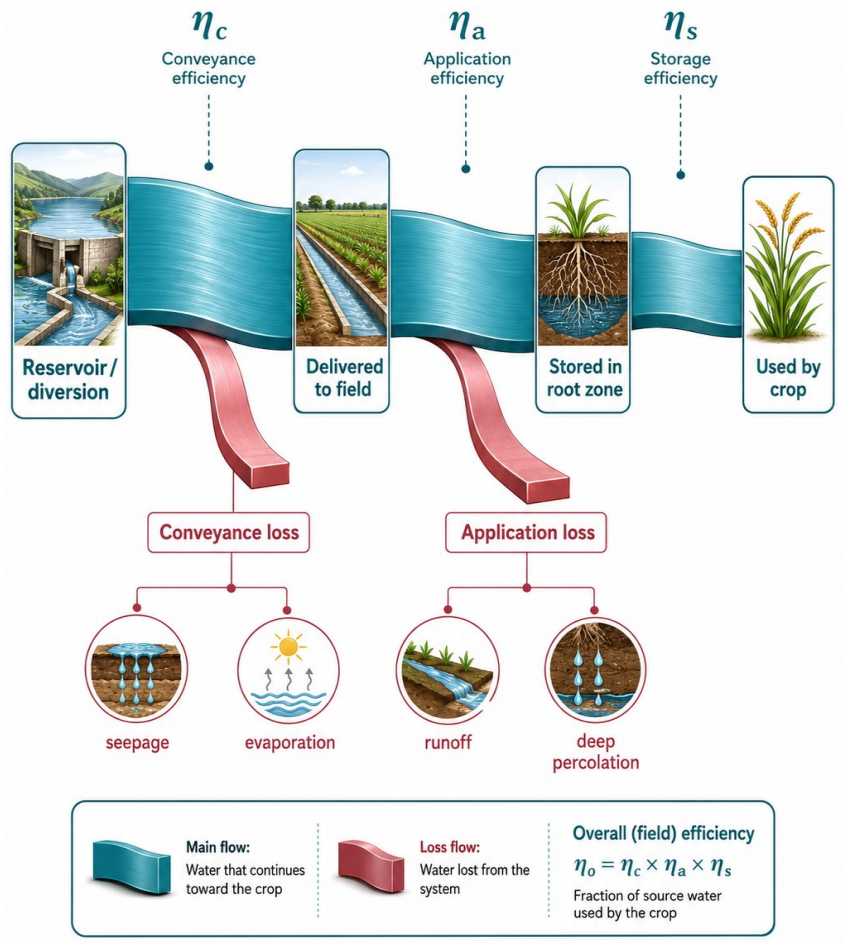


Fig. 9.1 Cascade of conveyance, application and storage losses.

10 IRRIGATION SCHEDULING

Scheduling decides ***when*** and ***how much*** to irrigate so the crop never suffers stress nor wastes water. Three approaches:

- ***Soil-moisture depletion (MAD)*** : irrigate when a set ***management-allowed deficit*** of available water is used, then refill to field capacity — the classic field method.
- ***Climatological (IW : CPE)*** : apply a fixed depth of irrigation water (IW) whenever cumulative pan evaporation (CPE) reaches a chosen value; the ***IW/CPE ratio*** (≈ 0.75–1.0) fixes timing from weather data.
- ***Plant indicators*** : canopy–air temperature, leaf water potential, or visible stress symptoms signal the need to irrigate.

HOW MUCH & WHEN — FACTORS

How much = net depth $d_n = A_s \cdot D \cdot (FC - MC)$ (refill to FC); when = ***interval = d_n / peak daily ET***. Consider soil water-holding capacity and root depth, crop growth stage and sensitivity, climatic demand (ET), water availability and delivery schedule. ***Example***: if available water in the root zone is 8 cm and peak ET is 0.5 cm/day, irrigate every 16 days, applying 8 cm net.

Net depth $d_n = A_s \cdot D \cdot (FC - MC)$ Interval = d_n /(peak daily ET)
gross depth = d_n/η_a ; system capacity sized to the peak-use period

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◆ **WORKED NUMERICAL — System capacity & irrigation period** [IFoS 2023 · P1/6(a) · 20M]

Problem. *25 ha, pump working 10 h/day; available moisture 16 cm/m; root depth 1 m; irrigate at 50% depletion; application efficiency 75%; peak crop use 5 mm/day; conveyance losses negligible. Find the irrigation period, net depth, depth pumped per application, and capacity in ha-cm/day and L/s.*

Available moisture = 16 × 1 = 16 cm; allowable depletion = 50% = 8 cm = net depth.

Irrigation period = 8/0.5 = **16 days.** **Net depth = 8 cm.**

Depth pumped (gross) = 8/0.75 = **10.67 cm.**

Gross daily need = 25 × 0.5 ÷ 0.75 = **16.67 ha-cm/day** = 1667 m^3/day in 10 h → Q = 1667/36000 = **46.3 L/s.**

PREVIOUS YEAR QUESTIONS

- Explain the different approaches for irrigation scheduling. [IFoS 2022 · P1/6(a) · 15M]
- Irrigation scheduling involves determining 'when to irrigate' and 'how much to irrigate'. Explain the factors to be considered in developing an irrigation schedule, with an example. [IFoS 2018 · P1/7(d) · 10M]
- What do you mean by irrigation scheduling? What are the various basis for scheduling irrigation? [OPSC·CSE (Main) 2023–24 · Paper-I Q.8(a) · 15M]

SOIL-MOISTURE DEPLETION (SAW-TOOTH)

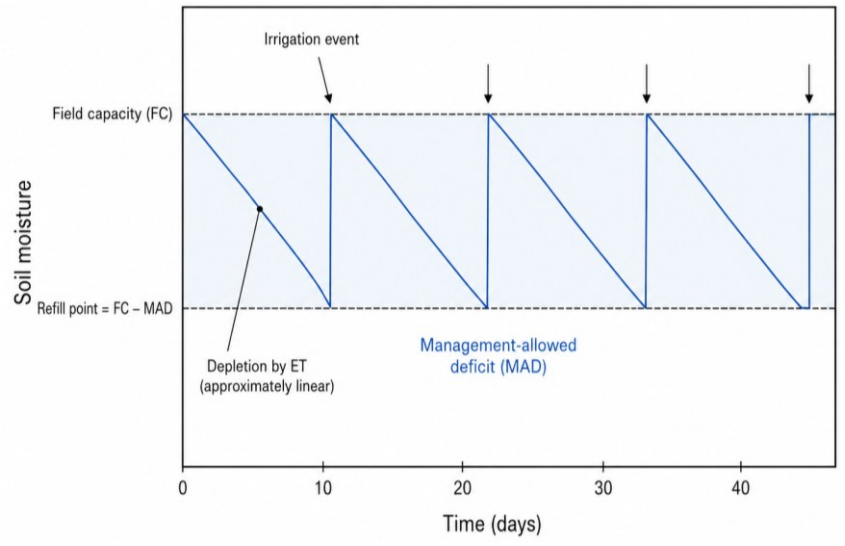


Fig. 10 Saw-tooth soil-moisture depletion between field capacity and the refill point.

11 SOURCES OF IRRIGATION & MINOR-IRRIGATION PLANNING

India irrigates from ***canals*** (major & medium), ***tanks***, and ***wells & tube-wells*** — now the ***largest source (~60%+)*** — plus lift and micro-irrigation. ***Minor-irrigation*** projects have a culturable command area up to 2000 ha (ground-water and small surface schemes).

FACTORS IN PLANNING A MINOR-IRRIGATION PROJECT

- water availability (surface + ground) and demand, command-area soils and topography, crop pattern and water requirement, conveyance and application method, cost–benefit and financial viability, environmental and social impact, and equity of distribution.

ECONOMIC VS FINANCIAL FEASIBILITY (DISTINGUISH)

Basis	Economic feasibility	Financial feasibility
Viewpoint	society / nation	the project or owner
Prices used	economic (shadow) prices	market prices
Test	benefit–cost ratio, national worth	cost recovery, repayment capacity
Benefits counted	direct + indirect / social	cash inflows only

ENVIRONMENTAL IMPACTS OF IRRIGATION

- ***Positive*** : higher, stabilised production; drought-proofing; groundwater recharge; greening and micro-climate improvement.
- ***Negative*** : waterlogging and a rising water table, secondary salinity/alkalinity, water-quality decline and eutrophication, and water-related health hazards — so drainage, lining and conjunctive use are given priority in irrigated commands.

PREVIOUS YEAR QUESTIONS

- E What are the different sources of irrigation in India? List the factors influencing planning and development of minor irrigation projects. What are the positive and negative impacts of irrigation on the ecosystem and environment? [IFoS 2018 · P1/5(a) · 8M]
- Discuss the important factors affecting planning and design of minor irrigation projects. [IFoS 2025 · P1/5(a) · 8M]
- Distinguish between economic feasibility and financial feasibility of irrigation systems. [IFoS 2022 · P1/7(c) · 10M]

SOURCES OF IRRIGATION IN INDIA

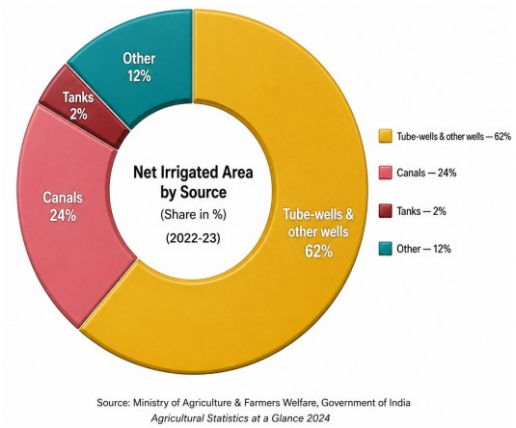


Fig. 11.1 Approximate share of net irrigated area by source

12 CONJUNCTIVE USE & WARABANDI

12.1 Conjunctive Use of Surface & Groundwater

Conjunctive use *— the planned, coordinated use of surface water and groundwater in a command so that the total yield and reliability exceed those of either source used alone.*

In a canal command, canal (surface) water is used mainly in the wet season while tube-wells draw the groundwater recharged by canal seepage and irrigation in the dry season — using the aquifer as a natural, loss-free storage and keeping the water table within a safe band. This makes it ***vital to integrated water-resource development***: it raises supply reliability, buffers drought, controls waterlogging and salinity, and improves basin-wide efficiency.

- ***Benefits*** : higher and more reliable supply, water-table control (checks waterlogging & salinity), drought buffering, reduced evaporation loss (aquifer storage), and better overall efficiency.
- ***Limitations*** : needs reliable data, monitoring and institutional control; risk of groundwater over-draft and quality deterioration if unmanaged; higher pumping cost.

12.2 Warabandi

Warabandi is a ***rotational water-supply*** system in which each cultivator receives the ***full discharge of the outlet*** for a fixed turn, its length proportional to landholding, on a ***7-day rotation*** running head to tail. It is designed for ***equity*** and high conveyance efficiency in water-short commands. Forms: ***kachcha*** (informal, farmer-arranged) and ***pakka*** (official, sanctioned roster).

PREVIOUS YEAR QUESTIONS

- How is conjunctive use of surface and groundwater vital in the integrated water resource development? [IFoS 2022 · P1/6(b) · 15M]
- Explain the concept of conjunctive use of surface and groundwater in canal command areas. What are the advantages and limitations of conjunctive use? [IFoS 2018 · P1/6(a) · 10M]
- Write short notes on: Warabandi system of water allocation. [IFoS 2025 · P1/6(c)(i) · part of 10M]

CONJUNCTIVE USE & WARABANDI

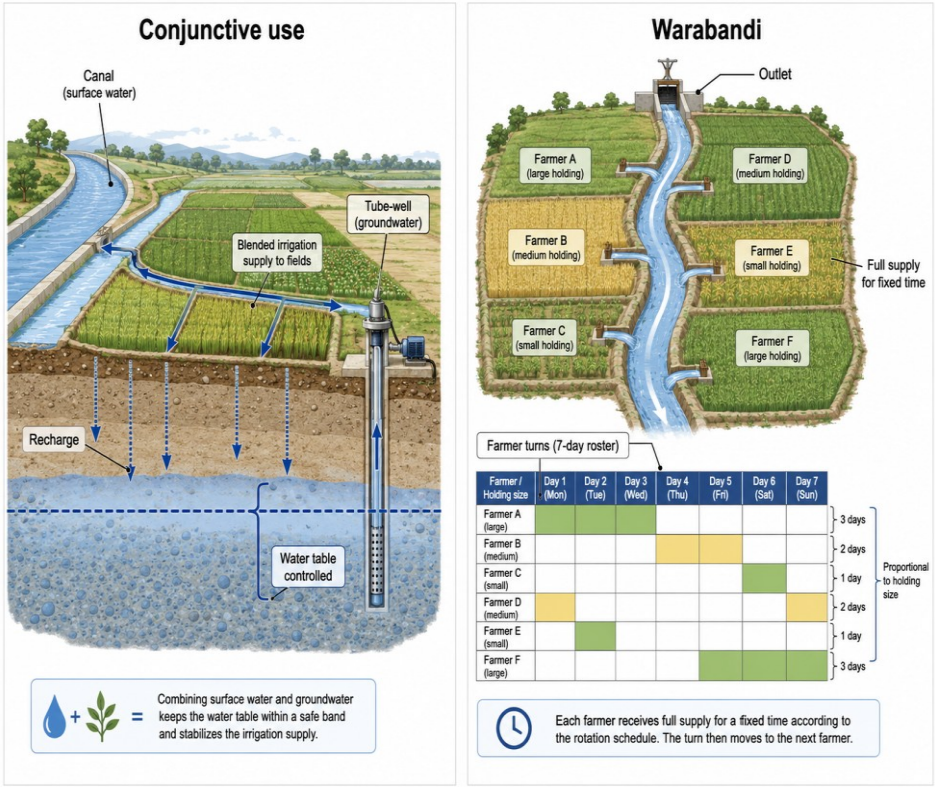


Fig. 12.1 Conjunctive use (left) and the Warabandi rotational roster (right).

FORMULA SHEET — CHAPTER 1

Quantity	Formula
Total soil-water potential	$\Psi t = \Psi g + \Psi m + \Psi p + \Psi o$
pF scale	$pF = \log_{10}(h)$, h in cm water
Net / available water depth	$d = A_s \cdot D \cdot (FC - MC)$; $AW = A_s \cdot D \cdot (FC - PWP)$

Gravimetric / volumetric	θ_m = M_w/M_d; θ_v = θ_m·ρ_b; d = θ_v·D
Darcy's law	q = −K(dH/dx); Q = K i A
Infiltration (Horton)	$f = f_c + (f_o - f_c)\, e^{(-kt)}$
Crop ET / requirement chain	ETc = Kc·ETo; CIR = ETc − R_e; GIR = NIR/(η_a·η_c)
Delta–duty–base period	Δ(m) = 8.64 B/D; Δ(cm) = 864 B/D
Efficiencies	η_c=W_f/W_r; η_a=W_s/W_f; η_s=W_s/W_n; η_d=1−y/d
Gross depth / interval	d_gross = d_n/η_a; interval = d_n/peak ET
Blaney–Criddle / pan	f = p(0.46T+8.13); ETo = K_p·E_pan

SUMMARY

- Soil is a three-phase system; water moves through the SPAC from high to low potential.
- Soil water = gravitational (drains), capillary (available, FC→PWP), hygroscopic (held); Ψt = Ψg+Ψm+Ψp+Ψo.
- The retention curve (developed on a pressure plate) links θ to suction; FC (⅓ bar) and PWP (15 bar) bound available water.
- Constants & coefficients: FC, PWP, moisture equivalent, hygroscopic coeff.; max available water = A_s·D·(FC−PWP).
- Darcy's law governs saturated flow; infiltration decays to a basic rate (Horton/Kostiakov).
- Measure moisture by gravimetric (standard) or indirect (tensiometer, neutron, pressure plate, TDR) methods.
- Crop water requirement met by ET; ETc = Kc·ETo; requirement chain CIR→NIR→FIR→GIR.
- Estimate ET directly (lysimeter) or climatologically (Penman-Monteith best; Blaney–Criddle, pan).
- Δ = 8.64 B/D links delta, base period and duty; duty improved by lining and rotational supply.
- Four efficiencies — conveyance, application, storage, distribution — track losses; WUE = yield/water.
- Schedule by MAD, IW:CPE or plant indicators; refill to FC, interval = net depth/peak ET.
- Conjunctive use and Warabandi raise reliability and equity of supply.

LAST-NIGHT REVISION

Must-remember	Value / formula
Forms of soil water	gravitational / capillary (available) / hygroscopic
FC / PWP / hygroscopic tension	⅓ bar / 15 bar / 31 bar
Available / readily available	FC − PWP; RAW ≈ 75%
Soil-water potential	Ψt = Ψg + Ψm + Ψp + Ψo (flow high→low)
Oven-dry	105 °C for 24 h
Depth of irrigation	d = A_s · D · (FC − MC)
Delta–duty	Δ(cm) = 864 B/D; 1 ha-cm = 100 m³
Efficiencies	η_c=W_f/W_r, η_a=W_s/W_f, η_s=W_s/W_n, η_d=1−y/d
ETc / pan	ETc = Kc·ETo; ETo = K_p·E_pan
Extraction pattern	40 : 30 : 20 : 10 down the root zone
IW : CPE	≈ 0.75–1.0 for scheduling

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CHAPTER

2

SURFACE, SPRINKLER & DRIP IRRIGATION METHODS

Border · Check-basin · Furrow · Sprinkler types & design · Drip components & fertigation · Filtration

SYLLABUS: Surface irrigation methods — border (straight & contour), check basin, basin, furrow (level / graded / contour), wild flooding, corrugation. Hydraulic phases of surface irrigation (advance, ponding, depletion, recession) and infiltration opportunity time. Sprinkler irrigation — types based on portability (portable, semi-portable, solid-set, side-roll, centre-pivot, rain-gun), system components and layout, hydraulic design principles, design steps with formulas, uniformity measures, adaptability and limitations. Drip / micro-irrigation — types (surface drip, sub-surface drip, bubbler, micro-sprinkler), components (mainline, submain, lateral, emitter, dripper), design steps. Fertigation — methods of fertilizer injection and location of fertigation units. Filtration systems — sand-media, screen, hydrocyclone and disc filters.

Chapter Outline

1. **Scope & Classification of Irrigation Methods**
2. **Hydraulic Phases of Surface Irrigation & Infiltration Opportunity Time**
3. **Border Irrigation — Design, Hydraulics & Adaptability**
4. **Check-Basin, Basin & Ring-Basin Methods**
5. **Furrow Irrigation, Wild Flooding & Corrugation**
6. **Sprinkler Irrigation — Concept, Adaptability & Limitations**
7. **Types of Sprinkler Systems (Portability, Rain Guns)**
8. **Sprinkler Components & Field Layout**
9. **Sprinkler Hydraulic Design & Design Steps**
10. **Sprinkler Uniformity & Field Evaluation**
11. **Drip / Micro-Irrigation — Concept, Types, Adaptability**
12. **Drip Components, Design Steps & Layout Precautions**
13. **Fertigation — Methods & Location of Injection**
14. **Filtration Systems in Micro-Irrigation**

MIND-MAP — Chapter 2 concept map

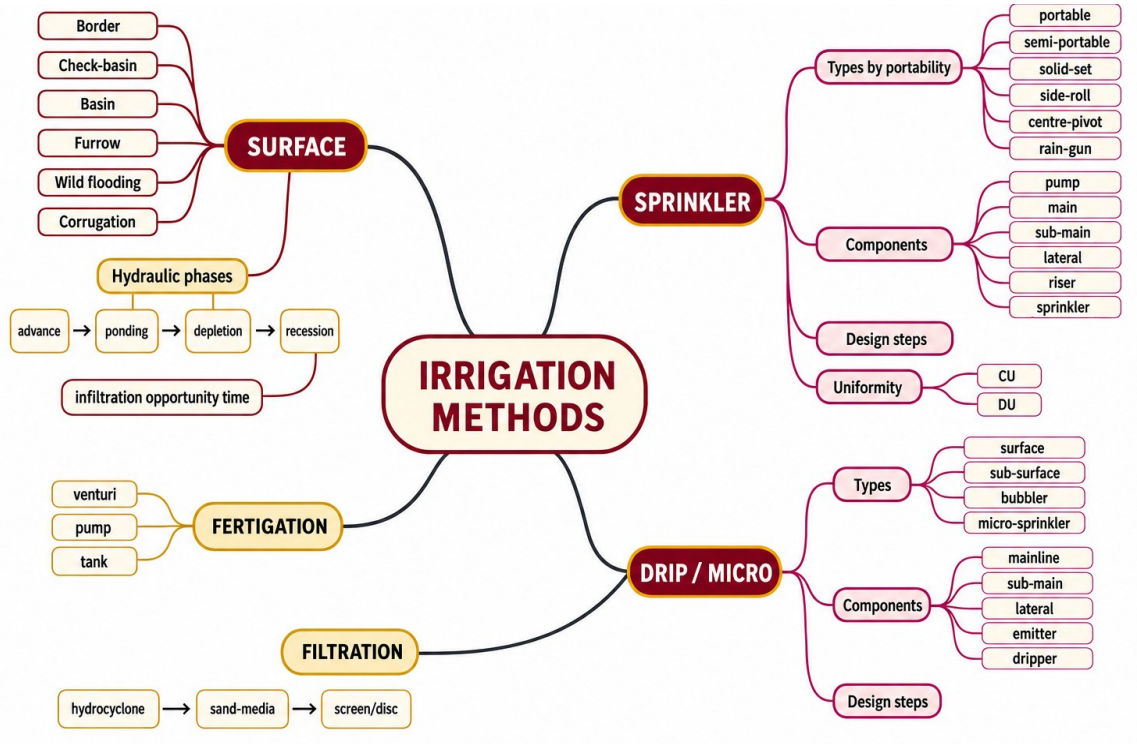


Fig. 2.0 — Chapter 2 concept map linking surface, sprinkler and drip irrigation with hydraulics, components, design steps, uniformity and filtration.

1 SCOPE & CLASSIFICATION OF IRRIGATION METHODS

Irrigation methods are the ways in which water — once conveyed from source to field — is ***distributed over the crop root zone***. The choice among them shapes water and energy consumption, land preparation, labour, capital cost, uniformity of application and, ultimately, yield. Chapter 2 covers the three families that dominate Indian practice — ***surface, sprinkler and drip (micro) irrigation*** — and the associated ***hydraulic principles, design steps, components, uniformity, adaptability and limitations***, along with fertigation and filtration that go with pressurised systems.

A working classification: ***surface*** — water flows in thin sheets or streams over the field under gravity (border, check-basin, basin, furrow, wild flooding, corrugation); ***sub-surface*** — water is applied below the soil surface through mole drains, tile lines or a controlled water table; ***pressurised overhead*** — water is broken into droplets in air (sprinkler, rain-gun, micro-sprinkler); and ***pressurised localised*** — water is dripped at low discharge on or below the soil surface (surface drip, sub-surface drip, bubbler).

FACTORS GOVERNING CHOICE OF METHOD

- ***Water availability & cost*** : scarce water → drip > sprinkler > surface; abundant but cheap → surface still viable.
- ***Topography & land slope*** : flat land (< 1 %) → basin/border; rolling/undulating → sprinkler; steep or terraced → drip.
- ***Soil texture & intake rate*** : light soils with high intake → sprinkler/drip; medium loams → any; heavy clays with low intake → check-basin, border.
- ***Crop type & spacing*** : close-growing (wheat, rice, fodders) → surface/sprinkler; widely-spaced row & orchard → drip; tall/dense → surface (sprinkler distorted).

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- ***Climate*** : high wind & evaporative demand → drip (least loss); calm humid conditions → sprinkler acceptable; saline water → drip (leaching + low salt on foliage).
- ***Water quality*** : suspended sediment, salinity, biological load → filtration/fertigation needed for micro-systems; brackish → drip preferred.
- ***Capital, labour & energy*** : surface — low capital, high labour, low energy; sprinkler — moderate capital & energy, low labour; drip — highest capital, lowest labour & energy per unit water.

2 HYDRAULIC PHASES OF SURFACE IRRIGATION & INFILTRATION OPPORTUNITY TIME

In every surface method the applied water passes through four distinct hydraulic phases from the time it is turned on to the time the soil surface is again dry. Understanding them explains why deep-percolation, run-off and distribution-uniformity losses arise, and drives the design of stream size, run length and cut-off timing.

THE FOUR PHASES

- ***Advance phase*** : water is turned on and the wetting front moves down-slope from the head to the tail end; the ***advance time t_a*** ends when the leading edge reaches the tail.
- ***Ponding (wetting / storage) phase*** : after advance is complete, water continues to be supplied and stands over the entire strip; the whole surface receives water simultaneously; ends when inflow is cut off (***cut-off time t_co***).
- ***Depletion phase*** : inflow has stopped but a positive water depth still exists on the surface, which continues to infiltrate; ends when the depth of water at the head becomes zero — the ***depletion time t_d***.
- ***Recession phase*** : water starts disappearing from the field, first at the head, later at the tail; the recession front travels down the strip; ends when the ***recession time t_r*** — no water is left anywhere on the surface.

Infiltration opportunity time (IOT / τ) — the length of time for which water stands on any point of the soil surface — the difference between the recession-curve time and the advance-curve time at that point. It ***directly controls the depth of water infiltrated*** (through the Kostiakov/Horton relation), and so determines the depth of application at every station along the run.

Four-phase surface-irrigation time–distance diagram (advance, ponding, depletion, recession + IOT)

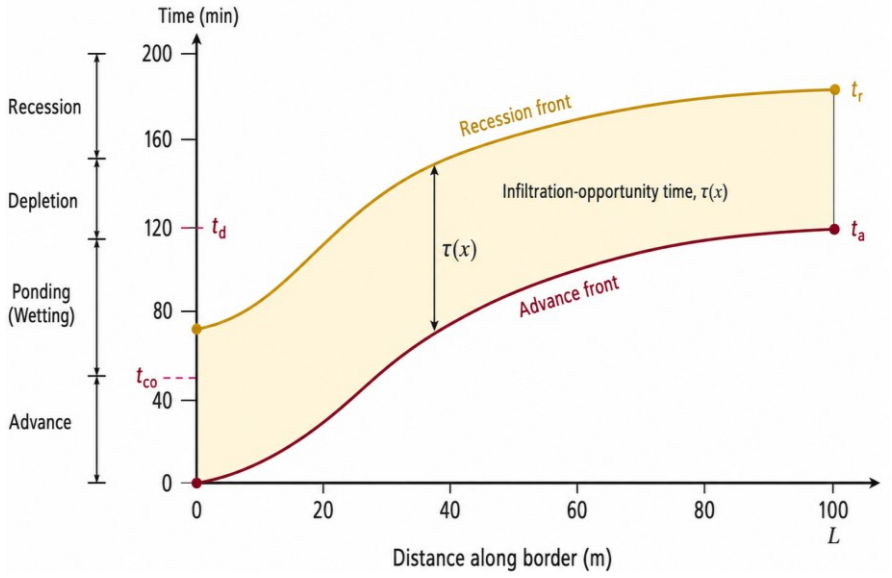


Fig. 2.1 — Time-distance diagram of the four hydraulic phases of surface irrigation with the infiltration opportunity time τ(x).

WHY THE IOT MATTERS

Because the infiltration rate is fastest at the beginning and decays with time, ***the head of the strip — where water stands longest — takes in more depth than the tail***. Design ***aims to make τ(x) as uniform as possible along the length***, so that the depth infiltrated matches the required net depth d_n at every point. This is achieved by ***choosing the right stream size, run length and cut-off time*** — the three design decisions of surface irrigation.

PREVIOUS YEAR QUESTIONS

- Discuss the important hydraulic phenomenon involved in border irrigation method.

  [IFoS 2020 · P1/5(e) · 8M]

- Describe the four phases of surface irrigation process with the help of a line diagram. Define and show the infiltration opportunity time in the diagram. Why is infiltration opportunity time important? In an 80 m long and 5 m wide border, a stream of 8 lps was delivered from the upper end to irrigate a wheat crop. The stream was cut off as soon as it reached the lower end of the border in 70 min. Layer-wise soil moisture contents before irrigation and at field capacity are given. Determine the application efficiency, if the root-zone depth is 90 cm and apparent specific gravity of soil is 1.4.

  [OPSC·CSE 2024–25 · P1/Q.15 · 20M]

MODEL Q Structure: (i) four-phase definitions in one line each; (ii) neat t–x plot showing advance & recession curves + shade the τ-band; (iii) explain τ = t_r(x) − t_a(x), and why non-uniform τ produces non-uniform depth; (iv) present the border-plot numerical (see Worked N-5 in §3): applied volume vs stored volume → η_app.***

3 BORDER IRRIGATION — DESIGN, HYDRAULICS & ADAPTABILITY

Border irrigation applies water as a ***moving sheet*** down long, narrow rectangular strips separated by low earthen ridges. It is the workhorse method for ***close-growing crops*** (wheat, gram, groundnut, berseem, alfalfa, pulses, small grains) on ***uniform, mildly-sloping land***.

3.1 Types of Border

- ***Straight border*** : longitudinal slope 0.1–0.5 %; the ridges run down-slope; used on level to gently-sloping land.
- ***Contour border*** : ridges follow the contour, so the border slopes down-strip but with negligible cross-slope; used on undulating land where straight borders would over-shoot.
- ***Graded border*** : uniformly sloped from head to tail; the standard case on most farm layouts.
- ***Level (dead-level) border*** : no longitudinal slope; the whole strip fills up like a shallow basin; suits heavy soils, high water tables and paddy-rice lands.

3.2 Recommended Design Parameters

Item	Typical value	Remarks
Longitudinal slope	0.1 – 0.5 % (up to 2 % on light soils, ≤ 4 % on grass)	Slope must be uniform; excessive slope causes erosion & poor uniformity
Cross slope	≈ 0 (level across width)	Prevents cross-flow and dry patches
Strip width	3 – 15 m (commonly 5 – 12 m)	Wider on flat land / heavy soil; narrower on undulating land
Strip length	60 – 300 m (heavy soil: 60–120 m; light: 90–150 m; medium: 90–250 m)	Longer strips on heavy soils; limit by stream size & intake rate

Stream size (unit inflow)	4 – 12 L/s per metre width	Depends on soil intake, slope, roughness
Ridge height	15 – 20 cm above design flow depth	To prevent overtopping
Flow depth	6 – 8 cm at head	Enough to travel down-slope without excessive velocity

3.3 Hydraulic Phenomena in Border Irrigation

Border hydraulics is a special case of the four-phase model of §2. Once inflow starts, the stream builds a wedge-shaped profile whose leading edge is the advance front. During advance, both surface flow and infiltration co-exist; the surface storage grows and the infiltration front recedes into the soil. When the stream is cut off — usually ***when the wetting front reaches 75–85 % of the run length (the 'cut-off ratio')*** — the wedge continues to move by 'surface recession' and the residual water finishes infiltrating during the depletion and recession phases.

GOVERNING EQUATIONS & CONTROLS

- ***Continuity*** : Q_in − Q_out = dV_s/dt + dV_i/dt, where V_s = surface storage and V_i = cumulative infiltration.
- ***Momentum*** : Saint-Venant equations reduce, in kinematic-wave form, to the Manning relation q = (1/n) $R^{\{2/3\}}$ $S^{\{1/2\}}$ × y, controlling advance speed.
- ***Design triple*** : stream size q, run length L and cut-off time t_co are chosen so that τ(x) at every point equals the τ required to infiltrate d_n.

$$L_{opt} \approx Q \cdot t / (d_n \cdot W) \times \eta_{app}$$

Simplified guide: for uniform advance, choose L so that the volume required to infiltrate d_n over W matches the supply Q for the design cut-off time t.

$$t = A \cdot d / (Q \cdot \eta_c)$$

Time to apply a net depth d over an area A with a source discharge Q and conveyance efficiency η_c; used in the border numerical below.

3.4 Adaptability & Limitations

Adaptability	Limitations
Close-growing crops (wheat, alfalfa, small grains, pastures, berseem).	Not for row crops of high value where flooding damages the crown.
Uniform, mildly-sloping land (0.1–0.5 %).	Steep or undulating land requires re-levelling → high land-preparation cost.
Medium- to heavy-textured soils with moderate intake.	Very light sandy soils — high deep percolation at the head; very heavy soils — long τ needed, low advance speed.
Large stream sizes available (≥ 30 L/s).	Small streams unable to cover wide strips → uneven advance & poor uniformity.
Suitable where labour is limited (little in-field handling).	Requires accurate land grading; poor grading causes waterlogging & runoff losses.

Border layout — plan & cross-section

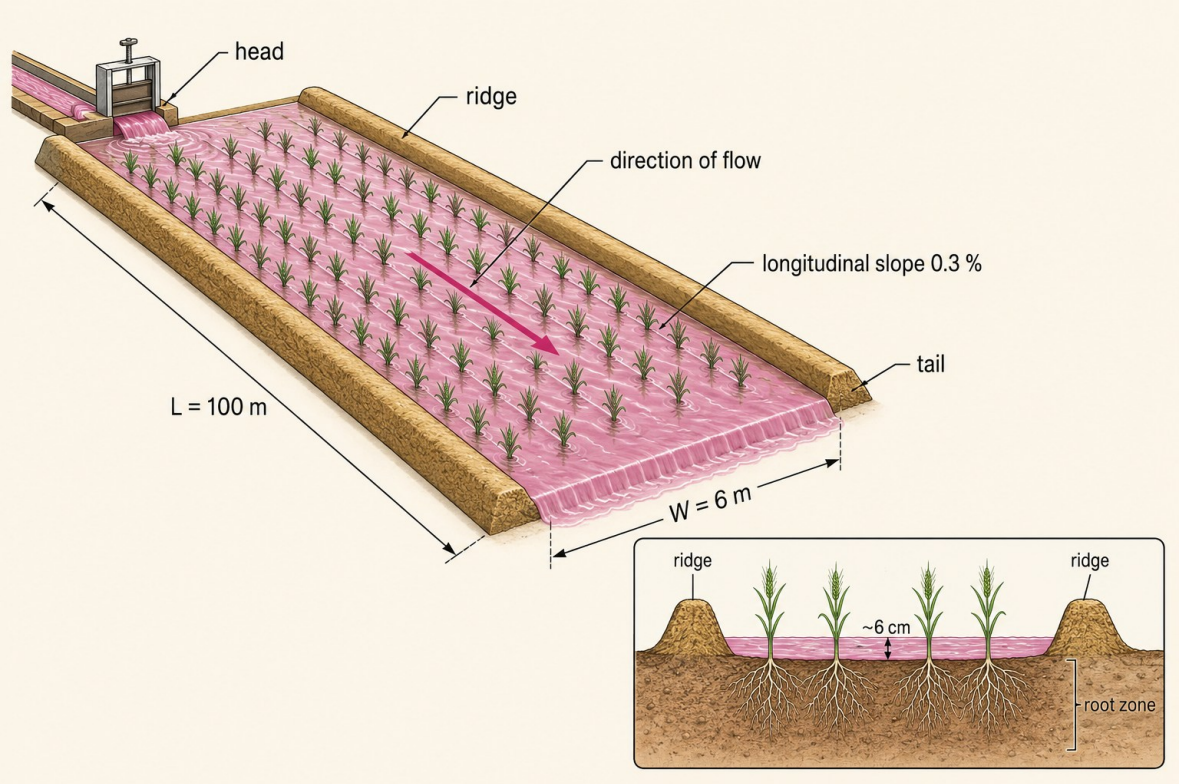


Fig. 2.2 — Basic border layout with inflow at the head, low earthen ridges, uniform longitudinal slope and a typical cross-section.

PREVIOUS YEAR QUESTIONS

- Discuss the basic details of border method of irrigation with a neat sketch. [IFoS 2021 · P1/5(a) · 8M]
- Describe in brief the hydraulics of Border irrigation. [UK·PSC RFO (Mains) 2015 · Q.4(ii) · 10M]
- Describe design parameters of border irrigation. What is the area commanded by a field setting a continuous supply of 0.60 m^3/s of water from a canal (use given data on strip length, unit inflow and application depth)?

[MH·PSC Forest Services (Mains) 2024 · Q.2(c) · 10M]

◆ **WORKED NUMERICAL — *Time to irrigate a border strip*** [IFoS 2021 · P1/7(b) · 10M]

Problem. *Estimate the time, in hours, required to give a 4 cm irrigation to a border strip 100 m long and 6 m wide with a discharge of 12 litres per second from a tube-well. Water conveyance efficiency = 72 %.*

Given. d = 4 cm = 0.04 m; L = 100 m; W = 6 m; Q_source = 12 L/s = 0.012 m^3/s; η_c = 0.72.

Find. t = time to apply the depth d at the field (hours).

Formula (from first principles). The volume required in the field $V_f = A \times d$. The source must supply $V_s = V_f / \eta_c$ because only fraction η_c reaches the field. Time $t = V_s / Q_{source}$.

Step 1 Field area. $A = L \times W = 100 \times 6 = 600\ m^2$.

Step 2 Volume required in the field. $V_f = A \times d = 600 \times 0.04 =$ **24.0 m^3**.

Step 3 Volume to be released at the source. $V_s = V_f / \eta_c = 24.0 / 0.72 = 33.33\ m^3$.

Step 4 Time of application. $t = V_s / Q_{source} = 33.33 / 0.012 = 2\,777.8$ s = 46.30 min.

Result. t = 46.30 min = 0.772 hr (≈ 46 min 18 s).

Unit check. $[m^3] / [m^3/s] = [s]$ ✓; conversion to min & hr verified.

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◆ **WORKED NUMERICAL — *Application efficiency of a border strip*** **[OPSC·CSE 2024–25 · P1/Q.15 · 20M]**

Problem. *In an 80 m long and 5 m wide border, a stream of 8 L/s was delivered from the upper end to irrigate a wheat crop. The stream was cut off as soon as it reached the lower end of the border in 70 min. Root-zone depth = 90 cm, apparent specific gravity = 1.4. Assume representative layer-wise moisture data (three 30-cm layers with initial moisture 18, 20, 22 % and field capacity 25 % throughout). Determine the application efficiency.*

Given. L=80 m; W=5 m; Q=8 L/s=0.008 m^3/s; t_co=70 min=4200 s; D=0.90 m; ρ_b=1.4; layers as above.

Find. Application efficiency η_app = (water stored in root zone) / (water applied) × 100.

Formula. d_stored (mm) = Σ (MC_f − MC_i)/100 × ρ_b × depth_layer (m) × 1000.

V_stored = d_stored × A. V_applied
= Q × t_co. η_app
= V_stored / V_applied.

Step 1 Water applied. V_applied = 0.008 × 4200 = 33.6 m^3.

Step 2 Depth stored per layer. L1: (25−18)/100 × 1.4 × 0.30 × 1000 = 29.4 mm; L2: (25−20)/100 × 1.4 × 0.30 × 1000 = 21.0 mm; L3: (25−22)/100 × 1.4 × 0.30 × 1000 = 12.6 mm. Total d_stored = 63.0 mm.

Step 3 Volume stored. A = 80 × 5 = 400 m^2; V_stored = 0.063 × 400 = 25.2 m^3.

Step 4 Efficiency. η_app = 25.2 / 33.6 × 100 = **75.0 %**.

Result. Application efficiency ≈ 75 % — a reasonable value for a properly-designed border.

Note. If the actual layer data in the PYQ differ, apply the same procedure with the given MC values. The excess ≈ 8.4 m^3 is lost to deep percolation + run-off.

4 CHECK-BASIN, BASIN & RING-BASIN METHODS

These methods hold water within enclosed plots until it soaks in. They are the ***simplest and oldest surface methods*** and remain the most common on smallholder farms.

4.1 Check-Basin Method

A ***rectangular level plot*** (5 × 5 m up to 30 × 30 m) is bounded by low earthen ridges 15–30 cm high. Water is admitted through a small opening in one ridge, spreads over the level surface and infiltrates. Suited to ***close-growing crops*** (wheat, gram, pulses) and to ***orchards under tree canopies*** (one basin per tree or one basin covering a small block).

4.2 Basin (Level-Basin) & Ring-Basin

- ***Basin (paddy) method*** : large level plots (up to 0.5 ha), bounded by bunds; the standard for transplanted rice, jute, some fodders; keeps water standing for days.
- ***Ring basin*** : a circular ridge around a single tree; used in orchards on rolling terrain where a rectangular basin is impractical.

DESIGN VALUES FOR CHECK-BASIN/BASIN

Parameter	Typical range
Basin size	4 × 4 m (light soil) to 30 × 30 m (heavy soil); orchards: 1 tree/basin
Ridge height	15–30 cm
Land slope	≤ 0.5 % (must be near-level after grading)
Stream size	≥ 2 L/s per m^2 of basin area for quick filling
Depth of water	5–15 cm
Application efficiency	60–80 % (well-designed), lower otherwise

4.3 Limitations of the Check-Basin Method (frequent PYQ)

- ***Land-preparation cost*** : plots must be near-level → costly grading and levelling, which reduces the topsoil depth at the higher end.
- ***Bunds waste land*** : earthen ridges occupy 3–5 % of the cultivated area; they also interfere with tillage and mechanised operations.
- ***High deep-percolation losses*** : water stands for a long time, so light soils suffer excessive deep percolation and nutrient leaching.
- ***Not suited to row crops of high value*** : root crops (potato, sugar-beet) and vegetables suffer from waterlogging around the crown.
- ***Requires large stream sizes*** : a small stream cannot flood a big basin quickly enough → non-uniform application; small streams need small basins → labour-intensive.
- ***Not on undulating land*** : steep or rolling topography → excessive levelling; often uneconomic.
- ***Poor drainage*** : standing water for days is unsuitable for crops sensitive to O_2 deficit.
- ***Salinity build-up*** : in dry regions, repeated flooding + shallow water table → salt accumulation at the surface after evaporation.
- ***Poor uniformity in large basins*** : infiltration opportunity time non-uniform; head area receives more depth than tail area.
- ***Mechanisation constraint*** : bunds break under tractors; harvesting equipment cannot cross basins easily.

PREVIOUS YEAR QUESTIONS

What are the limitations in the adoptability of check basin method? [IFoS 2023 · P1/5(c) · 8M]

Check-basin & ring-basin plan layouts

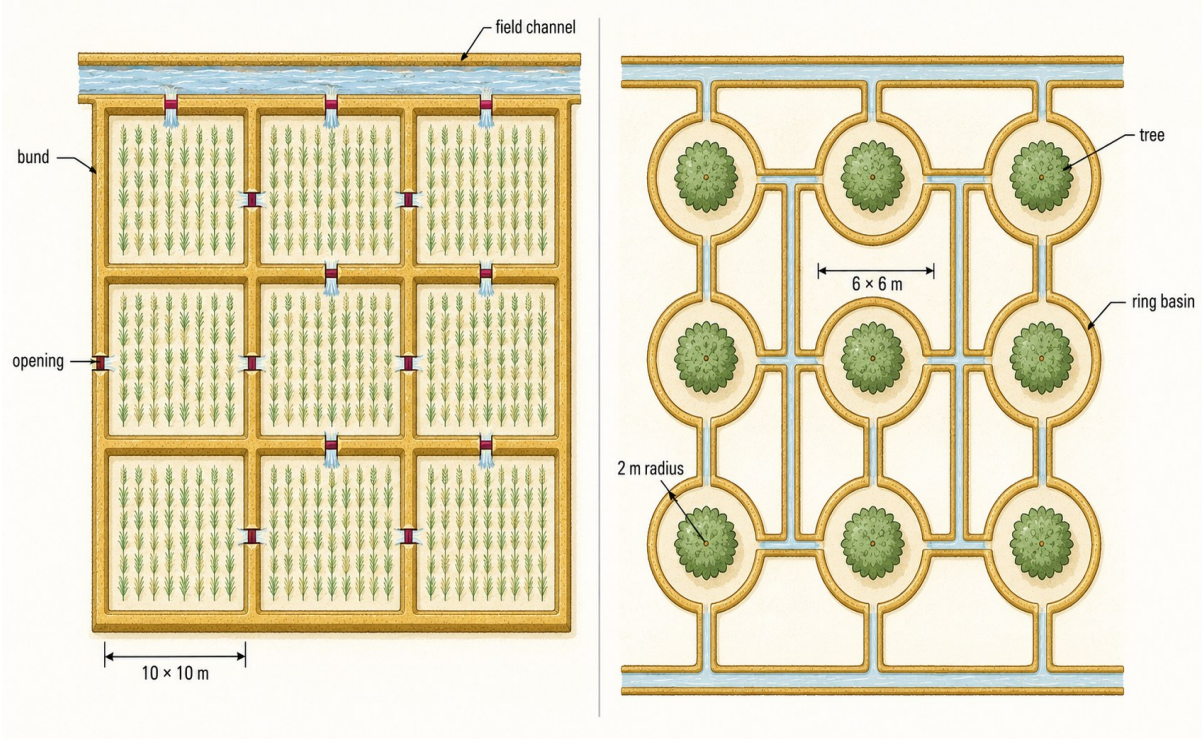


Fig. 2.3 — Check-basin plan for close-growing crops and ring-basin arrangement for orchard trees.

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5 FURROW IRRIGATION, WILD FLOODING & CORRUGATION

5.1 Furrow Irrigation

Furrow irrigation runs water in small parallel channels between crop rows — the crop is ***grown on ridges, water flows in furrows*** — so only 30–50 % of the surface is wetted. It is the standard for ***wide-spaced row crops*** (maize, cotton, sugar-cane, potato, tomato, sunflower, tobacco).

TYPES OF FURROW

- ***Level furrow*** : no slope; water pooled from head; suited to heavy soils, high water tables.
- ***Graded (straight) furrow*** : uniform slope 0.05–0.5 %; the commonest type; runs down-slope.
- ***Contour furrow*** : furrows follow the contour on sloping land (up to 5 %); short across-slope, prevents erosion.
- ***Corrugation furrows*** : small closely-spaced (40–75 cm) furrows for close-growing crops (small grains, forages) on steep or undulating land.

DESIGN VALUES (FURROW)

Parameter	Typical value
Slope	0.05 – 0.5 % (max 3 %)
Length	30 – 300 m (heavy: 100–300 m; light: 30–90 m)
Spacing	60 – 150 cm (matched to crop row width & soil lateral wetting)
Stream size q (per furrow)	0.5 – 2.5 L/s
Cross-section	V, U or trapezoidal; ridge height 20–30 cm
Wetted-area fraction	30–50 % (efficient use of water; less evaporation than borders/basins)

ADVANTAGES / LIMITATIONS OF FURROW

Advantages	Limitations
Only part of surface wetted → less evaporation; salts pushed to ridge tops (away from roots).	Needs uniform slope; land-preparation cost.
Adapts to wide row spacing; permits inter-cultivation; keeps foliage dry (disease-friendly).	Not for close-growing crops (rice, wheat); poor on very light sandy soils.
Small stream size sufficient (multiple furrows in a set).	Labour to open/close individual furrows unless siphons/gated pipe used.
Can be laid out on gentle to moderate slopes.	Deep percolation loss at head; runoff at tail; requires end management.

Furrow-irrigation cross-section and wetting pattern

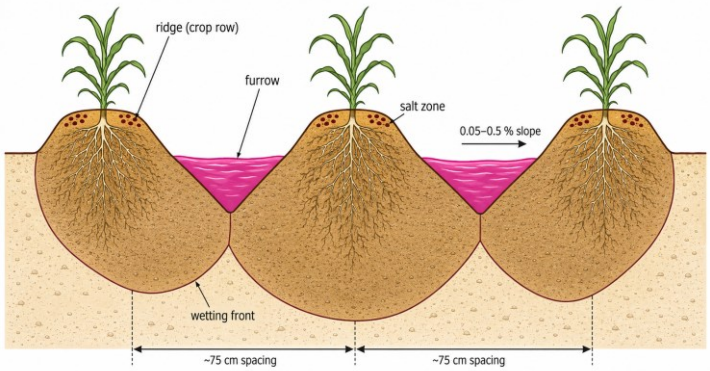


Fig. 2.4 — Furrow cross-section, wetting-front geometry and salt-accumulation pattern.

5.2 Wild Flooding

Water is released from a field channel and allowed to spread over the field ***without any prepared ridges or borders***. Used on ***rough, sloping and low-value pasture / range lands*** where levelling is uneconomic. Efficiency is low (30–50 %) and uniformity is poor, but capital cost is nil.

5.3 Corrugation

Water is run in ***small V-shaped rills ('corrugations')*** 6–10 cm deep, spaced 40–75 cm apart, made with a corrugator across the field. Water laterally wets the crop between corrugations. Used for ***close-growing crops on steep or shallow soils*** where borders and basins would erode or over-percolate. Corrugations follow the contour on slopes > 3 %.

6 SPRINKLER IRRIGATION — CONCEPT, ADAPTABILITY & LIMITATIONS

6.1 Concept & Working Principle

Sprinkler irrigation supplies water to the field ***under pressure through a network of pipes***, where rotating or fixed nozzles break the jet into droplets that fall on the crop like ***artificial rain***. The system consists of a ***pump, mainline, sub-main, laterals, risers and sprinkler heads***. Because water is delivered through a closed pipe network, ***conveyance losses are essentially zero*** and application uniformity depends chiefly on hydraulic design and wind conditions. Field application efficiencies typically fall in the range **65–80 %** versus **40–60 %** for surface methods.

6.1 Adaptability — where sprinkler is best suited

- ***Soil*** : shallow, light or coarse soils with high infiltration (borders/basins would over-percolate); undulating or rolling topography where levelling is uneconomic.
- ***Crops*** : close-growing field crops (wheat, mustard, groundnut, pulses), vegetables and fodders; not suited to rice or very tall crops such as sugar-cane.
- ***Climate*** : moderate winds (< 5 m/s), avoiding hot dry-air windy conditions; frost protection possible.
- ***Water*** : moderate supply available at pressure; salt-tolerant crops (low-salt water is preferable — foliage burn otherwise).
- ***Terrain*** : suits rolling and uneven land where surface methods would need heavy levelling.
- ***Water scarcity*** : higher application efficiency than surface; supports frequent light irrigations.
- ***Other niche uses*** : chemigation (application of pesticides/foliar), frost protection, dust suppression, land reclamation and germination flushing.

6.3 Advantages of Sprinkler Irrigation (frequent PYQ)

- ***High application efficiency (65–80 %)*** : closed pipe network eliminates conveyance losses; controllable depth per irrigation.
- ***Uniform application*** : does not depend on land grading; the wetted pattern is set by nozzle discharge & spacing, not by soil surface.
- ***Water saving*** : 30–50 % less than surface for the same yield; ideal in scarcity regions.
- ***No land grading & no field ridges*** : saves cost; allows cultivation on undulating and shallow-soil lands otherwise unfit for irrigation.
- ***Frequent, light irrigations possible*** : crop stress avoided; enables high crop yields and salt leaching in saline areas.

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- ***Chemigation & frost protection*** : water-soluble fertilisers and pesticides can be applied along with irrigation; freezing water on canopy releases latent heat and protects from frost.
- ***Suits any crop except rice / tall canes*** : wheat, oilseeds, pulses, vegetables, fodders, orchards (with under-canopy sprinklers).
- ***Reduces labour*** : automated systems (centre pivot, solid set) require little in-field labour.

6.4 Limitations

- ***High initial cost*** : pump, pipes, sprinklers and control valves — capital-intensive versus surface systems.
- ***Wind sensitivity*** : distribution pattern distorted at wind speeds > 5 m/s; uniformity drops sharply.
- ***Evaporation losses in hot & dry air*** : droplets travelling through hot dry air can lose 5–20 % before reaching soil.
- ***Energy requirement*** : operating pressure of 2.5–5 kg/cm² — recurring pumping cost; not economic where power is unreliable.
- ***Foliage burn with saline water*** : salts deposit on wet leaves; unsuitable for salt-sensitive crops with salty water.
- ***Unsuitable for rice & tall canes*** : rice needs ponding; canopy of tall crops interferes with spray pattern.
- ***Poor performance on soils of very low intake*** : nozzle application rate must be lower than intake — heavy clays force very slow rates.
- ***Clogging & maintenance*** : sand & scale block nozzles; needs filtration and periodic cleaning.
- ***Skilled operation*** : layout, pressure regulation, moving the laterals need trained labour.

6.5 When does a Sprinkler System Fall Below Surface Efficiency?

Sprinkler is not universally better — poor design or operation drops its efficiency below well-managed surface systems. Factors that reduce sprinkler efficiency to sub-surface levels:

- ***High wind & low humidity*** : droplet drift and mid-air evaporation losses (up to 30 % in extreme heat/wind).
- ***Wrong nozzle-pressure combination*** : under- or over-pressure produces coarse/fine spray → poor CU.
- ***Mismatched spacing*** : if spacing exceeds the recommended fraction of wetted diameter, dry patches appear.
- ***Application rate > soil intake rate*** : runoff even without ponding; leaves and stems intercept & re-evaporate water.
- ***Poor pressure regulation along the lateral*** : head loss makes distal sprinklers under-perform.
- ***Leaks and pipeline joints*** : ~5–15 % losses possible in poorly maintained systems.
- ***Foliage interception in tall crops*** : water hangs on canopy and evaporates without reaching root zone.
- ***Untrained operators & no scheduling*** : over- or under-irrigation cancels the design advantage.

PREVIOUS YEAR QUESTIONS

- Discuss about adaptability and limitations of sprinkler irrigation. [IFoS 2021 · P1/5(b) · 8M]
- Discuss the advantages of sprinkler irrigation. [UK·PSC ACF/RFO 2025 · Q.1(ii) · 10M]
- Enlist the components of Sprinkler Irrigation System. Briefly discuss the advantages and limitation of use of sprinkler system. [UK·PSC RFO (Mains) 2015 · Q.4(i) · 10M]
- In general, pressurised irrigation systems are considered to be more efficient than surface irrigation systems. What are some factors that may decrease the irrigation efficiency of some sprinkler systems to below that of some surface irrigation systems? [AP·PSC RFO (Mains) 2018 · Q.6(d) · 6M]

7 TYPES OF SPRINKLER SYSTEMS — PORTABILITY, COVERAGE & SPECIAL DEVICES

Sprinkler systems are classified by ***degree of portability of the pipes*** (i.e. how much of the network is moved between sets) and by the ***nature of the emitter*** (rotating impact, fixed spray, rain gun). The choice governs capital cost, labour requirement and adaptability.

7.1 Classification by Portability

System	What is moved	Best for	Note
Fully portable	Pump + mains + sub-mains + laterals + sprinklers — all portable	Small farms; supplemental irrigation on shifting fields.	Lowest capital cost; highest labour.
Semi-portable	Pump + sub-mains stay fixed; mains + laterals + sprinklers moved.	Medium farms; multi-plot single-source supply.	Common in India; moderate labour.
Semi-permanent	Only laterals & sprinklers moved; mains and sub-mains buried.	Large farms with fixed source and permanent field boundaries.	Lower operating labour; higher capital cost.
Solid-set (permanent)	Nothing moved during a season — enough laterals & sprinklers to cover the whole area.	Orchards, vineyards, nurseries; frost protection.	Highest capital; almost no labour; rapid on/off switching.
Side-roll (wheel-move)	The lateral itself rolls sideways on wheels between sets.	Rectangular fields with medium-tall row crops.	One-man moves; a wheel-line lateral of ~400 m long.
Centre-pivot	A single lateral pivots around a central point, laterally moving on wheeled towers.	Large circular fields (10–150 ha); light to medium soils.	Fully automated; irrigates a circular area (~78 % of a square).
Linear-move (lateral-move)	A pivot-like lateral moves in a straight line down the field.	Rectangular fields with abundant water.	Uniform application; automated.
Traveller / rain-gun	A single high-capacity gun sprinkler on a self-propelled cart or hose reel.	Sugarcane, cotton, forage; irregular fields; supplemental irrigation.	Very high pressure & flow; large droplet; needs low-wind conditions.

PREVIOUS YEAR QUESTIONS

Discuss the different types of sprinkler irrigation systems based on portability.

[IFoS 2020 · P1/6(c) · 15M]

7.2 Rain Guns — Working & Limitations

A ***rain gun*** is a single, high-capacity impact sprinkler that discharges through a large nozzle (15–50 mm) at high pressure (4–8 kg/cm²), with a jet range of 30–70 m. It is mounted on a tripod or on a wheeled cart and moved between sets, or on a self-propelled hose-reel traveller. Suitable for ***sugar-cane, cotton, forages, industrial waste-water disposal and pasture irrigation on large plots***.

LIMITATIONS OF RAIN-GUN IRRIGATION

- ***Very high pressure & energy cost*** : 4–8 kg/cm² operating pressure → high pumping cost.
- ***Wind-drift losses*** : large jet range is severely distorted by wind (> 3 m/s) — poor uniformity.
- ***Big-drop damage*** : large droplets can damage soft foliage, cause surface sealing on light soils, and lead to run-off/erosion.
- ***High application rate*** : often exceeds intake rate of medium/heavy soils → runoff & poor uniformity.
- ***Poor uniformity*** : wetted pattern is often elliptical and CU drops < 70 % under wind.
- ***Not for tall crops or orchards*** : obstructed pattern; damage to fruit/flowers.
- ***Skilled operators & robust pipeline needed*** : high-pressure pipes and joints; equipment cost high.
- ***Noise & mist nuisance*** : audible at 50 m+; mist drift on adjacent property.

PREVIOUS YEAR QUESTIONS

Briefly describe about rain guns and what are the limitations for application of rain gun irrigation system?

[HP·PSC RFO (Mains) 2021 · Q.3(a) · 10M]

Six-panel sprinkler-portability chart

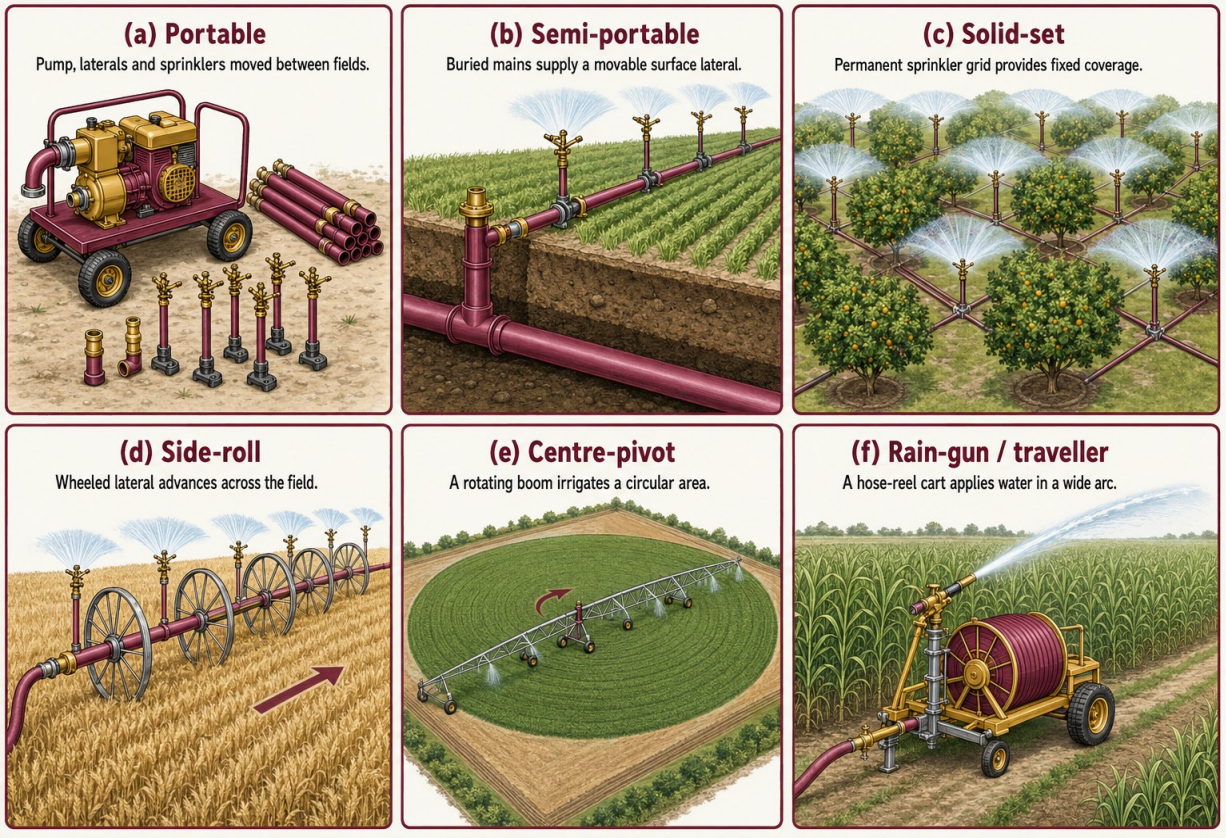


Fig. 2.5 — Six sprinkler configurations classified by portability, from fully portable to centre-pivot and rain-gun traveller.

8 SPRINKLER COMPONENTS & FIELD LAYOUT

8.1 Components of a Sprinkler System

- ***Pump & prime-mover*** : centrifugal pump (or turbine) driven by electric motor or engine; delivers water at design pressure (2.5–5 kg/cm² for medium-pressure systems).
- ***Suction pipe with foot valve & strainer*** : prevents priming loss; filters coarse debris at source.

- ***Head control unit*** : pressure gauge, water meter, non-return valve, air-release valve, filter, control valve, chemigation port.
- ***Main line*** : carries water from pump to sub-mains; PVC/HDPE (buried) or aluminium (portable); designed for the total system flow.
- ***Sub-main*** : branches from the mainline; connects laterals in a set.
- ***Laterals*** : carry water to the sprinklers; usually aluminium quick-couple pipes for portable systems; PVC/HDPE for permanent systems.
- ***Risers*** : vertical short pipes on the lateral holding each sprinkler above the crop canopy.
- ***Sprinkler heads (rotating impact / fixed-spray / gear-driven)*** : break the jet into droplets and distribute them over a circle (radius 10–30 m for medium sprinklers, up to 70 m for rain guns).
- ***Accessories*** : couplings, elbows, tees, end plugs, fertiliser injector (venturi/dosing pump), pressure regulators, thrust blocks.

Sprinkler system schematic — pump to sprinkler

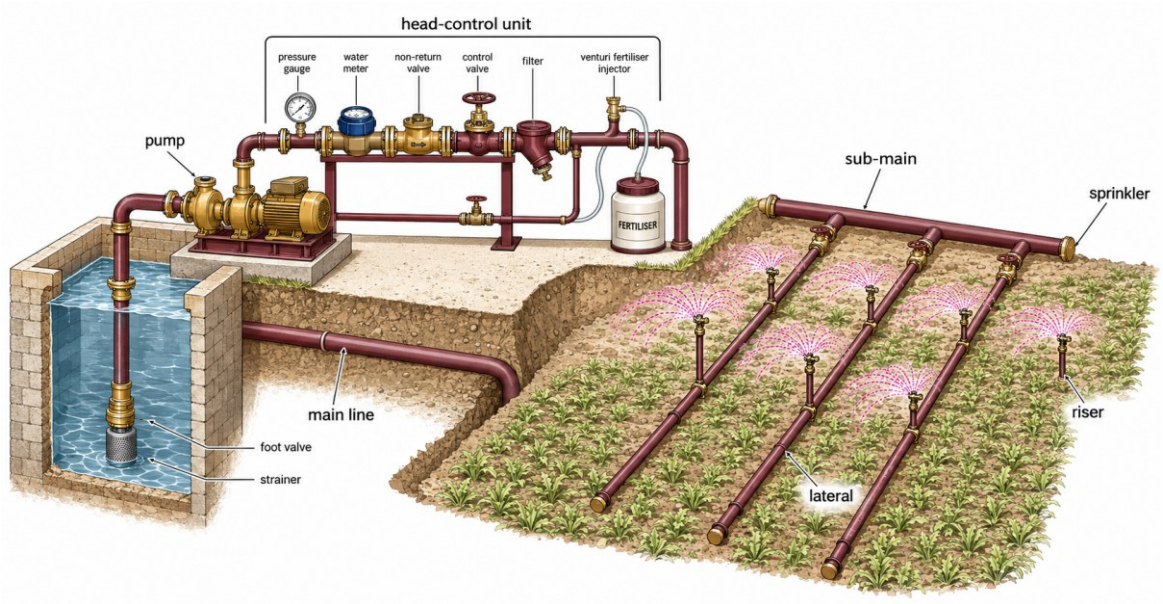


Fig. 2.6 — Semi-portable sprinkler system showing pump, head-control unit, mainline, sub-main, laterals, risers and sprinklers.

8.2 Field Layout — Guiding Rules

- ***Water source*** : place the pump at the lowest elevation of the plot (least static lift), or at the source; run the mainline up-slope to reduce diameter under high flow.
- ***Mainline direction*** : along the up-hill/down-hill line where the slope is gentlest; laterals then run perpendicular (across the slope) to keep pressure loss uniform.
- ***Lateral direction*** : across the slope so gravity and friction losses tend to cancel; where slope is > 3 %, keep laterals perpendicular to slope.
- ***Lateral length*** : chosen so that the pressure difference between the first and last sprinkler on a lateral is ≤ 20 % (Christiansen's criterion), giving discharge variation ≤ 10 %.
- ***Sprinkler spacing (Sm × Sl)*** : Sm along lateral ≤ 60 % of wetted diameter (calm), 50 % in wind; Sl between laterals ≤ 65–70 % of wetted diameter.
- ***Wind direction*** : run laterals at right angles to prevailing wind to reduce drift and improve uniformity.

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8.3 Model Layout for a 200 × 100 m Rectangular Plot

Given: rectangle 200 m (E-W) × 100 m (N-S); water source at the lower-left (south-west) corner; land slopes S → N (i.e., up-slope from source toward N-boundary).

- ***Mainline*** : laid along the western boundary (S → N), rising up-slope; length 100 m; carries total design discharge.
- ***Sub-main / manifolds*** : teed off the mainline at set intervals (every 20–30 m).
- ***Laterals*** : laid E-W (perpendicular to slope), length 200 m; spaced Sl = 18 m; each lateral has sprinklers @ Sm = 12 m.
- ***Sprinklers per lateral*** : N = L/Sm ≈ 200/12 ≈ 16 sprinklers.
- ***Sets*** : 6 lateral positions along the mainline (100/18 ≈ 5–6 sets) irrigated in rotation.
- ***Rationale*** : laterals across slope → each sprinkler on a lateral is roughly at same elevation → pressure variation controlled by friction only; up-slope mainline → static lift adds where diameter is large.

Sprinkler layout for a 200 × 100 m plot with SW source, S → N slope

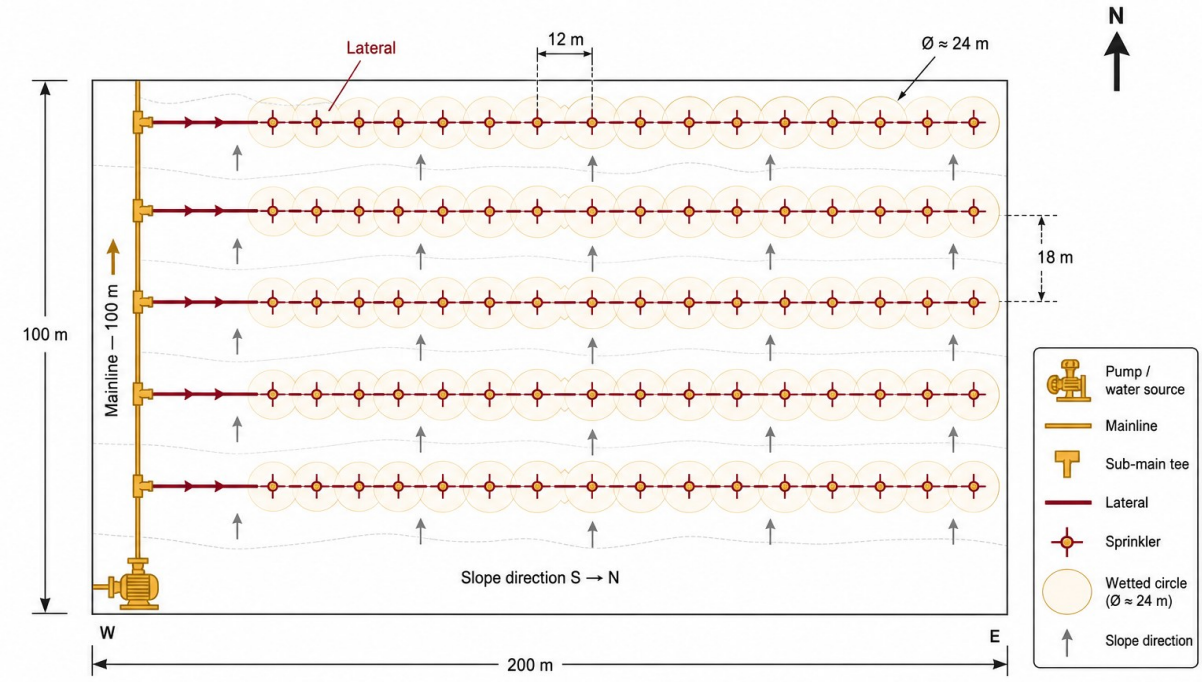


Fig. 2.7 — Sprinkler layout for a 200 m × 100 m wheat field with the source at the SW corner and slope S → N. Mainline on the western boundary; laterals perpendicular to slope.

PREVIOUS YEAR QUESTIONS

A field of wheat crop of size 200 × 100 m with water source located at the lower-left corner in the field is to be irrigated using sprinkler irrigation system. The prevailing land slope is south to north. Draw a layout of sprinkler mainline and lateral lines with brief explanation.

[IFoS 2018 · P1/6(c) · 10M]

MODEL Q In a layout answer: (i) note source, dimensions, slope; (ii) place the mainline along the shortest side that runs up-slope (western boundary here); (iii) laterals perpendicular to slope, spacing = design Sl; (iv) mark sprinklers along each lateral at Sm; (v) show the number of sets; (vi) justify with a 3-line rationale on friction, static-lift and wind orientation.***

9 SPRINKLER HYDRAULIC DESIGN & DESIGN STEPS

9.1 Hydraulic Principles Governing Sprinkler Design

A sprinkler system is a ***closed pipe network under pressure***. Its hydraulic design must ensure (a) each sprinkler discharges at the design flow, (b) pressure variation across the field is within limits, and (c) the application rate matches the soil intake and crop demand.

KEY HYDRAULIC RELATIONS

$$q = C_d \cdot a \cdot \sqrt{(2\,g\,H)}$$

Sprinkler discharge: q = discharge (L/s), C_d = discharge coefficient (0.90–0.98), a = nozzle area, H = operating head at the nozzle. Doubling H raises q only by √2 — pressure and discharge are not proportional.

$$R \approx 1.35 \sqrt{(d \cdot H)}$$

Wetted radius R (m): d = nozzle diameter (mm), H = operating head (m). Confirms that higher head + larger nozzle → wider throw.

$$h_f = f\,(L/D)\,(V^2 / 2g) \quad \text{[Darcy–Weisbach]} \quad \approx 10.67 \cdot L \cdot Q^{1.852} / (C^{1.852} \cdot D^{4.87}) \quad \text{[Hazen–Williams]}$$

Pipe friction loss; used to size mains, sub-mains and laterals. Christiansen's multiple-outlet correction F is applied to laterals with n outlets: h_f,lateral = F · h_f,pipe.

$$F = 1/(m+1) + 1/(2n) + \sqrt{(m-1)/(6\,n^2)}$$

Christiansen's F for a lateral with n outlets and pipe-flow exponent m (Hazen-Williams m = 1.852; Darcy m ≈ 2). Multiplies plain-pipe head loss to give lateral head loss.

$$\text{Application rate } I = q_s \cdot 3600 / (S_m \cdot S_l) \quad \text{[mm/hr, } q_s \text{ in L/s]}$$

Rate of water application; used with soil intake rate to size sprinklers and spacing.

$$Q_{sys} = N \cdot q_s = A \cdot d / (F \cdot T \cdot \eta_a)$$

System capacity: N = total operating sprinklers, q_s = discharge/sprinkler; alternatively from area A, gross depth d, irrigation interval F, hours/day T and application efficiency η_a.

DESIGN CRITERIA (CHRISTIANSEN)

- ***Pressure variation*** : along one lateral ≤ 20 % of average — makes discharge variation ≤ 10 %.
- ***Application rate ≤ basic soil intake rate*** : prevents runoff & sealing.
- ***Spacing ≤ 60 % of wetted diameter in calm; 50 % in wind*** : ensures overlap and uniform CU ≥ 85 %.
- ***Set operating time $T_s = d/I$*** : depth applied per set = application rate × set time.

PREVIOUS YEAR QUESTIONS

Describe the main hydraulic principles involved in designing of sprinkler irrigation system.

[IFoS 2024 · P1/7(b) · 10M]

9.2 Step-by-Step Design Procedure

The following ***10-step procedure*** is universally applied. It is the direct answer to every 'steps in design of sprinkler system' PYQ.

- ***Step 1 — Preliminary data*** : area A, plot geometry, source location, slope; crop, root depth D; soil texture, FC, PWP, ρ_b, basic intake rate I_b; climate & peak ET; water quality; power availability.
- ***Step 2 — Net & gross depth of application*** : $d_n = (FC - PWP) \cdot \rho_b \cdot D \cdot MAD$ (or from AWC); $d_g = d_n / \eta_a$; add leaching requirement LR where salinity is an issue: $d_g' = d_n / [(1 - LR)\cdot\eta_a]$.
- ***Step 3 — Peak ET & irrigation interval*** : F (days) = d_n / (peak daily ET). Round down to a convenient integer.

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- ***Step 4 — Application rate*** : I (mm/hr) ≤ basic intake I_b of the soil; typically 5–25 mm/hr.
- ***Step 5 — Sprinkler selection*** : choose sprinkler type, nozzle, operating pressure and wetted diameter from manufacturer tables to give the target discharge q_s and I.
- ***Step 6 — Spacing (Sm × Sl)*** : select spacings such that Sm × Sl × I / 360 = q_s (L/s); check overlap criterion (60 %/50 % of wetted diameter).
- ***Step 7 — Number of sprinklers & set time*** : sprinklers per lateral N_l = L_lateral / Sm; laterals per set N_s; set operating time T_s = d_g / I.
- ***Step 8 — System capacity Q_sys*** : Q_sys = N_total × q_s, cross-checked with Q_sys = A · d_g / (F · T · η_a).
- ***Step 9 — Pipe sizing & pressure requirement*** : size mainline, sub-main, laterals using Hazen–Williams so that friction losses + static lift + operating pressure at the last sprinkler ≤ total dynamic head; check Christiansen's F criterion on laterals.
- ***Step 10 — Pump selection*** : required head H_p = H_operating + h_f (main+sub-main+lateral) + h_riser + h_static; power P (kW) = ρ g Q H_p / (1000 · η_pump).

PREVIOUS YEAR QUESTIONS

What are the steps involved in the design of sprinkler irrigation system? Provide the formula, wherever required.

[IFoS 2019 · P1/8(b) · 10M]

9.3 Worked Design Numericals

◆ **WORKED NUMERICAL — *System capacity for a 20-ha wheat field*** [IFoS 2025 · P1/6(b)(ii) · 8M]

Problem. *A sprinkler irrigation system is to be installed in an area of 20 hectares. The crop to be irrigated is wheat with a gross application depth of 20 cm. The irrigation interval is 10 days with 12 operating hours per day. Determine the sprinkler system flow capacity in litres per second.*

Given. A = 20 ha = 200 000 m²; d_g = 20 cm = 0.20 m; F = 10 d; T = 12 hr/d.

Find. System capacity Q_sys (L/s).

Formula. Q_sys = A · d_g / (F · T · 3600). This equates the volume required per irrigation to the volume delivered in the total available operating hours in one irrigation cycle.

Step 1 Volume per irrigation. V = A · d_g = 200 000 × 0.20 = 40 000 m³.

Step 2 Available operating time. T_total = F · T · 3600 = 10 × 12 × 3600 = 432 000 s.

Step 3 System capacity. Q_sys = 40 000 / 432 000 = 0.09259 m³/s.

Result. Q_sys = 0.0926 m³/s = 92.6 L/s.

Unit check. [m³] / [s] = [m³/s] ✓; L/s = m³/s × 1000.

◆ **WORKED NUMERICAL — *System capacity from spacing & application rate*** [OPSC-CSE 2020–21 · P1/Q.3(a)(ii) · 12M]

Problem. *Determine the required capacity of a sprinkler system to apply water at the rate of 1.25 cm/hr. Two sprinkler lines of 186 m length are required. Sixteen sprinklers are spaced at 12 m intervals on each line. The spacing between lines is 18 m.*

Given. I = 1.25 cm/hr; two laterals; L_lat = 186 m; N_l = 16 sprinklers/lateral; Sm = 12 m; Sl = 18 m.

Find. System capacity Q_sys.

Formula. Discharge per sprinkler q_s = Sm · Sl · I / 360 (L/s, with Sm and Sl in m and I in cm/hr — derived from q_s = area/sprinkler × I converted to L/s). Q_sys = N_total · q_s.

Step 1 Discharge per sprinkler. q_s = 12 × 18 × 1.25 / 360 = 270 / 360 = 0.75 L/s.

Step 2 Total sprinklers operating. N_total = 2 × 16 = 32.

Step 3 System capacity. Q_sys = 32 × 0.75 = 24.0 L/s = 86.4 m³/h.

Result. Q_sys ≈ 24.0 L/s (0.024 m³/s).

Unit check. m × m × cm/hr → 3600 s/hr × (cm/100) = m³/s → × 1000 = L/s; the divisor 360 = 3600 × 0.01 works out. ✓

◆ **WORKED NUMERICAL — *Sprinkler capacity from spacing & rate (variant)*** **[OPSC·CSE 2024–25 · P1/Q.12 · 15M (numerical part)]**

Problem. *Work out the capacity of a sprinkler system to apply water at the rate of 1.5 cm/hr. Two sprinkler lines 200 m long, each with 18 sprinklers, are spaced at 11 m intervals on each line. Sprinkler-line spacing = 16 m.*

Given. I = 1.5 cm/hr; L_lat = 200 m; 2 laterals; N_l = 18/lat; Sm = 11 m; Sl = 16 m.

Formula. q_s = Sm · Sl · I / 360; Q_sys = 2 N_l · q_s.

Step 1 q_s = 11 × 16 × 1.5 / 360 = 264/360 = 0.733 L/s.

Step 2 Q_sys = 2 × 18 × 0.733 = 26.4 L/s.

Result. Q_sys = 26.4 L/s (0.0264 m³/s). Provide a pump giving ~95 m³/hr at the design head.

◆ **WORKED NUMERICAL — *Set time & days to irrigate 16 ha (5 cm depth)*** **[OPSC·Forest 2015–16 · P1/Q.6(a) · 10M]**

Problem. *Determine the sprinkler system capacity for the same 1.25 cm/hr + 2 × 186 m + 16 spr @ 12 m + line spacing 18 m + 1 hour for moving each 186 m sprinkler line. How many hours would be required to apply a 5 cm depth of irrigation to a square 16 ha area, assuming the system works 10 hours daily?*

Given. Q_sys = 24 L/s (from previous problem); d = 5 cm; A = 16 ha; T = 10 hr/d; move time = 1 hr/set.

Step 1 Application time per set. T_apply = d/I = 5/1.25 = 4.0 hr.

Step 2 Total time per set. T_set = T_apply + T_move = 4 + 1 = 5.0 hr.

Step 3 Area wetted per set. A_set = 2 lat × 186 m × 18 m = 6 696 m² = 0.6696 ha.

Step 4 Number of sets. n = A / A_set = 16 / 0.6696 = 23.89 → adopt 24 sets.

Step 5 Total operating time. T_total = 24 × 5 = 120 hr.

Step 6 Days required. Days = 120 / 10 = 12 days.

Result. Q_sys ≈ 24 L/s; total time = 120 hr = 12 days at 10 hr/day.

◆ **WORKED NUMERICAL — *Full design — net & gross depth, LR, interval, capacity*** **[IFoS 2017 · P1/6(d) · 10M]**

Problem. *Climate hot humid; soil fine sandy loam; wind 7 km/h; crop wheat; root depth 1.5 m; AW top 1 m = 167 mm/m; AW top 0.5 m = 183 mm/m; η_app = 80 %; ECw = 2.0 dS/m; ECe (10 % yield reduction) = 3.4 dS/m; area 10 ha; peak ET = 7.6 mm/d; MAD = 50 %; operating hours = 12/day.*

Determine *(i) net depth, (ii) gross depth, (iii) leaching requirement, (iv) irrigation interval, (v) sprinkler system capacity.*

Given & interpretation. Layer 1 (0-0.5 m): 183 mm/m → 91.5 mm; layer 2 (0.5-1.0 m): (167 − 91.5) = 75.5 mm in 0.5 m; layer 3 (1.0-1.5 m): assume same rate as top 1 m avg (167 mm/m) → 83.5 mm. Total AW in 1.5 m root zone = 91.5 + 75.5 + 83.5 = 250.5 mm.

(i) Net depth d_n. d_n = MAD · AW_total = 0.50 × 250.5 = **125.3 mm.**

(ii) Gross depth d_g (without LR). d_g = d_n / η_a = 125.3 / 0.80 = 156.6 mm.

(iii) Leaching requirement (USDA sprinkler). LR = ECw / (5 ECe − ECw) = 2.0 / (5 × 3.4 − 2.0) = 2.0 / 15.0 = **0.133 (13.3 %).** Adjusted gross depth d_g′ = d_n / [(1 − LR) · η_a] = 125.3 / (0.867 × 0.80) = 180.7 mm.

(iv) Irrigation interval F. F = d_n / peak ET = 125.3 / 7.6 = 16.5 d → adopt **F = 16 d.**

(v) System capacity Q_sys. Q_sys = A · d_g′ / (F · T · 3600) = 10 × 10 000 × 0.1807 / (16 × 12 × 3600) = 18 070 / 691 200 = 0.02614 m³/s = **26.1 L/s.**

Result summary. d_n = 125.3 mm; d_g = 156.6 mm (without LR) or 180.7 mm (with LR); LR = 13.3 %; F = 16 d; Q_sys ≈ 26.1 L/s (0.026 m³/s).

Unit check. mm × ha / (d × hr) reduces to m³/s via 10 × 10^4 × 10^{-3} / 3 600 = 0.02778. ✓

10 SPRINKLER UNIFORMITY & FIELD EVALUATION

Sprinkler performance is judged by ***how evenly water is distributed*** over the field. Two indices are universally used:

$$CU = 100 \cdot (1 - \Sigma|x_i - \bar{x}| / (n \cdot \bar{x}))$$

Christiansen's Coefficient of Uniformity: x_i = individual catch (mm), $\bar{x}$ = mean of all catches, n = number of catch cans. Acceptable ≥ 85 %; good ≥ 90 %.

$$DU = 100 \cdot (\text{average of lowest } ¼ \text{ catches}) / (\text{average of all catches})$$

Distribution Uniformity (low-quarter): a stricter index emphasising the driest 25 % of the field. Acceptable ≥ 75 %.

10.1 Field Procedure — Catch-Can Test

- ***Layout*** : place identical open-top containers (100–150 mm diameter, 25–30 cm high) in a rectangular grid — usually 3 × 3 m or 2 × 2 m — covering one full sprinkler-pattern block bounded by four adjacent sprinklers.

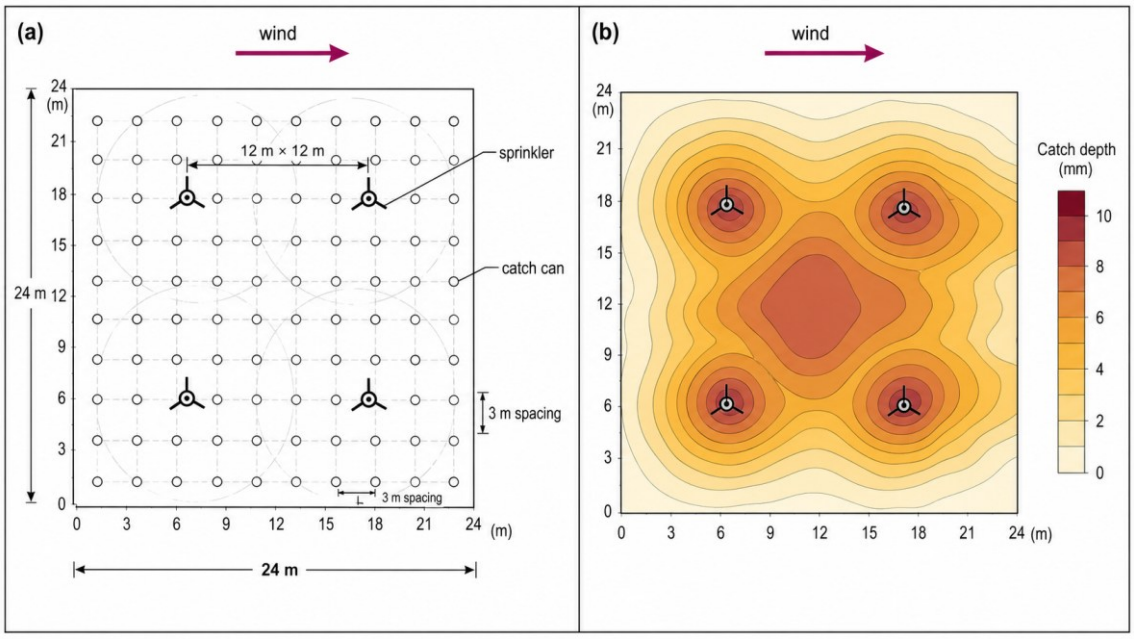


Fig. 2.8 — Catch-can field test layout and typical isohyet distribution used to compute CU and DU.

- ***Run the system*** : at the design pressure and duration under approximately still conditions (early morning or evening). Record wind speed, direction, temperature, humidity.
- ***Stop & measure*** : collect the water in each can with a measuring cylinder or by weight; convert to depth (mm).
- ***Compute*** : compute mean $\bar{x}$ and $\Sigma|x_i - \bar{x}|$; apply the CU formula; separately compute average of the lowest 25 % catches for DU.
- ***Report*** : CU, DU, mean depth, min–max, wind conditions, comment on adequacy (CU ≥ 85 % target).

10.2 Factors Affecting Uniformity

- ***Sprinkler spacing vs wetted diameter*** : Sm/D and Sl/D control the overlap; the closer, the more uniform (down to a limit).
- ***Operating pressure*** : under-pressure → doughnut pattern (dry near sprinkler); over-pressure → misting & drift.
- ***Wind speed & direction*** : distorts wetting pattern beyond 5 m/s; reduces effective spacing by up to 30 %.
- ***Nozzle wear & clogging*** : changes discharge coefficient and jet shape.
- ***Riser height & vertical alignment*** : tilted riser → asymmetric pattern.
- ***Rotation speed*** : uneven rotation → local dry/wet spots.
- ***Head loss along lateral*** : discharge variation between first and last sprinkler; controlled by Christiansen's F criterion.

PREVIOUS YEAR QUESTIONS

Discuss sprinkler irrigation uniformity and its measures and describe the procedure to estimate it in the field.

[IFoS 2017 · P1/6(c) · 10M]

11 DRIP / MICRO-IRRIGATION — CONCEPT, TYPES, ADAPTABILITY

11.1 Concept & Working Principle

Drip (or trickle / micro) irrigation delivers water in ***small, frequent, precisely-metered doses*** through ***emitters*** placed at each plant. The water moves through the soil by capillary and gravity to form a wetted bulb around the root zone; only a fraction of the total field surface is wetted (10–40 %). Because the water is delivered at low discharge (typically 1–8 L/hr per emitter) at low pressure (0.5–1.5 kg/cm² at the emitter) and only where the roots need it, drip achieves the highest field application efficiency of any method — **85–95 %**.

11.2 Classification of Drip / Micro-Irrigation Systems

(a) *By installation method*

- ***Surface drip*** : laterals & emitters on the soil surface; the standard for field crops, vegetables and orchards; easy to install, inspect and re-lay.
- ***Sub-surface drip (SDI)*** : laterals & emitters buried 15–45 cm below the soil surface; eliminates surface evaporation & weed germination; long-life systems (10–15 y); risk of root intrusion & rodent damage.

(b) *By emitter discharge rate*

- ***Low-flow drip*** : emitter $q_e \leq 4$ L/hr; the classic dripper — for orchards, high-value vegetables.
- ***Medium-flow (bubbler)*** : q_e = 8–150 L/hr; short-run bubblers around trees; simpler filtration.
- ***High-flow / micro-sprinkler / micro-jet*** : q_e = 20–200 L/hr; wetted radius 1–5 m; for widely-spaced trees.

(c) *By wetted-soil-surface area*

- ***Point-source*** : single emitter per plant wets a small bulb of soil; typical of orchards.
- ***Line-source*** : closely spaced emitters (or in-line drip tape) merge to form a continuous wet strip; row crops (cotton, tomato, sugar-cane, maize).

- ***Area-source*** : micro-sprinklers or bubblers wet a larger fraction (30–60 %) of the surface; light soils, wide-spaced trees.

PREVIOUS YEAR QUESTIONS

Discuss the different types of drip irrigation systems based on installation method, emitter discharge rate and wetted soil surface area.

[IFoS 2025 · P1/6(b)(i) · 7M]

11.3 Adaptability — Where Drip is Best Suited

- ***Crops*** : wide-spaced row crops and orchards (mango, banana, grapes, papaya, citrus, coconut, tomato, brinjal, chilli, cotton, sugar-cane).
- ***Soil*** : any soil from sand to clay — very light sandy soils where surface methods fail; heavy soils where sprinkler pattern would seal the surface.
- ***Topography*** : undulating, sloping, terraced or shallow-soil land where levelling for surface methods is uneconomic.
- ***Water availability*** : water-scarce, saline or brackish water areas; salt is pushed to the periphery of the wetted bulb, keeping the root zone within tolerance.
- ***Water quality*** : filtration required, but tolerates poorer chemical quality (salinity) than sprinkler; fertigation possible.
- ***Climate*** : hot, dry, windy climates (no drift/evaporation loss); frost-prone regions not for drip alone.

11.4 Advantages of Drip Irrigation

- ***Highest application efficiency (85–95 %)*** : water applied only where needed → very low evaporation & no runoff.
- ***Water saving (30–70 %)*** : versus surface systems; enables cropping in scarcity zones.
- ***Yield & quality increase*** : root zone kept at near-optimum moisture → 20–50 % higher yields; fewer fruit-cracks; better colour.
- ***Fertiliser use efficiency ↑*** : fertigation places nutrients directly in active root zone; N-use efficiency rises from 30 % to 70–80 %.
- ***Suits saline water*** : salts moved to bulb periphery; frequent light applications keep root zone salinity low.
- ***Weed suppression*** : dry inter-row soil → fewer weeds; no need for inter-row cultivation.
- ***Suits undulating & shallow soils*** : no need for land grading.
- ***Automation & low labour*** : valves + timer + controller run the system with negligible labour.
- ***Reduced disease pressure*** : foliage stays dry (no leaf wetness → fewer fungal diseases).
- ***Low operating pressure vs sprinkler*** : less energy per m^3 than sprinkler.

11.5 Limitations of Drip Irrigation

- ***High initial cost*** : ₹50 000 – ₹1 20 000 per ha depending on crop spacing; subsidies partially offset.
- ***Clogging*** : suspended sediment, salt precipitation, algae and roots block emitters — the single most common failure.
- ***Rodent & mechanical damage*** : laterals bitten by rats and squirrels; damaged by field operations.
- ***Salt accumulation at wetting-front periphery*** : if leaching irrigation not scheduled, salts accumulate and can move back into root zone during monsoon.

- ***Uneven root development*** : limited wetted volume → shallow root system → increased susceptibility to system failure or storm damage.
- ***Requires filtration*** : sand-media + screen filters mandatory even for clean water; adds cost & maintenance.
- ***Requires skilled operation & monitoring*** ; pressure, flow, filter cleaning, chemical treatment (chlorination / acid flush) must be routinely done.
- ***Not for close-growing crops*** : wheat, rice, small grains — spacing too tight to justify per-plant emitters.
- ***UV & thermal degradation*** : surface laterals shorten in life under direct sun; sub-surface avoids it.

PREVIOUS YEAR QUESTIONS

- Explain the advantages and limitations of a drip irrigation system. Describe the design criteria for drip irrigation system and mention the precautions in layout of drip irrigation system. [UK·PSC RFO 2012 · Q.3(i) · 10M]
- How does sprinkler irrigation differ from trickle irrigation? [AP·PSC RFO 2012 · Q.1(J) · 4M]

11.6 Sprinkler vs Drip — Differentiation

Feature	Sprinkler	Drip / Trickle
Water delivery	Overhead spray — droplets fall as artificial rain.	Point application at root zone via emitters (drops/trickle).
Wetted area	≈ 100 % of surface.	10–40 % (localised wetting bulb).
Operating pressure	2.5–5 kg/cm² (medium); rain-guns 4–8.	0.5–1.5 kg/cm² at emitter.
Emitter discharge	5–20 L/min per sprinkler.	1–8 L/hr per emitter (drip); higher for bubbler / micro-sprinkler.
Application efficiency	65–80 %.	85–95 %.
Wind sensitivity	High — drift & evaporation.	Nil — unaffected by wind.
Suitable crops	Close-growing & row crops except paddy & sugar-cane.	Wide-spaced row & orchard crops; not for close-growing.
Water quality	Sensitive to salinity (foliage burn).	Tolerates saline / brackish water; leaves dry.
Land preparation	Little — suits undulating land.	Little — suits undulating & sloping land.
Filtration need	Coarse only.	Multi-stage (hydrocyclone + sand-media + screen/disc).
Fertigation	Possible but less precise.	Ideal — direct root-zone placement.
Automation	Possible (centre-pivot).	Fully automatable — timer + solenoid valves.
Capital cost	Moderate.	High.
Water saving vs surface	30–50 %.	30–70 %.
Labour	Moderate (moving laterals).	Very low — largely fixed.
Disease pressure	Higher (wet canopy).	Lower (dry foliage).

12 DRIP COMPONENTS, DESIGN STEPS & LAYOUT PRECAUTIONS

12.1 Components of a Drip System

- ***Head / control unit*** : pump (or overhead tank), non-return valve, pressure gauges, air release, primary filter (hydrocyclone / sand-media), secondary filter (screen / disc), fertigation unit, main control valve, water meter.
- ***Main line*** : PVC / HDPE 63–110 mm; conveys water from head to sub-mains; laid buried.
- ***Sub-mains (manifolds)*** : PVC 40–75 mm; branch off the main; feed a set of laterals; carry a section valve, air-release and flush plug.
- ***Laterals*** : 12 – 20 mm LDPE tubing carrying emitters; length limited (typically 40–100 m) to keep pressure variation within ±10 %.
- ***Emitters / drippers*** : small pressure-dissipating devices delivering 1–8 L/hr; types — long-path (turbulent), labyrinth, orifice, in-line drip tape, pressure-compensating (PC), non-PC, on-line.
- ***Micro-sprinklers & bubblers*** : higher-discharge alternatives (20–150 L/hr) with wider wetting patterns.
- ***Fittings*** : start connectors, grommets, take-off tees, end-plugs, flush valves.
- ***Fertigation unit*** : venturi injector, fertiliser tank (bypass) or dosing pump — placed after the primary filter and before the secondary filter to prevent injection into pump/pressure gauge and to allow trapping of any precipitate.
- ***Automation (optional)*** : solenoid valves, timer, controller, tensiometer / soil-moisture sensors, flow & pressure telemetry.

Complete drip irrigation system schematic

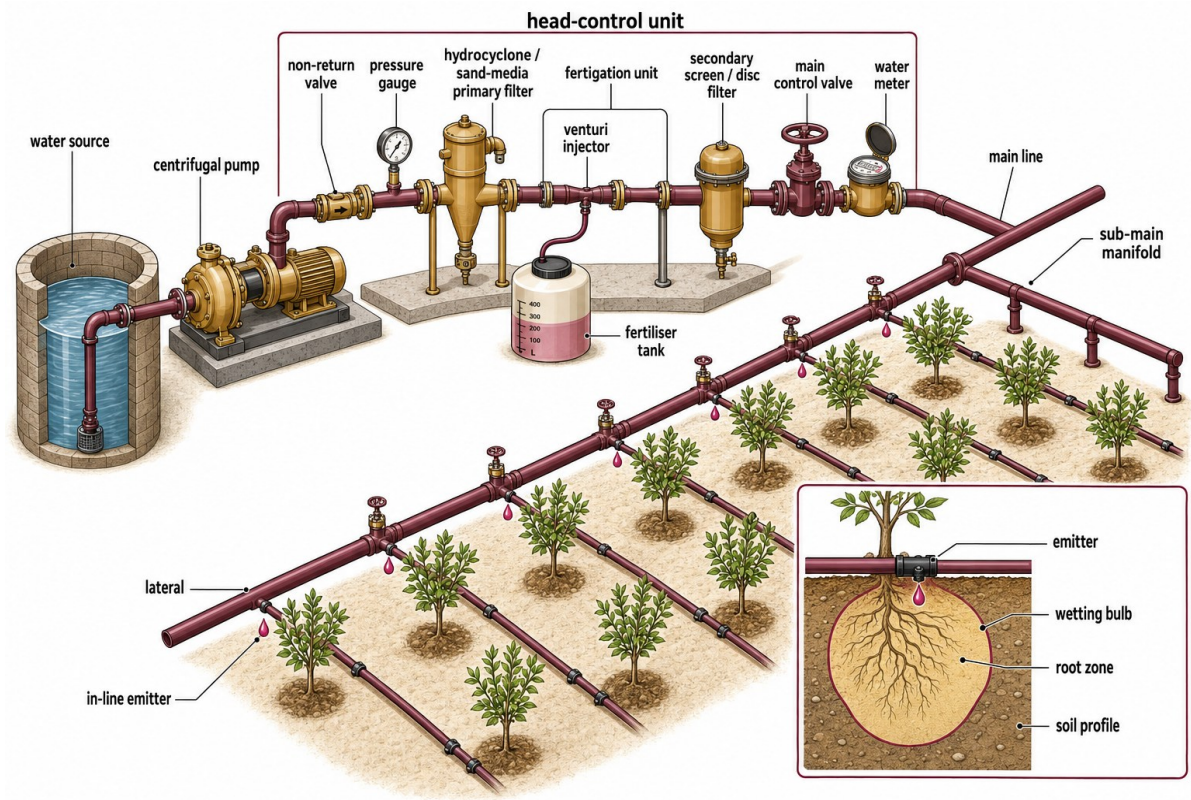


Fig. 2.9 — Complete drip system: source → pump → head-control unit (filters + fertigation) → mainline → sub-main → lateral → emitter → wetting bulb.

PREVIOUS YEAR QUESTIONS

- Draw a neat sketch showing the basic components of a drip irrigation system. Also describe the functions of each of them in brief.

  [IFoS 2017 · P1/6(a) · 10M]

- Discuss the major components of a drip irrigation system with necessary drawing.

  [IFoS 2016 · P1/6(b) · 10M]

- Explain the working principles and components of drip irrigation system.

  [OPSC·CSE 2020–21 · P1/Q.3(a)(i) · 8M]

12.2 Working of an Emitter — Types & Selection

Type	Principle	Merits	Demerits
Long-path (turbulent)	Water passes through a long, small-diameter tortuous path to dissipate pressure.	Cheap; good under wide pressure.	Susceptible to clogging by fine sediment.
Orifice	Single small aperture dissipates pressure.	Simple; low cost.	Very sensitive to clogging; discharge changes with pressure.
Labyrinth / vortex	Zig-zag or vortex chamber; turbulent flow.	Better anti-clog; used in-line tape.	Slightly higher head loss.
Pressure-compensating (PC)	Elastic diaphragm adjusts to maintain constant discharge over wide pressure range (0.5–4 kg/cm²).	Uniform discharge on undulating land or long laterals; suits sub-surface.	Costly; diaphragm ageing.
Micro-sprinkler & bubbler	Small spray or bubbling nozzle.	Wide wetting; higher q_e — suits trees.	Higher water use; sensitive to wind.

12.3 Drip Design — Criteria & Step-by-Step Procedure

DESIGN CRITERIA

- ***Emitter discharge & spacing sized to meet crop peak water requirement*** : per plant per day at design operating time.
- ***Uniformity (EU / CU) ≥ 90 %*** : keeps every plant within ±10 % of design discharge.
- ***Pressure variation ≤ 20 % across a sub-unit*** : (*i.e.* $\Delta q/q \leq 10\ \%$). Enforced by choosing lateral & sub-main sizes.
- ***Wetted area ≥ 33 %*** : (row crops) or ≥ 20 % (orchards) — ensures adequate root wetting.
- ***Salinity — leaching provided*** : either via periodic long-run irrigation or in-built leaching fraction.
- ***Application depth per irrigation matches root-zone AWC × MAD × wetted-area fraction*** : prevents deep percolation.
- ***System schedulable in shifts*** : sub-units of area ≤ $Q_{source} \cdot h / (d_g / F)$ — divides field into zones.

STEP-BY-STEP DESIGN (UNIVERSAL 10-STEP)

- ***Step 1*** : collect data — crop, spacing, root depth D; soil FC, PWP, ρ_b, wetted-area fraction P_w; climate & ET_c; water quality (EC, sediment); source flow.
- ***Step 2*** : compute peak plant water requirement V_p = plant-spacing area × ET_c × P_w × K_r (canopy factor); express in L/plant/day.

- ***Step 3*** : select emitter type & discharge q_e; number of emitters per plant n_e so that n_e · q_e · T_op ≥ V_p.
- ***Step 4*** : compute daily operating time T_op (hr/day) ≤ 20 hr (allow flush/maintenance window).
- ***Step 5*** : lay out lateral & sub-main; length such that pressure variation ≤ 20 %; use Hazen-Williams to size pipe.
- ***Step 6*** : compute total system flow Q_sys = N_plants · n_e · q_e (if simultaneous) or divide into zones so that Q_zone ≤ Q_source.
- ***Step 7*** : size mainline for Q_sys with velocity ≤ 1.5 m/s.
- ***Step 8*** : filtration — hydrocyclone (silt), sand-media (organic), screen or disc (final polish), sized for 1.5 × design flow.
- ***Step 9*** : select pump — head H_p = operating pressure + head loss (main + sub-main + lateral) + filter losses + static lift; power P = ρ g Q H_p / η_pump.
- ***Step 10*** : layout, install, commission, flush; document zone schedule and maintenance calendar.

PREVIOUS YEAR QUESTIONS

Enlist the steps involved in design of drip irrigation system. [IFoS 2022 · P1/5(a) · 8M]

WORKED NUMERICAL — *Drip system design — coconut orchard* **[OPSC·Forest 2023–24 · P1/Q.5(a) · 20M]**

Problem. *A farmer has 1 ha (100 m × 100 m) in a water-scarce region and plans a coconut plantation at 7.5 × 7.5 m spacing on sandy-loam. Peak pan evaporation Ep = 12 mm/day, pan coefficient Kp = 0.7, crop coefficient Kc = 0.8. Design a drip irrigation system, assuming reasonable additional data.*

Given. A = 1 ha (100 × 100 m); spacing 7.5 × 7.5 m → area/plant = 56.25 m²; Ep = 12 mm/d; Kp = 0.7; Kc = 0.8. Assumptions: canopy factor K_r = 0.7 (coconut wetted-area fraction 60–70 %); emitter discharge q_e = 4 L/hr; 4 emitters/plant.

Step 1 ETo & ETc. ETo = Kp · Ep = 0.7 × 12 = 8.4 mm/d; ETc = Kc · ETo = 0.8 × 8.4 = **6.72 mm/d.**

Step 2 Peak plant water requirement. V_p = area/plant × ETc × K_r = 56.25 × 6.72 × 0.7 = 264.6 L/plant/day.

Step 3 Number of plants. N = 10 000 / 56.25 = 177.8 → **178 plants/ha.**

Step 4 Emitters per plant & daily operating time. n_e = 4; q_e = 4 L/hr → Q_plant = 16 L/hr. T_op = V_p / Q_plant = 264.6 / 16 = 16.5 hr/day.

Step 5 System flow (if all plants simultaneously). Q_sys = N · Q_plant = 178 × 16 = 2 848 L/hr = 47.5 L/min = 0.79 L/s. If sectored into 4 zones of 44 plants (a common practice), zonal flow ≈ 0.20 L/s.

Step 6 Layout. Main line PVC 63 mm along one side (100 m); 4 sub-mains (25 m each) at 25-m intervals; laterals 16 mm LDPE, 12 rows × 100 m long; 4 point-source PC emitters around each tree at 0.5 m radius.

Step 7 Filtration. Hydrocyclone (sand-loaded well water) + 120-mesh screen filter; venturi fertigation unit between them.

Step 8 Pump. H_p ≈ 20 m (10 m operating + 5 m friction + 5 m static); Q = 0.8 L/s; P = 9.81 × 0.0008 × 20 / 0.6 ≈ 0.26 kW → 0.5 hp motor suffices.

Result summary. 178 plants, 4 emitters × 4 L/hr each, T_op ≈ 16.5 hr/day, Q_sys ≈ 0.8 L/s, 4-zone rotation, 0.5 hp pump. Assumptions on K_r, emitter q_e and n_e should be validated with local data.

12.4 Layout Precautions

- ***Lay main lines along the direction of steepest slope*** : so that laterals run along contour → uniform pressure along each lateral.
- ***Length of lateral & sub-main*** : chosen so total head loss + elevation change gives ≤ 20 % pressure variation (Δq/q ≤ 10 %).

- ***Air-release & vacuum valves*** : at all high points and dead ends to prevent pipe collapse & emitter suck-back of soil.
- ***Flush valves at ends*** : periodic flushing removes deposits; extends emitter life.
- ***Pressure regulators at manifolds*** : smooth out source-pressure variations, especially with electric-driven pumps.
- ***Protect surface laterals from UV & rodents*** : use UV-stabilised LDPE; rodent-repellent additives; consider sub-surface installation.
- ***Do not lay laterals uphill on long runs*** : cumulative friction + static head → last emitters under-perform.
- ***Group crops of similar water demand & emitter type*** : prevents over/under-irrigation within a zone.

◆ *Source: Michael, §19.5; Keller & Bliesner Ch.7–9; Nakayama & Bucks, Trickle Irrigation for Crop Production.*

13 FERTIGATION — METHODS & LOCATION OF INJECTION

Fertigation is the ***application of water-soluble fertilisers along with irrigation water*** through a drip or sprinkler system. It delivers nutrients directly into the active root zone in small, frequent doses, raising fertiliser-use efficiency to **70–90 %** (vs 30–50 % for broadcast application).

13.1 Methods of Fertilizer Injection

(a) *Bypass pressure-differential tank*

A closed tank filled with soluble fertiliser is plumbed in parallel across a small restriction (valve) on the mainline. Part of the water flow is diverted through the tank, dissolves the fertiliser and returns to the mainline. Advantages — cheap, no external power. Limitations — concentration varies with time (starts high, tapers off); needs topping up.

(b) *Venturi injector*

Water passes through a constriction (Venturi throat), which creates a suction that draws fertiliser solution from a small tank into the mainline. Advantages — simple, no power, constant concentration. Limitations — needs 20–30 % pressure drop across the injector; not accurate for very small doses.

(c) *Injection / dosing pump*

An electrically- or hydraulically-driven positive-displacement pump injects a metered dose of fertiliser stock into the pipeline at constant concentration. Advantages — precise, adjustable; suited to automation & large systems. Limitations — needs external power; higher cost.

(d) *Hydraulically-driven proportional injector*

Water pressure drives a piston/diaphragm pump that injects fertiliser in a fixed ratio to the flow — self-powered and proportional. Advantages of both venturi and dosing pump combined; used in commercial greenhouses.

13.2 Location of the Fertigation Unit — Why It Matters

Location is fixed by (i) protecting the pump and water source from fertiliser back-flow, (ii) allowing any un-dissolved fertiliser or precipitate to be trapped before it reaches the emitters, and (iii) ensuring good mixing before distribution.

- ***Between the primary filter and the secondary filter*** : this is the standard placement: primary filter (hydrocyclone/sand-media) removes source-water sediment; the fertigation unit injects the solution; the secondary (screen or disc) filter downstream traps any precipitate before it reaches the emitters.

- ***After a non-return (check) valve on the pump discharge*** : compulsory — prevents fertiliser back-siphoning into the pump, well and drinking-water source (safety & regulatory requirement).
- ***Before the manifold/sub-main division*** : ensures uniform concentration in every branch downstream.
- ***Away from the pump suction*** : never on the suction side — corrosion, cavitation and back-siphon risk.
- ***With adequate mixing length*** : about 10 pipe diameters downstream of injection point before the first take-off, to ensure uniform concentration.

PREVIOUS YEAR QUESTIONS

What are the different methods for fertilizer injection (fertigation)? The location of fertigation systems is very important in drip irrigation systems. Discuss in brief. [IFoS 2018 · P1/8(d) · 10M]

Fertigation methods comparison

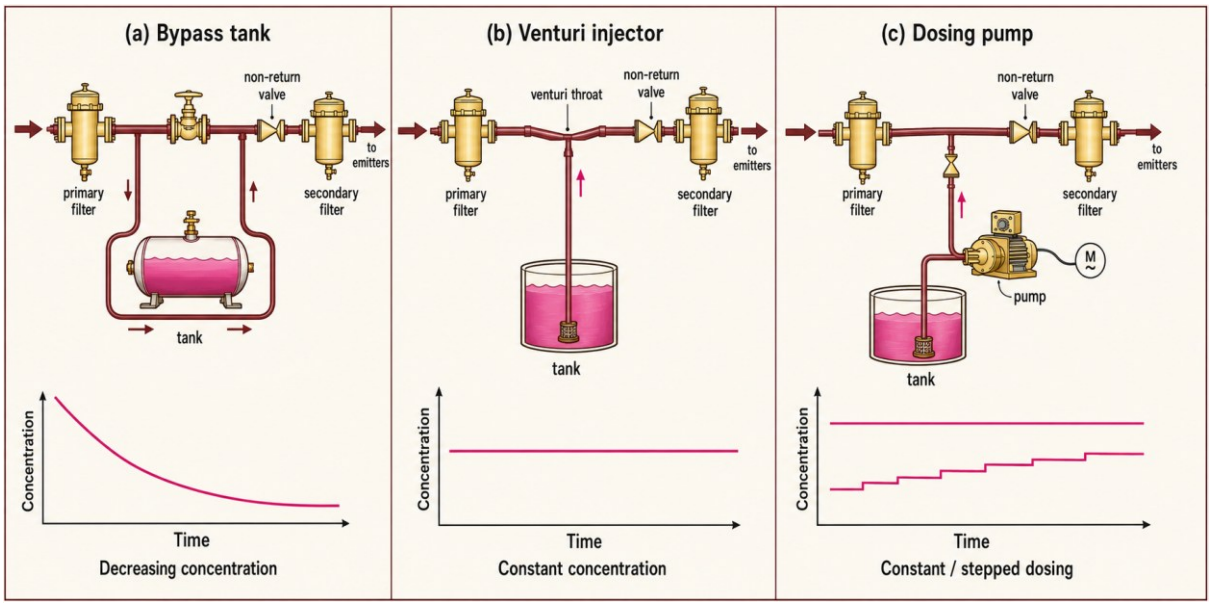


Fig. 2.10 — Three fertigation-injection methods (bypass tank, venturi, dosing pump) with concentration profiles and correct placement between the primary and secondary filters.

14 FILTRATION SYSTEMS IN MICRO-IRRIGATION

Emitters have very small orifices (0.3–1.5 mm) that clog easily. ***Every drip and sprinkler system therefore needs filtration***, the extent depending on water source and quality. Filtration is the ***single most important routine-maintenance issue*** in micro-irrigation and its failure is the commonest reason for system under-performance in the field.

14.1 Types of Filters — Working, Merits & Selection

(a) Hydrocyclone / sand-separator

Water enters tangentially into a conical chamber; the centrifugal force throws heavier sand particles outwards and downwards to a collection sump, while clean water rises through a central core to the outlet. Removes ***dense particles (sand, silt) heavier than water*** — first-stage filter for well or river water. Efficient above minimum flow; does not remove organic matter or algae.

(b) Sand-media filter

A pressure vessel packed with graded sand (particle size 0.6–1.5 mm) through which water passes downwards; suspended particles are trapped in the interstices of the sand bed. Removes ***organic matter, algae, small silt &***

sediment — the primary filter for surface or canal water. Requires periodic back-flushing (reverse flow) to dislodge trapped matter. Multiple tanks operate in parallel with automated flush sequencing.

(c) Screen filter

Water flows through a fine woven stainless-steel or plastic mesh (100–200 mesh; opening 74–150 µm) that traps particles larger than the aperture. Used as ***secondary / polish filter*** downstream of hydrocyclone and/or sand-media; also as primary for very clean water. Manual or self-cleaning types (with brush or suction scanner). Not suitable for high organic load — mesh blinds rapidly.

(d) Disc filter

A stack of thin plastic (usually polypropylene) discs with grooved faces is clamped together; water passes through the grooves in a 3-D tortuous path, trapping particles both by size and by depth. Removes ***both organic and inorganic particles***; combines the depth filtration of sand with the fine screening of mesh. Automatic back-flush by loosening the disc stack and reversing flow. Widely used as ***final / stand-alone filter*** for clean well water.

Filter	Removes	Best on	Cleaning	Rating
Hydrocyclone	Sand, coarse silt (SG > 1.5)	Well water, sandy rivers	Auto flush from bottom	No mesh rating; based on flow
Sand-media	Organic matter, algae, silt	Surface/canal/pond water	Back-flush every set / auto	≥ 200 mesh equivalent
Screen	Inorganic & fine silt	Clean water, polishing	Manual brush / auto scanner	100–200 mesh
Disc	Organic + inorganic combined	Well water; stand-alone use	Auto — disc-stack loosens	120–200 mesh

14.2 Filter Selection & Configuration

- ***Well water with sand*** : hydrocyclone (primary) → screen or disc (secondary).
- ***Canal / pond / river water*** : sand-media (primary) → screen or disc (secondary); include a sedimentation tank upstream if silt is very high.
- ***Clean pumped water*** : stand-alone screen or disc filter.
- ***Water with high algae/organic load*** : sand-media essential; chlorination injection recommended.
- ***Size for 1.5 × design flow*** : keeps head loss low; prolongs cleaning interval.
- ***Head loss criterion*** : clean filter Δp = 0.2–0.3 kg/cm²; back-flush when Δp reaches 0.5 kg/cm².

14.3 Sand-Media Filter vs Screen Filter (Comparison)

Feature	Sand-media filter	Screen filter
Principle	Depth filtration through graded sand bed.	Surface filtration through a fine mesh.
Removes	Organic matter, algae, fine silt.	Mainly inorganic silt & sand.
Filtration rating	Equivalent to 200 mesh or finer, adjustable with sand grade.	100–200 mesh (fixed by mesh).
Best on	Surface water, canal water, ponds with algae.	Clean well/tube-well water; polishing after sand-media.
Head loss (clean)	0.3–0.5 kg/cm²; higher than screen.	0.1–0.2 kg/cm²; lower.
Cleaning	Back-flush by reverse flow; automated with multiple tanks in parallel.	Manual brushing / flushing; or auto scanner.

Frequency of cleaning	Longer runs between cleanings for equivalent load (depth filtration).	Faster clogging with organic matter.
Size / footprint	Large steel pressure vessels; heavier.	Compact; light-weight.
Capital cost	Higher.	Lower.
Suitability	Primary filter for dirty water.	Secondary/polish filter or primary for clean water.

PREVIOUS YEAR QUESTIONS

- Differentiate between Sand Media filter and Screen filter (used in drip / micro-irrigation systems). [IFoS 2021 · P1/7(a·ii) · 5M]
- Explain different filtration systems used in drip irrigation. [IFoS 2019 · P1/8(c) · 10M]

Filter types — sectioned drawings

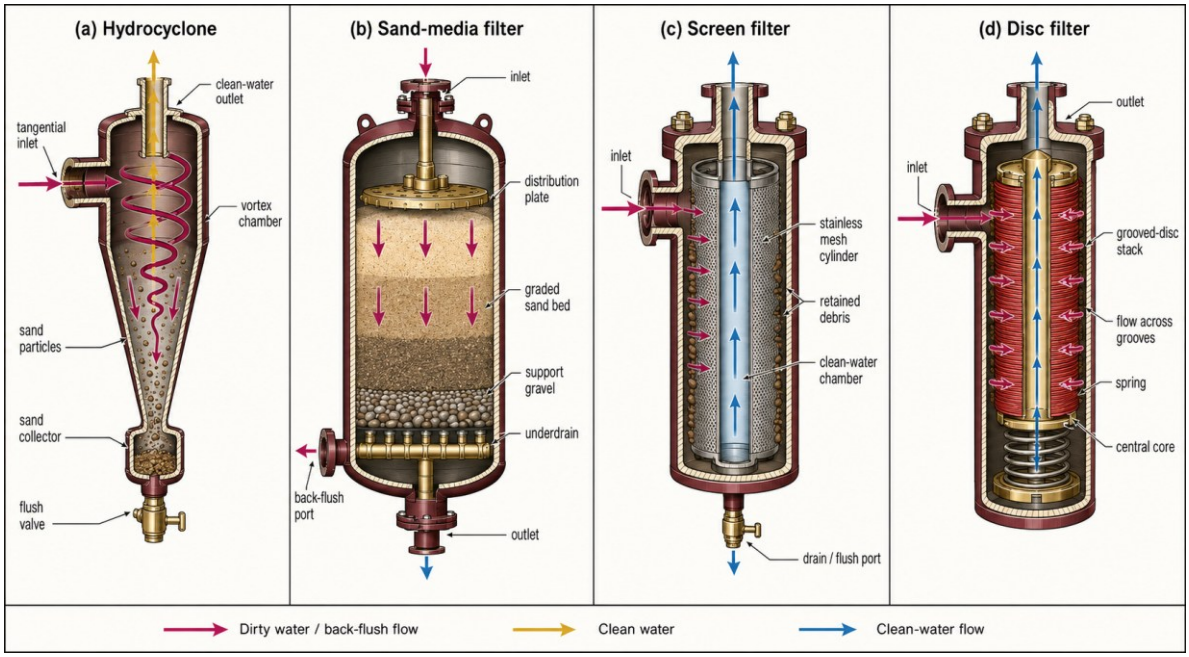


Fig. 2.11 — Sectional views of the four common filters in micro-irrigation: hydrocyclone, sand-media, screen and disc.

Source: Keller & Bliesner Ch.9; Michael §19.4; INCID Drip Manual §5.

FORMULA SHEET — CHAPTER 2

- ***Border/Basin time*** : t = A · d / (Q · η_c) — time to apply depth d over area A with source Q and conveyance eff η_c.
- ***Application efficiency*** : η_app = V_stored / V_applied = (Σ ΔMC × ρ_b × D_i × A) / (Q · t_co).
- ***Infiltration opportunity time*** : τ(x) = t_r(x) − t_a(x) — controls depth infiltrated at each point.
- ***Sprinkler discharge*** : q = C_d · a · √(2 g H); q ∝ √H (not proportional).
- ***Sprinkler wetted radius*** : R ≈ 1.35 √(d · H) — d in mm, H in m.
- ***Sprinkler discharge per unit*** : = Sm · Sl · I / 360 (L/s) — with Sm, Sl in m and I in cm/hr.
- ***System capacity (sprinkler / drip)*** : Q_sys = A · d_g / (F · T · η_a) = N · q_s (or N_plants · n_e · q_e).
- ***Christiansen's Uniformity*** : CU = 100 · (1 − Σ|x_i − x̄| / (n · x̄)). Target ≥ 85 %.
- ***Distribution Uniformity (low ¼)*** : DU = 100 · (avg lowest ¼) / (avg all). Target ≥ 75 %.
- ***Christiansen's F (multi-outlet)*** : F = 1/(m+1) + 1/(2n) + √(m−1)/(6n²); h_f,lat = F · h_f,pipe.
- ***Pipe friction (Hazen–Williams)*** : $h_f = 10.67 \cdot L \cdot Q^{1.852} / (C^{1.852} \cdot D^{4.87})$, with SI units.

- ***Leaching requirement (sprinkler)*** : LR = ECw / (5 ECe − ECw). Add: d_g′ = d_n / [(1 − LR)·η_a].
- ***Leaching requirement (drip / high-freq)*** : LR = ECw / (2 · max ECe).
- ***Net & gross depth*** : d_n = MAD · AWC · D_root; d_g = d_n / η_a.
- ***Irrigation interval*** : F = d_n / peak ET.
- ***Drip water requirement per plant*** : V_p = area/plant × ETc × K_r (canopy fraction).
- ***Drip operating time*** : T_op = V_p / (n_e · q_e).
- ***Pump power*** : P (kW) = ρ g Q H / (1000 · η_pump); H = H_op + h_f + h_static.
- ***Application rate (sprinkler)*** : I = q_s · 3600 / (Sm · Sl) (mm/hr, q_s in L/s).

SUMMARY

- Irrigation methods split into surface (border, check-basin, basin, furrow, wild flooding, corrugation), pressurised overhead (sprinkler, rain-gun), and pressurised localised (drip, sub-surface drip, bubbler, micro-sprinkler).
- Surface irrigation has four hydraulic phases — advance, ponding, depletion, recession; τ(x) = t_r − t_a is the infiltration opportunity time and drives design.
- Border strip 60–300 m × 3–15 m; slope 0.1–0.5 %; stream 4–12 L/s per m width; cut off when advance front is 75–85 % down-slope; suits close-growing crops on gently sloping land.
- Check-basin — low ridges around level plots; simple; limitations: level land needed, bunds waste land, poor for row crops, high land preparation cost.
- Furrow — water in furrows between ridge-planted rows; wetted area 30–50 %; salts pushed away from roots; suits wide-spaced row crops.
- Sprinkler — closed pipe network under 2.5–5 kg/cm²; 65–80 % efficiency; classification by portability (portable → semi → solid-set → side-roll → centre-pivot → rain gun).
- Sprinkler design uses q = C_d a √(2gH), R = 1.35√(dH), Christiansen's F for laterals; 10-step procedure; system capacity Q = A·d_g / (F·T·η_a).
- Uniformity — CU (Christiansen) ≥ 85 %; DU (low ¼) ≥ 75 %; measured by catch-can test.
- Drip / micro — 1–8 L/hr emitters at 0.5–1.5 kg/cm²; 85–95 % efficiency; classified by installation (surface/SDI), discharge (low/med/high), and wetted-area (point/line/area).
- Drip components: head unit (pump + filters + fertigation + valves) → mainline → sub-main → lateral → emitter; layout keeps pressure variation ≤ 20 %.
- Fertigation methods: bypass tank, venturi, dosing pump; injector placed between primary and secondary filter, downstream of NRV.
- Filters: hydrocyclone (sand), sand-media (organic), screen (fine polish), disc (combined); typical stack for well water = hydrocyclone → screen/disc; canal water = sand-media → screen/disc.

LAST-NIGHT REVISION — ONE PAGE

- ***Border*** : 60–300 m long × 3–15 m wide; slope 0.1–0.5 %; unit inflow 4–12 L/s/m; cut off at 75–85 %; hydraulic phases: advance–ponding–depletion–recession; IOT = t_r − t_a.
- ***Check-basin limitations*** : level land needed; bunds waste 3–5 % area; poor for row crops; costly grading; small streams unsuitable; poor drainage; salinity in dry regions; mech constraint; poor uniformity in large basins.
- ***Furrow*** : slope 0.05–0.5 %; spacing 60–150 cm; stream 0.5–2.5 L/s per furrow; wetted 30–50 %; suits wide-spaced row crops; salts pushed to ridge tops.

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- ***Sprinkler adaptability*** : light/undulating land; close-growing & row crops (not rice); low-wind, moderate ET; supplemental irrigation; frost & chemigation.
- ***Sprinkler limitations*** : wind > 5 m/s; evaporation loss; energy cost; saline water burns foliage; not rice/canes; low-intake soils; skilled labour; clogging.
- ***Sprinkler types (portability)*** : portable → semi-portable → semi-permanent → solid-set → side-roll → centre-pivot → linear-move → rain-gun/traveller.
- ***Sprinkler design (10 steps)*** : data → d_n & d_g → F & I → sprinkler & spacing → set time → Q_sys → pipe sizes → pump.
- ***Key sprinkler formulas*** : $q = Sm \cdot Sl \cdot I/360$; $Q_{sys} = A \cdot d_g/(F \cdot T \cdot \eta_a)$; $CU = 1 - \Sigma|x_i - \bar{x}|/(n\bar{x})$; $LR = ECw/(5ECe - ECw)$.
- ***Uniformity procedure*** : catch-can grid 3 × 3 m over one sprinkler-block; run at design pressure; measure catches; compute CU (≥ 85 %) and DU (≥ 75 %).
- ***Drip types*** : (a) installation — surface / SDI; (b) discharge — low / med (bubbler) / high (micro-sprinkler); (c) wetted-area — point / line / area.
- ***Drip components*** : pump → non-return → primary filter → fertigation → secondary filter → mainline → sub-main → lateral → emitter.
- ***Drip design (10 steps)*** : data → V_p per plant → q_e & n_e → T_{op} → layout → Q_{sys} → mainline → filtration → pump → commissioning.
- ***Fertigation methods*** : bypass tank (cheap, tapering conc); venturi (constant conc, no power); dosing pump (precise, powered); place between primary & secondary filter, after NRV.
- ***Filters*** : hydrocyclone (sand only, no organic); sand-media (organic + silt; back-flush); screen (100–200 mesh polish); disc (organic + inorganic; auto flush).
- ***Sand-media vs Screen*** : depth vs surface filter; organic vs inorganic; back-flush vs brush; higher Δp vs lower.
- ***Sprinkler vs Drip*** : 100 % vs 10–40 % wetting; 65–80 % vs 85–95 % η; 2.5–5 vs 0.5–1.5 kg/cm²; sensitive vs immune to wind; overhead vs point delivery.
- ***Numerical shortcuts*** : Border time = $A \cdot d/(Q \cdot \eta_c)$; Sprinkler $q_s = Sm \cdot Sl \cdot I/360$ (L/s); System $Q = A \cdot d/(F \cdot T \cdot 3600)$; Days = $(sets \times T_{set})/T_{daily}$.
- ***Rain-gun limits*** : very high pressure/energy; drift in wind; big-drop damage; runoff on medium/heavy soils; poor CU; not for tall or delicate crops.
- ***India micro-irrigation*** : ~15–17 M ha under drip+sprinkler; PMKSY 45–55 % subsidy; leaders MH, AP, KA, GJ, TN; Odisha adoption modest with clogging + cyclone damage + subsidy delays as top field issues.

CHAPTER

3

WATER MEASUREMENT & CONVEYANCE

Weirs · Flumes · Orifices · Velocity-area & pipe-flow methods · Underground pipelines

SYLLABUS : Open-channel flow-measurement devices — weirs (rectangular, triangular/V-notch, Cipoletti, trapezoidal), sharp-crested vs broad-crested, end-contraction effects, submerged weirs. Critical-depth flumes — Parshall flume and cut-throat flume, working principles and field installation. Orifice-type devices — free orifice, submerged orifice and orifice bucket. Pipe-flow measurement — Venturi meter, Pitot tube, orifice meter, coordinate method for horizontally discharging pipes. Velocity-area methods — current meter, floats. Underground pipeline (UGPL) system — mainline, sub-main, risers, hydrants; specialised structures (air-relief / vacuum valves, end plugs, stand-pipes, pressure-relief valves, over-flow stand); common field troubles and remedies.

Chapter Outline

1. **Scope, Classification of Water-Measurement Devices**
2. **General Concepts — Accuracy, Precision, Drift; Selection Criteria**
3. **Weirs — Rectangular, Cipoletti, Triangular, Trapezoidal (Sharp-Crested)**
4. **Broad-Crested Weirs · End-Contractions · Submerged Weirs · Installation Rules**
5. **Critical-Depth Flumes — Parshall & Cut-Throat**
6. **Orifice-Type Devices — Free, Submerged & Orifice Bucket**
7. **Pipe-Flow Measurement — Venturi Meter, Pitot Tube, Orifice Meter**
8. **Coordinate Method for Horizontal Pipes**
9. **Velocity-Area Methods — Current Meter, Floats**
10. **Underground Pipeline (UGPL) System — Concept, Advantages, Limitations**
11. **UGPL Components — Mainline, Sub-main, Risers, Hydrants, Alfalfa/Orchard Valves**
12. **UGPL Protective / Control Structures — Air Vents, End Plugs, Stand-Pipes, Pressure-Relief**
13. **UGPL Common Troubles & Remedies**
14. **Summary of Formulae & Selection Charts**

MIND-MAP — *Chapter 2 concept map*

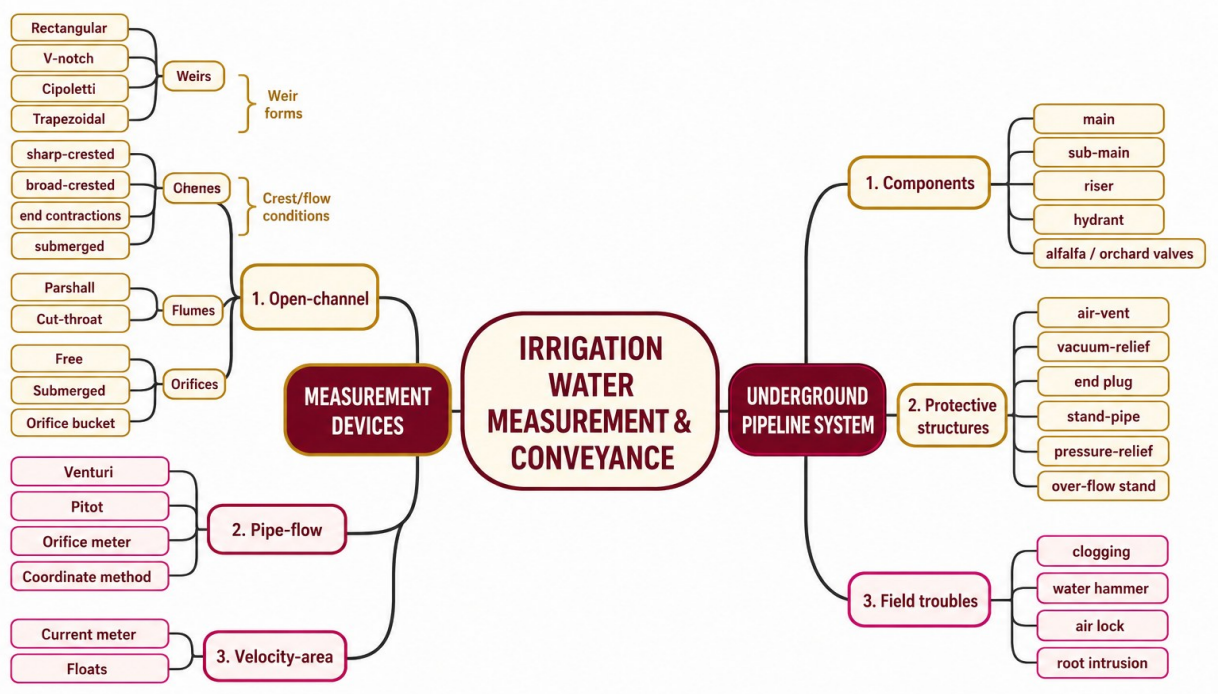


Fig. 3.0 — Chapter 3 concept map linking measurement devices (weirs, flumes, orifices, pipe methods, velocity-area) with the underground-pipeline conveyance system.

1 SCOPE, CLASSIFICATION OF WATER-MEASUREMENT DEVICES

Water measurement is the ***determination of flow rate (volume per unit time)*** through a channel or pipe; it is essential for equitable distribution among users, for scheduling irrigation, for volumetric charging, and for auditing losses along conveyance networks. On a farm, water may be measured either in the ***open channel*** that carries it from source to field, or in the ***pressurised pipe*** of an underground or overhead network. The choice of device is dictated by head available, accuracy required, cost, ease of installation and maintenance, and whether the flow is free or submerged.

1.1 Broad Classification of Devices

Family	Principle	Devices	Where used
Weirs	Overflow structure — Q related to head over crest	Rectangular, Cipoletti, Triangular (V-notch), Trapezoidal	Open channels; small to medium farm streams
Critical-depth flumes	Contracted throat forces critical flow → depth uniquely fixes Q	Parshall, Cut-throat, WSC, Long-throated	Open channels with sediment or debris — no ponding needed
Orifice-type	Q from head across a sharp-edged opening	Free orifice, Submerged orifice, Orifice bucket	Head-regulators, farm turnouts, canal off-takes
Pipe-flow meters	Differential pressure/velocity in a full pipe	Venturi, Orifice meter, Pitot tube, Elbow meter, Ultrasonic	Underground/overhead pipelines
Velocity-area	Q = A × mean V; V measured directly at points	Current meter, Surface & sub-surface floats, Salt/dye dilution	Rivers, large channels; discharge gauging

Volumetric / weight	Direct measurement into a calibrated container	Bucket-and-stopwatch; weigh-tank	Small flows; laboratory calibration
Coordinate method	Trajectory of jet from a horizontal pipe → Q by projectile geometry	For pipe discharging freely into atmosphere	Tube-wells, siphon outlets

1.2 Selection Criteria

- ***Range of flow*** : device should span the expected Q with linear/predictable response; V-notches best for small Q, rectangular for larger.
- ***Available head loss*** : weirs and flumes need a fall (0.05–0.20 m); Parshall flume is the most head-economical; orifices need a differential.
- ***Accuracy needed*** : volumetric > current meter > weir > flume > float; typical accuracies ±1 % to ±10 %.
- ***Sediment & debris*** : Parshall and cut-throat flumes are self-cleaning; weirs pond and silt up.
- ***Free vs submerged flow*** : critical for weirs (accuracy drops when tail-water submerges the crest); Parshall flume handles submergence to 70 % without corrections.
- ***Portability & cost*** : cut-throat flume portable and low-cost; Parshall flume is a permanent installation.
- ***Operator skill*** : weirs and orifices need only a staff-gauge reading; current meter and dilution methods need training.
- ***Field vs laboratory*** : volumetric only for laboratory or very small field flows; weirs/flumes practical for field farm-outlets.

PREVIOUS YEAR QUESTIONS

- Enlist the structures to be used in measuring irrigation water and also write their suitability.
  [IFoS 2024 · P1/5(a) · 8M]
- Briefly explain various irrigation water measurement devices that can be installed in an irrigation channel. Use appropriate diagrams, wherever necessary.
  [IFoS 2019 · P1/8(a) · 10M]
- Brief the different method of irrigation water measurement. Explain about the measuring devices and their suitability.
  [OPSC·Forest 2023–24 · P1/Q.5(c) · 10M]

Source: Michael, Irrigation Theory and Practice, §10.1–10.3; Modi §7.1; SK Garg, Chap.11.

2 GENERAL CONCEPTS — ACCURACY, PRECISION, DRIFT; FIELD PRACTICE

2.1 Key Metrological Terms

Accuracy — closeness of a measured value to the ***true value***. Expressed as a percentage (e.g. ± 2 % of full-scale). Improved by proper installation, calibration and standard operating conditions.

Precision — closeness of ***repeated measurements of the same quantity to one another***. A device can be precise (very repeatable) yet inaccurate (biased). Improved by mechanical stability and by minimising reading error.

Drift — gradual change in the output of an instrument over time when the true input is unchanged. Causes: ageing, temperature, sediment build-up on the crest, wear of moving parts, calibration slip. Controlled by ***periodic re-calibration and cleaning***.

Sensitivity — smallest change in flow that produces a detectable change in reading. V-notch weirs are more sensitive than rectangular weirs at small discharges.

Hysteresis — difference in output for the same input approached from below vs from above; matters in gauge readings while flow is rising vs falling.

Range / turn-down ratio — ratio of maximum to minimum flow that can be measured with the specified accuracy; higher for V-notch, low for orifice meter.

PREVIOUS YEAR QUESTIONS

Accuracy, precision, drift — state the principle of flow measurement using a Venturi tube.

[OPSC·CSE 2022–23 · P2/Q.11(b) · 5M]

2.2 General Rules of Good Practice (any device)

- ***Approach conditions*** : straight, prismatic approach length ≥ 10× channel width upstream; free of eddies and cross-currents; water surface tranquil at the gauge section.
- ***Levelling*** : crest / throat level; staff gauge vertical; zero of the gauge at the crest / throat elevation.
- ***Sedimentation*** : keep the upstream pool clear of silt; clean the crest before every reading.
- ***Reading*** : read to the nearest millimetre; average of three readings taken at 30 s intervals; use a stilling well to damp waves.
- ***Free flow / submergence*** : verify the tail-water elevation is below the crest by the minimum specified drop; report submergence ratio for flumes.
- ***Calibration*** : compare with a volumetric or current-meter measurement at commissioning and once per season.
- ***Record*** : log gauge readings, discharge, tail-water, date, time and observer; correct systematically for bias.

Source: Michael §10.2; Modi §7.2; ISO 1438 & 9826 field guidelines.

3 WEIRS — RECTANGULAR, CIPOLETTI, TRIANGULAR, TRAPEZOIDAL (SHARP-CRESTED)

Weir — an ***overflow structure*** built across an open channel, over which water flows in a controlled manner, so that the discharge Q may be computed from the ***head H above the crest***. A sharp-crested (thin-plate) weir has a thin plate (2–3 mm) with a sharp upstream edge; the nappe (falling sheet) springs free of the crest. It is the standard laboratory-grade water-measurement device.

3.1 Rectangular (Sharp-Crested) Weir

The simplest and most-used farm-outlet weir. Derived from Bernoulli's energy equation integrated across the water column above the crest. If the weir spans the full width of the channel there are no ***end contractions***; if the crest is narrower than the channel there are one or two end contractions and the effective length is reduced.

$$Q = (2/3) \cdot C_d \cdot L \cdot \sqrt{(2\,g)} \cdot H^{3/2}$$

Rectangular weir. Q in m^3/s; L = effective crest length (m); H = head over crest (m); g = 9.81 m/s^2; C_d typically 0.61–0.63 for a well-formed sharp crest.

$$L_{eff} = L - n \cdot 0.1 \cdot H \quad \text{(Francis correction)}$$

n = 0, 1 or 2 for suppressed, single- or double-contracted weir. Reduces L by 0.1 H for each end contraction.

POINTS TO REMEMBER

- ***C_d value*** : 0.62 typical for sharp-crested rectangular weir; 0.611 (Rehbock) with velocity-of-approach correction.
- ***Head range*** : 6 cm ≤ H ≤ ⅔ P (P = crest height) for reliable readings; below 6 cm surface tension distorts the nappe.
- ***Ventilation of nappe*** : air must enter below the nappe; if starved, the pressure drops → Q increases falsely; provide small vent holes.
- ***Suppressed weir*** : L = channel width; needs full ventilation; used in flumes and small channels.
- ***Contracted weir*** : L < channel width; end vortices reduce discharge; apply Francis correction.
- ***Velocity of approach*** : if V_a is appreciable, replace H by H + h_a in the formula and subtract h_a^{1.5}; h_a = V_a² / 2g.

3.2 Cipoletti (Trapezoidal) Weir

A ***trapezoidal sharp-crested weir with side slopes 1 (horizontal) : 4 (vertical)***. The extra area of flow on the two inclined sides exactly compensates for the discharge lost to end contractions on a plain rectangular weir, so the discharge formula reduces to the ***suppressed-rectangular form*** with no contraction correction needed.

$$Q = (2/3) \cdot C_d \cdot L \cdot \sqrt{(2\,g)} \cdot H^{3/2} \quad \text{(Cipoletti; } C_d \approx 0.63\text{)}$$

L = crest length at the top of the vertical section. No end-contraction correction. Alternative: Q = 1.859 · L · H^{3/2}.

Cipoletti vs Rectangular — the frequent PYQ

Feature	Rectangular	Cipoletti
Shape	Rectangular notch, vertical sides	Trapezoidal notch, sides 1:4 (H:V)
End contractions	May be suppressed or contracted; Francis correction (L − 0.1 nH) needed if contracted	No correction — side slope compensates
Formula	$Q = (2/3) \cdot C_d \cdot L \cdot \sqrt{(2g)} \cdot H^{1.5}$ with L_eff	Same formula with L (crest at top of vertical); simpler in the field
C_d	≈ 0.62	≈ 0.63
Head range	≥ 6 cm; H ≤ 0.5 P	Same
Ease of computation	Requires effective L	Direct — no correction
Best use	Larger flows in wider channels	Small farm channels; frequently used at head-regulators
Nappe ventilation	Must be ventilated	Same
Standard formula	$Q = 1.84 \cdot L_{eff} \cdot H^{1.5}$ (metric)	$Q = 1.859 \cdot L \cdot H^{1.5}$

PREVIOUS YEAR QUESTIONS

- E Differentiate between Cipoletti weir and rectangular weir. [IFoS 2021 · P1/7(a·i) · 5M]
- Define a weir. Draw the neat sketch of a rectangular weir placed in a channel and label it. [IFoS 2016 · P1/5(a) · 10M]

Rectangular sharp-crested weir — section & plan

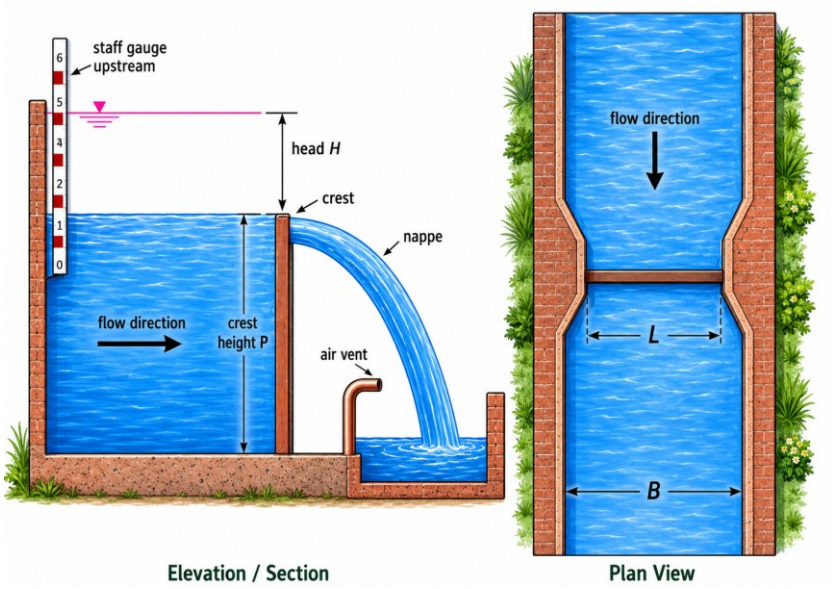


Fig. 3.1 — Rectangular sharp-crested weir: section showing nappe, head H and crest height P; plan showing crest length L in the channel.

3.3 Triangular (V-Notch) Weir

A ***V-shaped thin-plate notch*** with the vertex pointing downwards. Its parabolic Q–H relation makes it the ***most sensitive weir for small discharges*** — the head varies noticeably even for small changes in Q. Standard central angles are 90° (right-angled), 60°, 45°, 30° and 22½°.

$$Q = (8/15) \cdot C_d \cdot \tan(\theta/2) \cdot \sqrt{(2\,g)} \cdot H^{5/2}$$

Triangular weir; θ = full central angle at the vertex; C_d ≈ 0.58–0.60. For θ = 90°, simplifies to Q = 1.417 · H^(5/2) (with C_d = 0.60).

NOTES

- ***Best sensitivity for small Q*** : H depends on Q^0.4 → resolution grows as flow drops; ideal for canal turnouts < 100 L/s.
- ***Head range*** : 6 cm ≤ H ≤ 0.6 m; nappe must fall freely and be well aerated.
- ***C_d ≈ 0.58*** : for a well-formed 90° notch — accepted BIS/ISO value.
- ***No end contraction correction*** : V-notch has no crest length; all cross-section is contracted equally.

3.4 Trapezoidal Weir (general)

If side slopes differ from the Cipoletti 1:4, the trapezoidal weir behaves as a rectangular weir plus a triangular weir added on either side. Discharge is the sum of the two components:

$$Q = (2/3) \cdot C_{d1} \cdot L \cdot \sqrt{(2\,g)} \cdot H^{3/2} + (8/15) \cdot C_{d2} \cdot \tan(\theta/2) \cdot \sqrt{(2\,g)} \cdot H^{5/2}$$

L = crest length at the vertical section; θ = full angle between the two inclined sides; C_d1 and C_d2 are the coefficients for the rectangular and triangular components respectively.

PREVIOUS YEAR QUESTIONS

- Write in brief on the following: (i) Venturi meter (ii) Parshall flume (iii) Cipolletti weir (iv) Tensiometer.
  [IFoS 2016 · P1/6(a) · 10M]
- Give the mathematical expressions for measurement of water flow by orifice (submerged and free flow), trapezoidal weir, 90° V-notch and rectangular weir with appropriate sketches.
  [AP·PSC RFO 2012 · Q.3(D) · 8M]

V-notch and Cipoletti weir — plate views

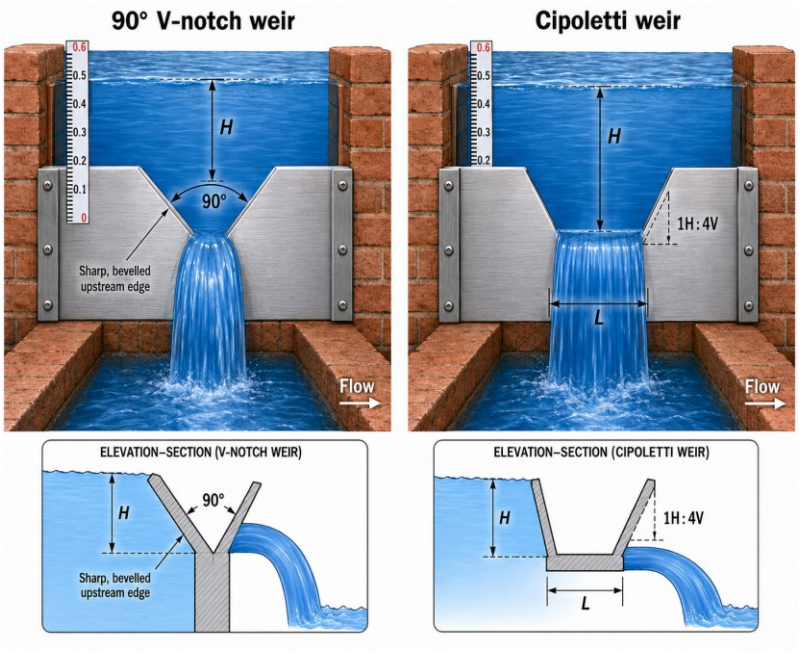


Fig. 3.2 — V-notch (ϑ = 90°) and Cipoletti (side slope 1H:4V) weir plates; sharp-crested thin-plate design.

◆ **WORKED NUMERICAL — *Rectangular → V-notch weir (depth over V-notch)*** **[OPSC·CSE 2020–21 · P1/Q.2(c)(ii) · 12M]**

Problem. *Water flows over a rectangular weir 1 m wide at a depth of 150 mm and afterwards passes through a triangular right-angled weir. Taking C_d for the rectangular and triangular weir as 0.62 and 0.59 respectively, find the depth over the triangular weir.*

Given. Rectangular weir: L = 1 m, H_R = 150 mm = 0.15 m, C_d,R = 0.62. Triangular weir: right-angle (θ = 90°), C_d,T = 0.59. Continuity: same Q flows over both.

Formula. Rect: $Q = (2/3)\cdot C_{d,R}\cdot L\cdot\sqrt{(2g)}\cdot H_R^{(3/2)}$.

Tri: $Q = (8/15)\cdot C_{d,T}\cdot\tan(\theta/2)\cdot\sqrt{(2g)}\cdot H_T^{(5/2)}$. Equate & solve for H_T.

Step 1 Q over the rectangular weir. $Q = (2/3)(0.62)\ (1)\ (\sqrt{19.62})\ (0.15)^{(1.5)}$

$= 0.4133 \times 4.429 \times 0.0581$

$Q = 0.1064\ m^3/s.$

Step 2 Coefficient of the triangular weir. $K_T = (8/15)\cdot(0.59)\cdot\tan 45°\cdot\sqrt{19.62}$

$= 0.5333 \times 0.59 \times 1 \times 4.429 = 1.3938.$

Step 3 Solve H_T. $Q = K_T \cdot H_T^{(5/2)} \rightarrow H_T = (Q / K_T)^{(2/5)}$

$= (0.1064 / 1.3938)^{(0.4)}$

$=$ **0.3573 m ≈ 357.3 mm.**

Result. Depth over the triangular weir H_T ≈ 0.357 m (357 mm).

Unit check. $m^3/s / (m^{(5/2)} / s) = m^{(5/2)} \rightarrow$ root fifth gives m. ✓

◆ **WORKED NUMERICAL — *Discharge over a V-notch, θ = 80°*** **[AP·PSC RFO 2018 · Q.8(c) · 4M (part)]**

Problem. *Calculate the discharge over a triangular notch of angle 80° when the water head over the*

notch is 0.40 m. Assume the standard value of the coefficient of discharge.

Given. θ = 80°; H = 0.40 m; take C_d = 0.60 (standard).

Formula. $Q = (8/15)\cdot C_d\cdot\tan(\theta/2)\cdot\sqrt{(2g)}\cdot H^{5/2}$.

Substitution. $Q = (0.5333)\ (0.60)(\tan 40°)(\sqrt{19.62})\ (0.40)^{5/2}$

$= 0.320 \times 0.839 \times 4.429 \times 0.1012 =$ **$0.1204\ m^3/s = 120.4\ L/s.$**

Result. $Q \approx 0.120\ m^3/s$ (120 L/s).

4 BROAD-CRESTED WEIRS · END CONTRACTIONS · SUBMERGED WEIRS · INSTALLATION RULES

4.1 Sharp-Crested vs Broad-Crested Weir

Feature	Sharp-crested (thin-plate)	Broad-crested
Crest	Sharp bevelled edge, 2–3 mm thick	Wide rectangular crest, breadth b in flow direction; b > 0.4 H
Nappe	Springs clear of the crest	Sits on the crest — no free nappe
Formula	$Q = (2/3)\cdot C_d\cdot L\cdot\sqrt{(2g)}\cdot H^{1.5}$; $C_d \approx 0.62$	$Q = C_d\cdot L\cdot(2/3)^{1.5}\cdot\sqrt{g}\cdot H^{1.5} \approx 1.71\cdot C_d\cdot L\cdot H^{1.5}$; $C_d \approx 0.85–1.0$
Head range	6 cm ≤ H ≤ 0.5 P; sensitive to small Q	0.15 m ≤ H ≤ 1.5b; suits larger flows
Accuracy	± 2 %	± 3–5 %
Aeration	Needs air vent below nappe	Not needed
Silt & debris	Susceptible — silt reduces H	Withstands silt & floating debris
Use	Farm outlets, laboratory	Canals, spillways, permanent measurement structures

$$Q_{broad} \approx 1.705 \cdot C_d \cdot L \cdot H^{3/2} \quad \text{(broad-crested, English/SI, } C_d \approx 0.85–1.0)$$

Simplified broad-crested-weir equation. The number 1.705 = $(2/3)^{1.5}\cdot\sqrt{g}$ in SI.

4.2 End Contractions and Velocity of Approach

END CONTRACTIONS (FRANCIS RULE)

When a rectangular sharp-crested weir crest is narrower than the channel, water at each end contracts as it passes over the crest, reducing effective width. Francis proposed a linear correction:

$$L_{eff} = L - n \cdot 0.1 \cdot H$$

n = 0 (suppressed), 1 (single contraction), 2 (both ends contracted). Valid when L > 3H.

VELOCITY OF APPROACH

Where the upstream cross-section is small, the water arrives at the crest with an appreciable velocity V_a. This adds a velocity head $h_a = V_a^2/2g$ to the effective head. The corrected discharge equation for a rectangular weir is:

$$Q = (2/3) \cdot C_d \cdot L_{eff} \cdot \sqrt{(2\,g)} \cdot [\,(H + h_a)^{3/2} - h_a^{3/2}\,]$$

Iterate: assume $V_a = 0$, get first Q; compute $V_a = Q / A_{up}$; get h_a; substitute; repeat until convergent.

4.3 Submerged Weirs

A weir is ***submerged (drowned)*** when the tail-water level rises above the crest, so the nappe is not free. Discharge falls below the free-flow value and depends on both upstream head H_1 and downstream head H_2.

$$Q_{sub} = Q_{free} \cdot [\,1 - (H_2 / H_1)^{3/2}\,]^{0.385} \quad \text{(Villemonte, 1947)}$$

Submerged-weir correction. Q_{free} = free-flow discharge at head H_1; H_2 = tail-water depth above the crest. Also expressed as $Q_{sub} = Q_{free} \cdot f(\sigma)$, where $\sigma = H_2/H_1$ is the submergence ratio.

MODULAR LIMIT

Every weir has a ***modular limit*** — the maximum submergence at which free-flow calibration still applies. For a sharp-crested rectangular weir the modular limit is $\sigma \approx 0.66$; above it, tail-water gauge must be recorded and the submerged formula used.

4.4 Installation & Operation Rules (any weir)

- ***Straight, prismatic approach channel*** : length ≥ 10 × channel width upstream; free of bends and obstructions.
- ***Adequate crest height P*** : P ≥ 3H so that velocity of approach is negligible; else apply V_a correction.
- ***Level & vertical crest*** : crest strictly horizontal; upstream face vertical; the sharp edge must be square.
- ***Sharp crest, thin plate*** : bevelled at 45° on the downstream side to a 2–3 mm-thick edge; smooth finish.
- ***Stilling well for gauge*** : staff gauge upstream, at 3 H to 4 H from the crest, in a stilling well to damp waves; datum = crest level.
- ***Free nappe & aeration*** : air must enter freely below the nappe; provide vent pipes on suppressed weirs.
- ***Free flow verification*** : tail-water at least (H/3) below the crest; else record it and apply submerged correction.
- ***Clean & maintain*** : remove silt, moss and debris from the upstream pool and the crest before every reading; recalibrate seasonally.
- ***Head range*** : 6 cm ≤ H ≤ 0.5 P for sharp-crested; 0.15 m ≤ H ≤ 1.5 b for broad-crested.

PREVIOUS YEAR QUESTIONS

Describe a weir. In order to ensure reliable results from a weir, what rules need to be followed during weir installation and operation?

[UK·PSC RFO (Mains) 2021 · Q.3(i) · 10M]

WORKED NUMERICAL — *Rectangular weir (40 cm × 10 cm head) — all cases* [OPSC·CSE 2015–16 · P1/Q.3(a) · 30M]

Problem : *Compute the discharge of a rectangular weir 40 cm long with a head of 10 cm under the following conditions: (a) no end contractions (suppressed); (b) two end contractions; (c) one end contraction; (d) with velocity of approach; (e) as a broad-crested weir. Take C_d = 0.62 for sharp-crested and 0.85 for broad-crested. Approach channel 60 cm wide × (H + 5 cm) deep.*

Given. L = 0.40 m; H = 0.10 m; C_d = 0.62 (sharp), 0.85 (broad); channel width 0.60 m.

Formula. $Q = (2/3)\cdot C_d \cdot L_{eff} \cdot \sqrt{(2g)} \cdot H^{3/2}$. With V-approach, replace H by (H + h_a) and subtract $h_a^{3/2}$.

(a) Suppressed weir. $L_{eff} = L = 0.40$ m. $Q = (2/3)(0.62)(0.40)(4.429)(0.10)^{1.5}$

$= 0.4133 \times 4.429 \times 0.03162 =$ **$0.02316\ m^3/s \approx 23.16\ L/s$.**

(b) Two end contractions. $L_{eff} = L - 0.2H = 0.40 - 0.02 = 0.38$ m.

$Q = 0.02316 \times 0.38 / 0.40 =$ **$0.02200\ m^3/s \approx 22.00\ L/s$.**

(c) One end contraction. $L_{eff} = L - 0.1H = 0.39$ m. $Q = 0.02316 \times 0.39 / 0.40$

$Q =$ **$0.02258\ m^3/s \approx 22.58\ L/s$.**

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(d) With velocity of approach.

Approach area $A_{up} = 0.60 \times (0.10 + 0.05) = 0.09\ m^2$.

$$V_a = Q_a / A_{up} = 0.02316 / 0.09$$

$$= 0.257\ m/s.$$

$$h_a = V_a^2 / 2g = 0.0034\ m.$$

$$Q = (2/3)(0.62)(0.40)(4.429)[(0.1034)^{\{1.5\}} - (0.0034)^{\{1.5\}}]$$

$$= 1.099 \times (0.03327 - 0.000198)$$

$$= \mathbf{0.02420\ m^3/s \approx 24.20\ L/s.}$$

(e) Broad-crested ($C_d = 0.85$).

$$Q = 1.705 \cdot C_d \cdot L \cdot H^{\{1.5\}}$$

$$= 1.705 \times 0.85 \times 0.40 \times 0.03162$$

$$= \mathbf{0.01833\ m^3/s \approx 18.33\ L/s.}$$ (Alternatively with $C_d = 0.55$ form $Q = 0.01190\ m^3/s$.)

Result summary. (a) 23.16, (b) 22.00, (c) 22.58, (d) 24.20, (e) 18.33 L/s. End contractions reduce Q; velocity of approach increases it; broad-crested crest gives lower Q for the same head.

5 CRITICAL-DEPTH FLUMES — PARSHALL & CUT-THROAT

A ***critical-depth flume*** is a rigid channel with a contracted throat that forces the flow to pass through critical depth. Because critical depth is uniquely related to discharge, a single upstream depth reading gives Q — no downstream reading is needed under free flow. Flumes are ***self-cleaning*** and need very little head loss (Parshall: 0.05–0.20 m).

5.1 Parshall Flume

WORKING PRINCIPLE

The Parshall flume consists of ***(i) a converging section*** that accelerates the flow, ***(ii) a throat with a downward-sloping floor*** where critical depth occurs and forms a standing wave, and ***(iii) a diverging section with an upward-sloping floor*** that recovers head. Upstream gauge H_a is read in a stilling well; a second gauge H_b in the throat is needed only if the flume is submerged.

$$Q = K \cdot W \cdot H_a^{\{n\}} \quad \text{(Parshall)}$$

K and n depend on the throat width W. For W = 1 ft (0.305 m): $Q = 0.372 \cdot H_a^{\{1.522\}}$ (m^3/s). Standard sizes W = 1 in to 50 ft; free flow ensured while $H_b/H_a \le 0.7$.

ADVANTAGES OF PARSHALL

- ***Self-cleaning*** : throat velocity is high; sediment does not deposit.
- ***Low head loss*** : only 15–25 % of the head above the crest — the least of any weir/flume.
- ***Free-flow range wide*** : submergence up to 70 % without correction; up to 95 % with submergence correction.
- ***Simple field reading*** : only one gauge under free flow.
- ***Standard sizes*** : well-tabulated for W = 1 in to 50 ft; extensive rating tables.

5.2 Cut-Throat Flume

Developed by Skogerboe et al. as a ***simplified, flat-bottomed variant of the Parshall***. It has converging and diverging walls but no parallel throat and no floor slope — the whole flume rests on the channel bed. This makes it easy and cheap to fabricate, portable, and easy to install as a temporary measurement.

$$Q = C \cdot H_a^{\{n\}} \quad ; \quad Q_{sub} = Q_{free} / [1 - (H_b/H_a)^{n1}]$$

Cut-throat flume; C and n from calibration tables for the given (throat width, flume length). Free flow while $H_b/H_a \leq 0.65$.

5.3 Parshall vs Cut-Throat (frequent PYQ)

Feature	Parshall flume	Cut-throat flume
Bottom	Sloped in throat (down) and diverging section (up)	Flat throughout — sits on channel bed
Throat	Parallel-walled throat with sloped floor	No parallel throat — converging + diverging only
Fabrication	Complex — bevelled floor & precise geometry	Simple — thin plates on flat bed
Portability	Permanent installation	Portable — good as a temporary field flume
Cost	Higher	Lower
Free-flow range (H_b/H_a)	Up to 0.7 free, 0.95 with correction	Up to 0.65 free, 0.90 with correction
Head loss	0.05–0.20 m (low)	0.10–0.25 m
Calibration	Standard, widely tabulated for W = 1 in–50 ft	Also standardized (Skogerboe et al.) for W = 25–1830 mm
Best use	Permanent gauging in canals, WUAs, farms	Temporary/portable measurement; small farm channels

Parshall flume — plan & profile with three characteristic sections

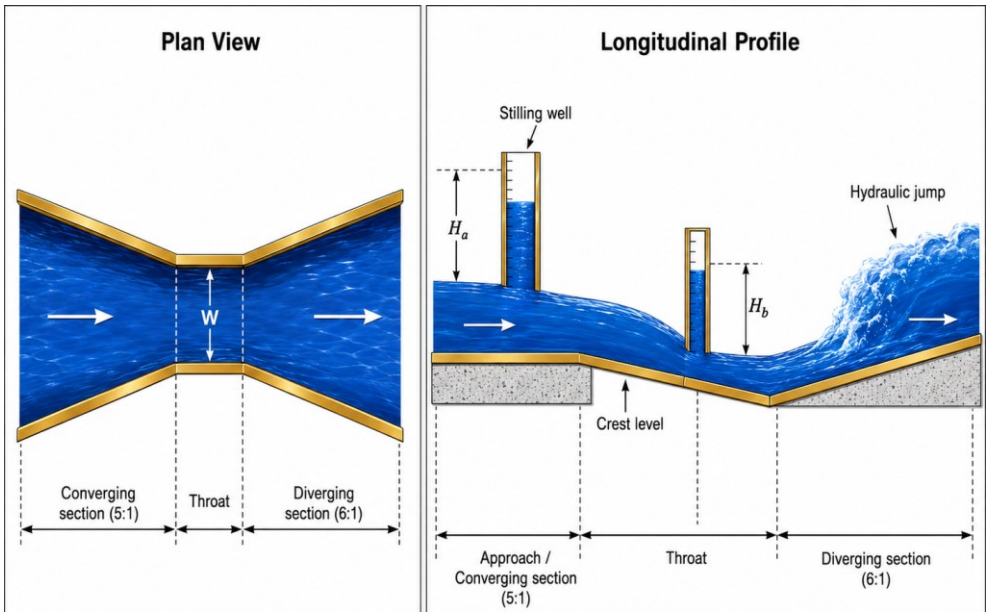


Fig. 3.3 — Parshall flume: plan view showing converging–throat–diverging sections; longitudinal profile with H_a and H_b gauges and the downstream hydraulic jump.

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PREVIOUS YEAR QUESTIONS

- What is Parshall flume? Explain the working procedure of Parshall flume. How is it different from cut-throat flume?

  [IFoS 2018 · P1/5(e) · 8M]

- Write short notes on: Pitot tube; Cut-throat flume. [AP·PSC RFO 2018 · Q.8(c) · 4M (short-note part)]

Source: Michael §10.6; Modi §7.9; Skogerboe et al., Cut-throat Flumes, USU 1972; USBR Water Measurement Manual §8.

6 ORIFICE-TYPE DEVICES — FREE, SUBMERGED & ORIFICE BUCKET

Orifice — a ***sharp-edged opening*** in the side or floor of a tank/channel through which water discharges. If the downstream water level is below the top of the opening the orifice ***discharges freely***; if it is above the top of the opening the orifice is ***submerged***.

6.1 Free Orifice

$$Q = C_d \cdot a \cdot \sqrt{(2\,g\,H)}$$

Free (small) orifice. a = area of orifice; H = head from centreline of orifice to water surface; $C_d \approx 0.61$ for a sharp-edged orifice (product of coefficients of contraction $C_c \approx 0.64$ and velocity $C_v \approx 0.98$).

6.2 Submerged Orifice

$$Q = C_d \cdot a \cdot \sqrt{(2\,g \cdot \Delta H)}$$

Submerged orifice. ΔH = difference in water surface between upstream and downstream; $C_d \approx 0.61$.

6.3 Orifice Bucket (Constant-Head Orifice)

The ***orifice bucket*** (also called constant-head orifice or CHO turnout) is a farm-outlet control consisting of two gates in series with a bucket-shaped stilling pool between them. The upstream gate meters the flow through a submerged rectangular orifice while the downstream gate holds the head across the orifice constant. Because ΔH is fixed by the downstream gate, Q depends only on the orifice opening — the operator sets the discharge by adjusting one gate.

ADVANTAGES

- ***Constant head*** : ΔH held by downstream gate → Q independent of tail-water changes.
- ***Simple field operation*** : open the upstream gate to a marked opening → known Q.
- ***Wide range*** : single structure covers a large Q range by varying the orifice opening.
- ***Low head loss*** : compared with weirs at the same accuracy.

Free & submerged orifice — sections

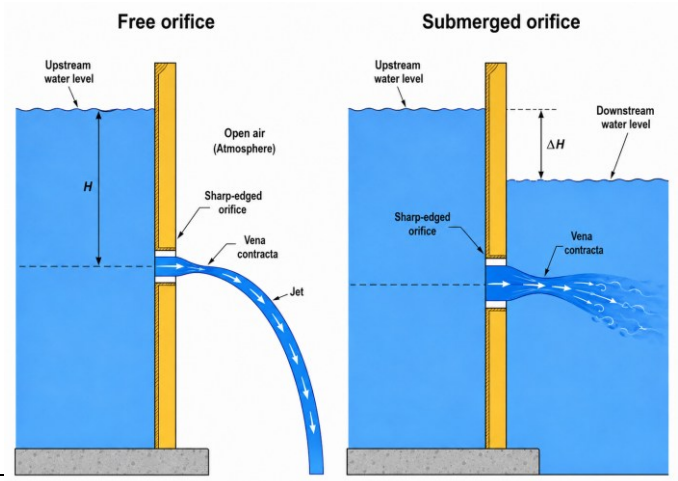


Fig. 3.4 — Free orifice (H measured from centreline to upstream surface) and submerged orifice (ΔH between upstream and downstream surfaces).

7 PIPE-FLOW MEASUREMENT — VENTURI METER, PITOT TUBE, ORIFICE METER

7.1 Venturi Meter — Principle & Formula

The Venturi meter is a converging–throat–diverging tube inserted in a pipe. It measures discharge from the ***differential pressure*** between the upstream (section 1) and the throat (section 2). Application of Bernoulli's equation between the two sections, together with continuity, gives the theoretical velocity at the throat. Multiplying by C_d accounts for real-fluid losses; the ***gradual conical diverging section*** (5°–7° cone) recovers most of the pressure head, so overall head loss is low (10–15 %).

$$Q = C_d \cdot a_1 \cdot a_2 \cdot \sqrt{(2\,g\,H)} / \sqrt{(a_1^2 - a_2^2)}$$

Venturi meter. a_1 = pipe area, a_2 = throat area, H = manometer differential head; C_d ≈ 0.95–0.99. Written in the common 'coefficient × √H' form: Q = k √H with k = C_d a_1 a_2 √(2g) / √(a_1² − a_2²).

POINTS TO REMEMBER

- ***Bernoulli-based*** : assumes steady, incompressible, frictionless flow between the tappings — C_d corrects the assumption.
- ***Ratio a_2/a_1*** : typically 0.4–0.7; smaller ratio → larger H but higher head loss.
- ***Head loss*** : only 10–15 % of the differential (long diverging cone) — the lowest of any pipe-flow meter.
- ***C_d ≈ 0.98*** : well-machined meters approach unity; wear and cavitation cause drift.
- ***Straight upstream length*** : ≥ 5 pipe diameters upstream and 3 D downstream.
- ***Independent of Reynolds number*** : above Re ≈ 10^5, C_d essentially constant.

PREVIOUS YEAR QUESTIONS

State the principle of flow measurement using a Venturi tube.

[OPSC·CSE 2022–23 · P2/Q.11(b) · 5M (Venturi part)]

7.2 Orifice Meter

A thin plate with a sharp-edged central hole inserted between flanges. Cheaper than a Venturi but has higher permanent head loss (40–90 % of the differential) because the jet expansion is abrupt.

$$Q = C_d \cdot a_o \cdot \sqrt{(2\,g\,H)} / \sqrt{(1 - (a_o/a_1)^2)}$$

Orifice meter. a_o = orifice area, a_1 = pipe area, H = manometer differential; C_d ≈ 0.60–0.65 for standard concentric orifices.

7.3 Pitot Tube — Principle & Working

A Pitot tube is a small L-shaped or U-shaped tube whose open end faces the flow. The moving water is brought to rest at the tube tip; the rise of water above the free surface (or above the static pressure tapping) is the ***velocity head*** at that point.

$$u = C_v \cdot \sqrt{(2\,g\,h)} \quad ; \quad Q = \int u \cdot dA$$

Pitot tube. u = local velocity, h = stagnation-static differential head, C_v ≈ 0.97–1.00. Traverse across the section to obtain the velocity profile and integrate for Q, or apply a factor k (≈ 0.85 for turbulent pipe flow) if using the centreline velocity alone.

NOTES ON THE INVERTED-PITOT ARRANGEMENT

- ***Two tappings*** : one facing upstream (stagnation) and one flush with the pipe wall (static); the difference measures the velocity head.
- ***Field application*** : mounted in tube-well discharge pipes or on canal current-meter frames; readings taken by manometer or a transparent standpipe.

- ***Corrections*** : Pitot needs correction for compressibility only at very high V (not agriculture); at low Re the tube reading corresponds to point velocity — traverse required.
- ***Insertion depth*** : for a rough estimate use 0.632 R (point of mean velocity, Prandtl's ⅐-power law) as insertion depth to read mean pipe velocity in one shot.

◆ **WORKED NUMERICAL — *Discharge from an inverted-Pitot reading*** **[OPSC·CSE 2018–19 · P1/Q.4(a)(ii) · 12M]**

Problem. *The rise of water in an inverted-Pitot tube fitted in a pipe of 10 cm diameter showed 3.1 m and 0.8 m above the water surface (stagnation and static columns respectively). Determine the flow rate in the pipe.*

Given. D = 0.10 m; h_stag = 3.1 m; h_static = 0.8 m → differential h = 3.1 − 0.8 = 2.3 m.

Formula. u = √(2 g h) (point velocity at Pitot tip).

Q = A · V_mean,

with V_mean = k · u_centre (k ≈ 0.85 for turbulent pipe flow) or V_mean = u itself if Pitot at radius 0.632 R.

Step 1 Velocity at the tip. u = √(2 × 9.81 × 2.3) = √45.126 = 6.718 m/s.

Step 2 Pipe area. A = π D² / 4 = π × (0.10)² / 4 = 0.007854 m².

Step 3 Discharge (centreline reading). Assuming the tip is at the pipe centre: Q_centre = A · u

= 0.007854 × 6.718 = 0.05276 m³/s ≈ 52.76 L/s.

Step 4 Mean-velocity correction. Q_mean = A · 0.85 · u = 0.007854 × 5.710 = 0.04485 m³/s ≈ 44.85 L/s.

Result. Q ≈ 52.76 L/s (centreline reading) or ≈ 44.85 L/s (mean-velocity correction, k = 0.85). State the assumption alongside the answer.

Unit check. [m²] × [m/s] = [m³/s] ✓.

PREVIOUS YEAR QUESTIONS

Write in brief on the following: (i) Venturi meter (ii) Parshall flume (iii) Cipolletti weir (iv) Tensiometer.
[IFoS 2016 · P1/6(a) · 10M (Venturi + Parshall + Cipoletti + Tensiometer)]

Pipe-flow meters — Venturi, Orifice, Pitot

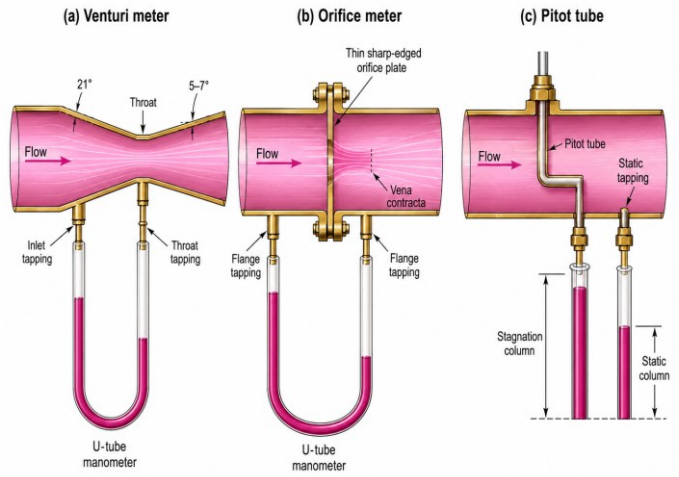


Fig. 3.5 — Three pipe-flow meters: Venturi (low head loss), Orifice meter (high head loss but cheap), Pitot tube (point-velocity measurement).

8 COORDINATE METHOD FOR DISCHARGING HORIZONTAL PIPES

For a pipe discharging freely into the atmosphere in a horizontal direction (typical of tube-well outlets, siphons and drain outfalls), the ***trajectory of the jet*** can be used to compute the exit velocity — no manometer or gauge is needed. The jet, once it leaves the pipe, moves horizontally at velocity V while falling vertically under gravity.

8.1 Derivation

Set the pipe outlet as the origin. Let (x, y) be the horizontal and vertical coordinates of a chosen point on the jet measured from the outlet. Time for the jet to fall a distance y is $t = \sqrt{(2y / g)}$; horizontal distance travelled in that time is $x = V \cdot t$. Eliminating t:

$$V = x \cdot \sqrt{(g / (2y))} \quad ; \quad Q = A \cdot V = (\pi D^2 / 4) \cdot x \cdot \sqrt{(g / (2y))}$$

Coordinate method for a horizontally-discharging pipe. x = horizontal distance to the chosen point on the jet; y = vertical drop to that point (both measured from the pipe outlet); D = internal pipe diameter.

8.2 Field Procedure

- ***Level the pipe outlet*** : horizontal; the outlet must be a clean, square-cut opening in air.
- ***Set a coordinate frame*** : origin at the pipe outlet; horizontal x-axis in the direction of flow; vertical y-axis downward.
- ***Choose a fixed y*** : often y = 0.5 m below the pipe centre; measure the horizontal distance x from the outlet to the point where the jet crosses this line.
- ***Repeat & average*** : take three readings; the jet must flow full for the method to apply.
- ***Compute V, Q*** : apply the formula above with the pipe's internal diameter.

PREVIOUS YEAR QUESTIONS

Discuss the coordinate method of measuring discharge from pipes discharging horizontally.

[IFoS 2020 · P1/5(b) · 8M]

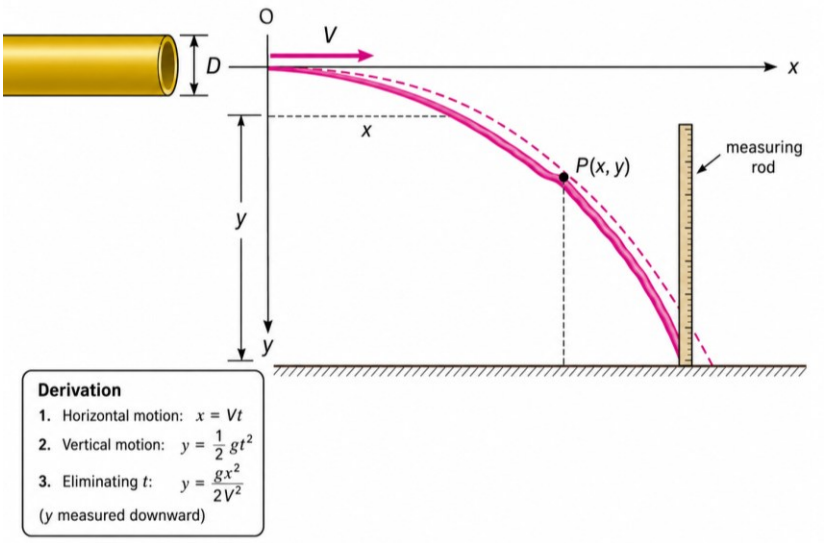


Fig. 3.6 — Coordinate method: horizontal outlet pipe with jet trajectory; measurement of (x, y) yields V and Q.

Coordinate-method setup — horizontal pipe & jet trajectory

9 VELOCITY-AREA METHODS — CURRENT METER AND FLOATS

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The ***velocity-area principle*** — Q = A × $\bar{V}$ — is the basis of all river-gauging and large-channel discharge measurement. The cross-section area A is measured by cross-sectional survey; the mean velocity $\bar{V}$ is obtained by point-velocity measurements integrated over the section.

9.1 Current-Meter Method

WORKING PRINCIPLE

A current meter has a horizontal-axis cup wheel (Price or Pygmy) or a vertical-axis propeller (Ott, Neyrpic). The wheel rotates at a rate proportional to the local water velocity; a rating equation (calibration) converts revolutions per second to velocity:

$$V = a + b \cdot N$$

Current-meter rating. N = revolutions per second; a and b are calibration constants supplied by the manufacturer. For a Price meter, a ≈ 0.01–0.03, b ≈ 0.55–0.65 in SI.

FIELD METHOD — A CHANNEL GAUGING

- ***Divide the section*** : into 10–20 vertical strips; record depth d_i and width w_i of each strip.
- ***Measure velocity at each vertical*** : by the ***one-point method*** — velocity at 0.6 d from the surface — for depths < 0.75 m; ***two-point method*** — average of velocities at 0.2 d and 0.8 d — for deeper verticals; ***three-point method*** — 0.2, 0.6, 0.8 depth, average — for very deep verticals.
- ***Compute strip discharges*** : Q_i = w_i · d_i · $\bar{V}$_i; total Q = Σ Q_i.
- ***Accuracy*** : well-executed gauging gives ± 2–5 %; needs calibration in a laboratory towing tank.

9.2 Float Method

A cheap, quick, low-accuracy method for shallow channels. A ***surface float*** is timed over a measured reach L; the surface velocity V_s is obtained. Because surface velocity exceeds mean velocity, a coefficient α ≈ 0.85 (0.80 for rough, 0.95 for smooth) is applied to get the mean:

$$\bar{V} = \alpha \cdot V_s \quad ; \quad Q = A \cdot \bar{V}$$

Float method. α ≈ 0.85 for typical earthen channels; use a sub-surface (rod) float for better accuracy where possible.

TYPES OF FLOATS

- ***Surface floats*** : wooden discs or bottles; measure V_s only; simplest & least accurate.
- ***Sub-surface (canister) floats*** : weighted so they sit below the surface; give velocity closer to the mean.
- ***Rod (tube) floats*** : a hollow rod almost as long as depth; the rod moves at the depth-averaged velocity — best of the three.

PREVIOUS YEAR QUESTIONS

List the different methods of water flow measurement on an agricultural farm for an underground/overground pipeline and for open channel network. Also, briefly discuss their principles of measurement.

[IFoS 2025 · P1/6(a) · 15M]

▣ *Current-meter gauging & three float types*

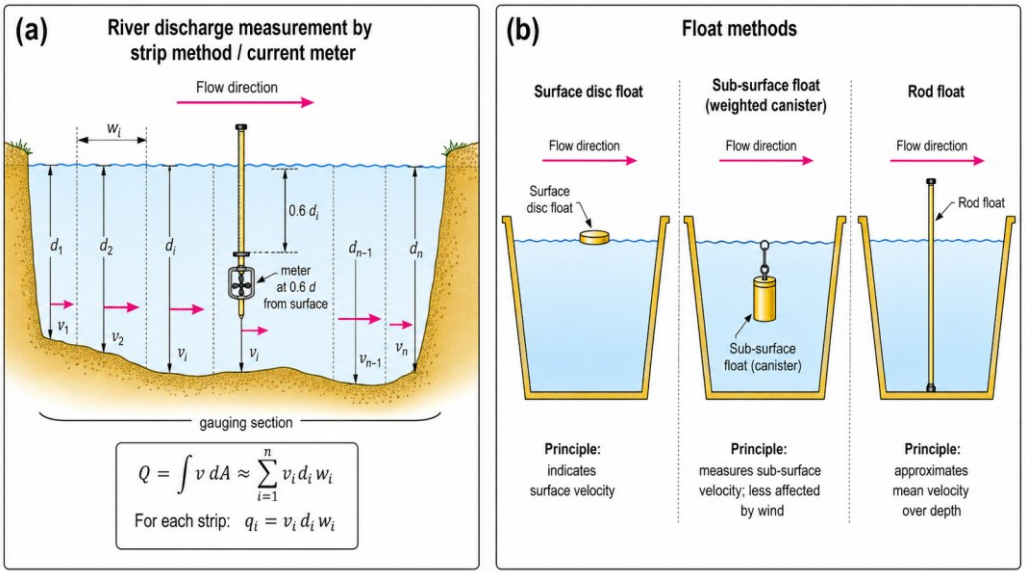


Fig. 3.7 — (a) Current-meter gauging in a divided cross-section; (b) three float types with their measurement depth.

10 UNDERGROUND PIPELINE (UGPL) SYSTEM — CONCEPT, ADVANTAGES, LIMITATIONS

An ***underground pipeline (UGPL) system*** carries irrigation water from the source (tube-well, canal outlet, storage tank) to the field through a network of buried PVC, HDPE or PE pipes, and delivers it to the crop at designed pressure through ***risers and hydrants***. It replaces open earthen channels and eliminates conveyance losses (seepage 20–40 % and evaporation 5–15 % in an earthen network fall almost to zero). UGPL is a standard component of **PMKSY *drip and sprinkler installations*** and of many piped canal-command distribution networks in India.

10.1 Advantages of UGPL

- ***Very high conveyance efficiency*** : no seepage / evaporation → 95–100 % of water reaches the field.
- ***No land loss*** : pipes buried; farming can proceed over the buried alignment; open channels waste 3–5 % of area.
- ***No weed & silt problem*** : closed pipes have no weeds, no silting; no annual cleaning.
- ***Water at pressure*** : head available at each riser feeds sprinkler / drip laterals directly.
- ***Flexibility of layout*** : pipes follow the shortest route irrespective of topography; may cross depressions or rise up gentle slopes without loss.
- ***Reduced management labour*** : no gate operation or channel repair every season.
- ***Longer life*** : PVC 30 years; HDPE 40–50 years, versus 10–15 years of a lined channel.
- ***Fits automation*** : solenoid valves, hydrants and controllers automate field distribution.
- ***Prevents mosquito breeding*** : no stagnant open water at intermediate points.

10.2 Limitations

- ***High initial cost*** : ₹25 000 – ₹80 000 per ha depending on pipe diameter, depth and number of hydrants.
- ***Skilled installation*** : laying, joining, thrust-block and bedding require trained crew.
- ***Vulnerability to water hammer*** : sudden valve closure can burst pipes; needs air / relief valves.
- ***Difficult repair*** : locating a leak in a buried system needs pressure-testing and excavation.

- ***Rodent, root & soil damage*** : shallow buried lines can be damaged by root intrusion and by rodent burrowing.
- ***Air-lock risk*** : air pockets at high points reduce capacity; require vents.
- ***Requires clean water*** : suspended silt causes clogging of hydrants and downstream micro-irrigation emitters.

PREVIOUS YEAR QUESTIONS

Explain about the underground pipeline system with components.

[OPSC·CSE 2022–23 · P1/Q.9(a) · 5M]

11 UGPL COMPONENTS — MAINLINE, SUB-MAIN, RISERS, HYDRANTS, ALFALFA VALVES

A typical UGPL system has three pipe classes (main, sub-main, and field pipes/risers), plus a family of ***outlet, control and protection fittings***. The correct sizing and placement of each is what makes the system deliver design flow at design pressure at every field outlet.

11.1 Pipe Network

- ***Mainline*** : carries the full design flow from source (tube-well, canal outlet, storage tank) to the sub-mains; PVC / HDPE 90–200 mm; buried 60–90 cm below surface; velocity ≤ 1.5 m/s.
- ***Sub-main*** : branches from the mainline at each field block; 50–110 mm; buried; ends in a hydrant or a stand-pipe.
- ***Risers*** : short vertical PVC or GI stub-outs from the sub-main, rising 30–90 cm above the ground; carry the hydrant that connects the surface hose or portable pipe.
- ***Bedding & backfill*** : pipe rests on a 10 cm sand bed; sand cover 10–15 cm above pipe crown before soil backfill; compact in layers.
- ***Thrust blocks***: cast in situ at bends, tees and end-plugs to resist the axial thrust from internal pressure.

11.2 Outlet & Control Devices

HYDRANTS (OUTLET VALVES)

A ***hydrant*** is the surface valve on top of a riser through which water is drawn to the surface pipe, sprinkler lateral or drip hose. Common types:

- ***Alfalfa valve (upright valve)*** : a large, low-head hydrant with a screw-type lid; delivers a big stream to a surface ditch or bay; used with border irrigation.
- ***Orchard valve*** : a small alfalfa valve that fits directly on the riser; used to irrigate individual trees or basins.
- ***Multiple-outlet hydrant (T-hydrant)*** : has two or three quick-couple outlets on a single riser; feeds sprinkler laterals.
- ***Screw-thread hydrant*** : standard threaded outlet for coupling with the sprinkler main-line or portable hose.
- ***Automatic hydrant*** : solenoid-actuated valve for pressurised drip / sprinkler blocks under a controller; enables sectored operation.

PREVIOUS YEAR QUESTIONS

Explain the working of hydrants used in underground pipeline irrigation system.

[OPSC·CSE 2018–19 · P1/Q.4(b)(i) · 8M]

11.3 Working of a Hydrant (Step-by-Step)

- ***Position*** : mounted on a riser stub that projects 30–90 cm above the field; a concrete pad protects the base.
- ***Body & seat*** : cast-iron or GI body with an internal seat; the water enters from below, flows up through the seat and out through the top outlet when open.
- ***Lid / disc*** : a machined disc seated on a rubber ring, lowered onto the seat by a threaded stem; when tight, closes the flow.
- ***Operation*** : turn the handle → threaded stem raises the disc → water passes upward; direction of flow makes water pressure hold the disc off the seat during operation (self-relieving).
- ***Coupling*** : outlet is threaded or quick-couple type; the sprinkler main or portable hose fits and is locked.
- ***Closing*** : reverse handle → disc lowered onto seat by the stem; internal pressure now seals it more tightly (pressure-assisted seal).
- ***Maintenance*** : annual replacement of the rubber seat; grease the stem; check for leaks; drain if freezing is possible.

UGPL system schematic — source to hydrant with all components

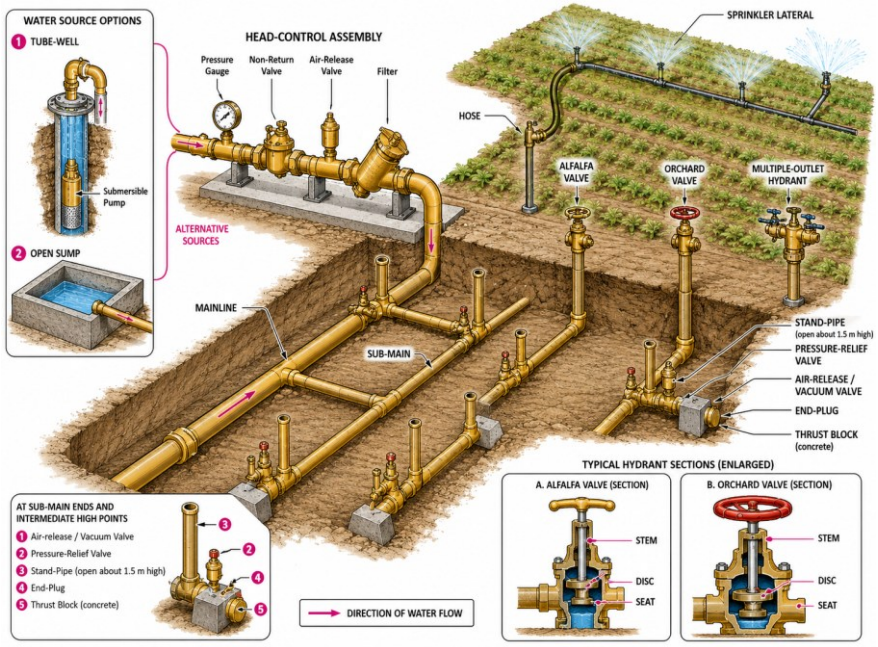


Fig. 3.8 — Complete UGPL system: source → head-control → buried mainline → sub-mains → risers with hydrants; protective air-vent, pressure-relief valve, stand-pipe and end-plug shown at their standard locations.

PREVIOUS YEAR QUESTIONS

- (Refer Ch2 Fig 2.6 for sprinkler head-control unit that connects to UGPL upstream.)
  [IFoS 2016 · P1/6(b) · 10M — cross-referenced]
- Describe the various components of underground pipeline system with the help of a neat diagram.
  [UK·PSC RFO 2015 · Q.2(iii) · 10M]
- Explain about structures and devices used for underground pipeline system and mention common troubles encountered in underground pipelines. [OPSC·CSE 2015–16 · P1/Q.2(a) · 30M]

12 UGPL PROTECTIVE & CONTROL STRUCTURES — AIR VENTS, END PLUGS, STAND-PIPES, RELIEF

Every UGPL needs a set of protective structures whose job is to ***limit internal pressure, admit or release air, and safely absorb transient shocks***. Without them a system will fail within a season through water hammer, air-lock, vacuum collapse or pipe blow-out at bends and end-plugs.

12.1 Air-Vent (Air-Release & Vacuum-Relief) Valves

TWO FUNCTIONS OF AN AIR-VENT

- ***Air-release under pressure*** : during filling and during normal operation, air trapped at high points is released through the vent : prevents air-lock that would choke off flow.
- ***Vacuum relief on shut-down*** : when the pump stops or a downstream valve is closed too quickly, water column separates and creates a vacuum in the pipe. The vent admits air, so atmospheric pressure prevents pipe collapse.

TYPES & PLACEMENT

- ***Small orifice (kinetic) vent*** : releases small pockets of air continuously during operation; usually placed at all high points on the profile.
- ***Large orifice (vacuum) vent*** : admits or releases large volumes when the line fills or drains; placed at the pump discharge and immediately downstream of every isolation valve.
- ***Combination vent*** : both functions in a single body; the standard modern choice.
- ***Location rules*** : all summits of the pipe profile; downstream of pumps; upstream and downstream of every isolating valve; at all dead ends before the plug; every 400–800 m of straight pipe on a flat profile.

PREVIOUS YEAR QUESTIONS

How do air vents and end plugs protect the underground pipeline from damage?

[IFoS 2023 · P1/7(a) · 10M]

12.2 End Plug

An ***end plug*** is a permanent seal at the terminal end of the mainline / sub-main. It resists the axial thrust of the internal pressure ***acting on the pipe cross-section*** ($F = P \cdot A$, potentially several kN even at 2 kg/cm²). It must be:

- ***Backed by a thrust block*** : concrete pad cast against undisturbed soil; sized so soil bearing pressure < allowable.
- ***Fitted with an air-release / vacuum valve*** : prevents air-lock at the closed dead-end and admits air on drain-down.
- ***Provided with a flush plug or valve*** : for periodic flushing of settled silt and biofilm at the dead end.
- ***Solvent-welded or gasketed*** : using pipe-grade cement (PVC) or rubber ring (HDPE); tested to design pressure.

How end plugs & air vents protect the UGPL (the direct PYQ answer)

- ***End plug seals the terminal end*** : prevents water loss and out-flow at the dead-end; withstands longitudinal thrust of the pressurised water column.
- ***Air vent releases trapped air*** : air pockets cause head loss, air-lock, uneven distribution and pressure surges; venting keeps the pipe full-bore.
- ***Air vent admits air on drain-down*** : prevents partial vacuum → prevents pipe collapse (especially thin-wall PVC).

- ***Together, they eliminate the two commonest failure modes*** : blow-out at the plug (axial thrust) and pipe collapse at high points (air-lock / vacuum).

12.3 Stand-Pipe (Over-Flow Stand)

A stand-pipe is a ***vertical open-topped pipe*** (usually 100–200 mm dia., 1.0–1.5 m above ground) tee'd off the buried mainline. It serves three purposes:

- ***Pressure indicator*** : the water level inside equals the piezometric head — the operator can see it.
- ***Over-flow safety*** : if downstream valves close and pressure rises, water simply spills out the top of the stand-pipe, protecting the pipe from bursting.
- ***Air escape / vacuum relief*** : open top admits and releases air freely at that point.

12.4 Pressure-Relief Valve

A ***spring-loaded valve*** set at a pressure just above the design working pressure (say design 3 kg/cm² → relief 3.5 kg/cm²). It automatically opens and discharges water when the pressure exceeds the setting — protects against ***water hammer surges and pump run-out pressures***. Placed near the pump discharge and downstream of every isolating valve on the main.

12.5 Sluice / Butterfly / Non-Return Valves

- ***Sluice (gate) valve*** : full-bore isolation at branches and pump discharge; slow-closing to avoid hammer.
- ***Butterfly valve*** : compact isolation on large mains; can also throttle.
- ***Non-return (check) valve*** : prevents back-flow into the pump when it stops; mandatory downstream of every pump.

PREVIOUS YEAR QUESTIONS

Discuss the specialised structures used with underground pipeline system to control the water and protect the pipeline from damage.

[IFoS 2020 · P1/5(a) · 8M]

13 UGPL COMMON FIELD TROUBLES & REMEDIES

Trouble	Cause	Effect	Remedy
Water hammer / surge	Sudden closure of downstream valve; pump trip; check-valve slam	Pressure rise up to 5–10× design → pipe burst, joint failure	Slow-closing valves; pressure-relief valve at pump; air chambers; NRV downstream of pump; graded stop-start
Air lock	Air trapped at high points; system not fully vented on fill	Reduced flow; uneven distribution among hydrants; noise	Air-release / combination vent at every summit; slow-fill procedure
Vacuum collapse	Rapid drain-down; downstream valve closed while draining	Thin-wall PVC/HDPE crushed; pipe deformation	Vacuum-relief valves at high points and pump discharge; slow shut-down
End-plug blow-out	Axial thrust of internal pressure; missing or under-	Water loss, plot flooding, expensive	Cast thrust block against undisturbed soil; fit air/vacuum

	sized thrust block	repair	vent; use proper solvent weld
Joint leakage	Poor solvent welding, torn rubber ring, differential settlement	Continuous seepage; wasted water; local waterlogging	Careful joint-making; sand bedding; expansion coupling on long straights; test at 1.5× design pressure
Clogging / sedimentation	Silty water; dead-end pipe; low velocity in end sections	Reduced Q at hydrants; downstream micro-irrigation emitter clogging	Provide flush valves at all dead ends; periodic flushing; primary filter at head
Root intrusion	Tree roots enter pipe through joint seals seeking moisture	Reduced flow; joint damage	Route pipes away from trees; use root-barrier sleeves; periodic mechanical cleaning; solvent welded joints (not gasketed) near trees
Rodent damage	Rats/moles chew soft plastic pipe in shallow burial	Small leaks turn into large blow-outs	Bury pipes ≥ 60 cm below surface; sand backfill; concrete encasement in problem areas
UV & thermal damage	Above-ground stub or exposed riser	PVC embrittlement; joint failure	Paint exposed pipe with UV coating; use HDPE risers; sleeve with concrete or GI
Soil settlement	Poor bedding; loose backfill	Sagging pipe; longitudinal cracks	Sand bedding & controlled backfill compaction (85 % Proctor)
Corrosion (steel/GI parts)	Damp saline soil; stray currents	Pitting → leaks at fittings, hydrants	Cathodic protection; epoxy-coated fittings; drain wet points
Freeze damage (cold pockets)	Standing water in shallow pipe	Split pipe on freeze	Depth below frost line; drain to a low point in winter

PREVIOUS YEAR QUESTIONS

Explain about structures and devices used for underground pipeline system and mention common troubles encountered in underground pipelines. (See also §12 for control structures.)

[OPSC·CSE 2015–16 · P1/Q.2(a) · 30M]

MODEL Q For any UGPL protection PYQ, structure the answer as: (a) name and function of each protective structure (air-release, vacuum-relief, end plug with thrust block, stand-pipe, pressure-relief valve, non-return, sluice/butterfly); (b) placement rules — high points, dead ends, pump discharge, downstream of every isolating valve; (c) failure modes prevented — water hammer, air lock, vacuum collapse, plug blow-out; then close with a labelled sketch of a typical mainline showing all six structures.***

14 SUMMARY OF FORMULAE & DEVICE-SELECTION CHART

14.1 Device-Selection Chart

Device	Q range (typical)	Head loss	Accuracy	Best conditions
V-notch (90°) weir	1–100 L/s	≥ 6 cm	± 2 %	Small farm flows; sensitive to low

				Q
Rectangular weir	30–3 000 L/s	≥ 6 cm	± 2 %	Wider channels; larger Q
Cipoletti weir	30–2 000 L/s	≥ 6 cm	± 2–3 %	Farm outlets; simpler formula
Trapezoidal weir	30–5 000 L/s	≥ 6 cm	± 2–3 %	Custom side slopes
Broad-crested weir	0.05–20 m^3/s	≥ 15 cm	± 3–5 %	Permanent installations; large Q
Parshall flume	10 L/s–90 m^3/s	≥ 5 cm (very low)	± 2–5 %	Silty channels; permanent
Cut-throat flume	5 L/s–5 m^3/s	≥ 10 cm	± 3–5 %	Temporary / portable
Free orifice	1–500 L/s	≥ 10 cm	± 3–5 %	Small canal turnouts
Submerged orifice	1–500 L/s	5–15 cm	± 3–5 %	When free-flow head not available
Orifice bucket (CHO)	10–500 L/s	≥ 30 cm	± 2–3 %	Canal outlets; wide range in one structure
Venturi meter	Any pipe Q	10–15 % of ΔH	± 1–2 %	Permanent buried mains
Orifice meter (pipe)	Any pipe Q	40–90 % of ΔH	± 2–3 %	Cheap; where head loss acceptable
Pitot tube	Point velocity	Negligible	± 2–5 %	Traverse in pipes or channels
Coordinate method	Tube-well outputs	None (open jet)	± 5 %	Horizontal pipes discharging into air
Current meter	5 L/s–20 m^3/s	None	± 2–5 %	Rivers, large channels; needs gauging
Float	0.5–10 m^3/s	None	± 10–15 %	Quick estimate; low accuracy

FORMULA SHEET — CHAPTER 3

- ***Rectangular weir (suppressed)*** : $Q = (2/3)\cdot C_d\cdot L\cdot\sqrt{(2g)}\cdot H^{3/2}$; $C_d \approx 0.62$. $Q \approx 1.84\cdot L\cdot H^{1.5}$.
- ***Rectangular weir (Francis correction)*** : $L_{eff} = L - n\cdot 0.1H$ (n = 0, 1, 2).
- ***Cipoletti weir*** : $Q = (2/3)\cdot C_d\cdot L\cdot\sqrt{(2g)}\cdot H^{3/2}$; no contraction correction; $C_d \approx 0.63$; $Q \approx 1.86\cdot L\cdot H^{1.5}$.
- ***Triangular (V-notch) weir*** : $Q = (8/15)\cdot C_d\cdot\tan(\theta/2)\cdot\sqrt{(2g)}\cdot H^{5/2}$; $C_d \approx 0.58–0.60$.
- ***90° V-notch (simplified)*** : $Q = 1.417\cdot H^{5/2}$ (with $C_d = 0.60$).
- ***Trapezoidal weir (general)*** : $Q = Q_{rect} + Q_{tri}$ (sum of rectangular + two-side triangular).
- ***Velocity-of-approach correction*** : $Q = (2/3)\cdot C_d\cdot L\cdot\sqrt{(2g)}\cdot[(H + h_a)^{3/2} - h_a^{3/2}]$; $h_a = V_a^2/2g$.
- ***Submerged weir (Villemonte)*** : $Q_{sub} = Q_{free}\cdot[1 - (H_2/H_1)^{3/2}]^{0.385}$.
- ***Broad-crested weir*** : $Q \approx 1.705\cdot C_d\cdot L\cdot H^{3/2}$; $C_d \approx 0.85–1.0$.
- ***Free orifice*** : $Q = C_d\cdot a\cdot\sqrt{(2gH)}$; $C_d \approx 0.61$.
- ***Submerged orifice*** : $Q = C_d\cdot a\cdot\sqrt{(2g\cdot\Delta H)}$.
- ***Parshall flume*** : $Q = K\cdot W\cdot H_a^{n}$; free flow while $H_b/H_a \le 0.7$.
- ***Venturi meter*** : $Q = C_d\cdot a_1\cdot a_2\cdot\sqrt{(2gH)}/\sqrt{(a_1^2 - a_2^2)}$; $C_d \approx 0.95–0.99$.
- ***Orifice meter (pipe)*** : $Q = C_d\cdot a_o\cdot\sqrt{(2gH)}/\sqrt{(1 - (a_o/a_1)^2)}$; $C_d \approx 0.60$.
- ***Pitot tube*** : $u = \sqrt{(2gh)}$; $Q = k\cdot A\cdot u$ ($k \approx 0.85$ for mean velocity from centreline).
- ***Coordinate method*** : $V = x\cdot\sqrt{(g/(2y))}$; $Q = (\pi D^2/4)\cdot V$.
- ***Current-meter rating*** : $V = a + b\cdot N$; strip-wise $Q_i = w_i\cdot d_i\cdot\bar{V}_i$; total $Q = \Sigma Q_i$.
- ***Float method*** : $\bar{V} = \alpha\cdot V_s$ ($\alpha \approx 0.85$ for surface float).

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- ***Water-hammer surge (Joukowsky)*** : ΔP = ρ·c·ΔV; c = √(K/ρ) modified for pipe elasticity — governs UGPL protection design.
- ***Thrust at end plug*** : F = P·A; sized against soil bearing capacity of the thrust block.

SUMMARY

- Water-measurement devices divide into weirs, flumes, orifices, pipe-flow meters, velocity-area methods, volumetric methods and the coordinate method for horizontal pipes.
- Sharp-crested weirs (rect / Cipoletti / V-notch / trap) give ±2 % accuracy when installed with a stilling well, ventilated nappe, straight approach and free discharge.
- Cipoletti weir eliminates the end-contraction correction of the rectangular weir by the 1:4 side slope.
- V-notch weir is the most sensitive weir for small Q because Q ∝ H^{5/2}.
- Broad-crested weir is more robust and less accurate than sharp-crested; used on permanent installations.
- Submerged weirs need the Villemonte correction once tail-water rises above the crest by more than about 30 %.
- Parshall flume is the standard permanent flume — self-cleaning, low head loss, single-gauge reading in free flow.
- Cut-throat flume is a flat-bed, portable alternative to Parshall — easier to fabricate but slightly larger head loss.
- Free orifice: Q = C_d·a·√(2gH); submerged: Q = C_d·a·√(2g·ΔH); orifice bucket (CHO) uses two gates to hold constant head.
- Venturi meter has the lowest head loss (10–15 % of the differential); orifice meter is cheaper but with 40–90 % head loss.
- Pitot tube gives point velocity; the inverted arrangement uses stagnation and static columns to read the velocity head.
- Coordinate method uses the jet trajectory of a horizontal pipe to compute V from V = x·√(g/(2y)).
- Current-meter and float methods are the standard velocity-area techniques for large channels.
- UGPL replaces earthen channels with buried PVC/HDPE pipes — 95–100 % conveyance efficiency; no seepage or land loss.
- UGPL components: mainline, sub-main, risers, hydrants (alfalfa / orchard / multiple-outlet), plus protective structures (air-vent, end plug with thrust block, stand-pipe, pressure-relief valve, non-return valve).
- Air-vents release air (avoid air-lock) and admit air on drain-down (avoid vacuum collapse). End plugs seal terminal ends and, backed by a thrust block, absorb axial thrust.
- Common UGPL troubles: water hammer, air lock, vacuum collapse, end-plug blow-out, joint leakage, clogging, root/rodent damage — all traceable to poor design, laying or omitted protective devices.

LAST-NIGHT REVISION — ONE PAGE

- ***Definitions*** : Weir = overflow structure; Q from head above crest. Flume = contracted section forcing critical depth. Orifice = sharp-edged opening.
- ***Rect weir*** : Q = (2/3)·C_d·L·√(2g)·H^{1.5}; L_eff = L − 0.1nH (Francis); C_d ≈ 0.62; H ≥ 6 cm; H ≤ 0.5P.
- ***Cipoletti vs Rect*** : Side slope 1H:4V compensates for contractions → no L_eff correction. Same formula, C_d ≈ 0.63.
- ***V-notch*** : Q = (8/15)·C_d·tan(θ/2)·√(2g)·H^{5/2}. 90°: Q ≈ 1.417·H^{5/2}. Best for small Q.

- ***Broad-crested*** : Q ≈ 1.705·C_d·L·H^{1.5}; C_d 0.85–1.0; robust to silt and debris; less accurate.
- ***Submerged weir*** : Villemonte: Q_sub = Q_free·[1 − (H_2/H_1)^{1.5}]^{0.385}. Modular limit ≈ 0.66.
- ***Weir installation*** : straight approach ≥ 10 W; P ≥ 3H; stilling well; vented nappe; free tail-water; regular cleaning.
- ***Parshall vs Cut-throat*** : Parshall = sloped-floor throat, permanent, K·W·H_a^n formula; Cut-throat = flat-bed, portable, cheaper, converging + diverging only.
- ***Orifice*** : Free Q = C_d·a·√(2gH); Submerged Q = C_d·a·√(2g·ΔH); C_d ≈ 0.61. CHO orifice bucket = constant head.
- ***Venturi*** : Q = C_d·a_1·a_2·√(2gH)/√(a_1²−a_2²); C_d ≈ 0.98; head loss 10–15 %.
- ***Orifice meter*** : Same form with a_o; C_d ≈ 0.60; head loss 40–90 %.
- ***Pitot*** : u = √(2gh); traverse or apply k ≈ 0.85 for mean V.
- ***Coordinate method*** : V = x·√(g/(2y)); Q = A·V; for horizontal pipe outlet into air.
- ***Current meter*** : V = a + b·N; 0.6d method (shallow), 0.2d & 0.8d (deep); strip-wise Q_i integration.
- ***Floats*** : $\bar{V}$ = 0.85·V_s (surface); rod float > sub-surface > surface.
- ***UGPL advantages*** : ~100 % conveyance eff, no land loss, no weeds/silt, pressure at each riser, long life.
- ***UGPL components*** : mainline → sub-main → riser → hydrant (alfalfa / orchard / multi-outlet); protective: air-vent, end plug + thrust block, stand-pipe, pressure-relief, non-return, sluice.
- ***Hydrant working*** : threaded stem lifts disc off seat; flow up; internal pressure holds disc off during operation; on closing, pressure seals it.
- ***Air-vent placement*** : all summits, downstream of pump, both sides of every valve, at end plugs.
- ***End plug + thrust block*** : axial thrust F = P·A; concrete pad against undisturbed soil; vent + flush fitted.
- ***Stand-pipe*** : open vertical pipe → pressure indicator + over-flow safety + air escape.
- ***Common troubles*** : water hammer, air lock, vacuum collapse, plug blow-out, joint leak, clogging, root/rodent damage, UV & thermal, corrosion.
- ***Selection thumb-rules*** : small precise Q → V-notch; silty channel → Parshall; buried main → Venturi/Venturi + Ultrasonic; tube-well outlet → coordinate method; rivers → current meter.

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CHAPTER

4

CANAL DESIGN, OPEN CHANNEL FLOW & FLUID MECHANICS

Canal network & lining · Manning–Chezy · Most-efficient section · Specific energy · Hydraulic jump · Reynolds–Froude · Bernoulli · Pipe flow

SYLLABUS : Canal design and construction — irrigation canals (main, branch, distributary, minor), canal cross-sections, canal network components, canal lining (rigid and flexible), regulators, escapes and falls. Open-channel flow — uniform vs non-uniform flow; Chezy and Manning equations; hydraulic radius and hydraulic mean depth; most-efficient (best-hydraulic) section; specific energy, critical flow and hydraulic jump; gradually varied flow surface profiles. Fluid mechanics fundamentals — fluid properties, pressure measurement and manometry, hydrostatic forces; Bernoulli's equation; Reynolds and Froude numbers; laminar vs turbulent flow; pipe-flow theory — Darcy–Weisbach equation, friction factor, major and minor losses; continuity equation. (UPSC IFoS, Paper I.)

Chapter Outline

1. **Scope & the Fluid–Channel–Canal System**
2. **Fluid Mechanics Fundamentals (properties · manometry · hydrostatics · continuity · Bernoulli)**
3. **Flow Regimes & Dimensionless Numbers (Reynolds · Froude · classification of OCF)**
4. **Uniform Flow & Resistance Equations (Chezy · Manning · Darcy–Weisbach)**
5. **Most-Efficient (Best-Hydraulic) Section & Channel Design**
6. **Specific Energy, Critical Flow & the Froude Criterion**
7. **Hydraulic Jump (sequent depths · types · applications)**
8. **Gradually Varied Flow & Surface Profiles**
9. **Pipe Flow (Darcy–Weisbach · friction factor · losses)**
10. **Canal Design, Network, Lining & Open-Drain Design**
11. **Formula Sheet · Summary · Last-Night Revision**

MIND-MAP — *Chapter 4 concept map*

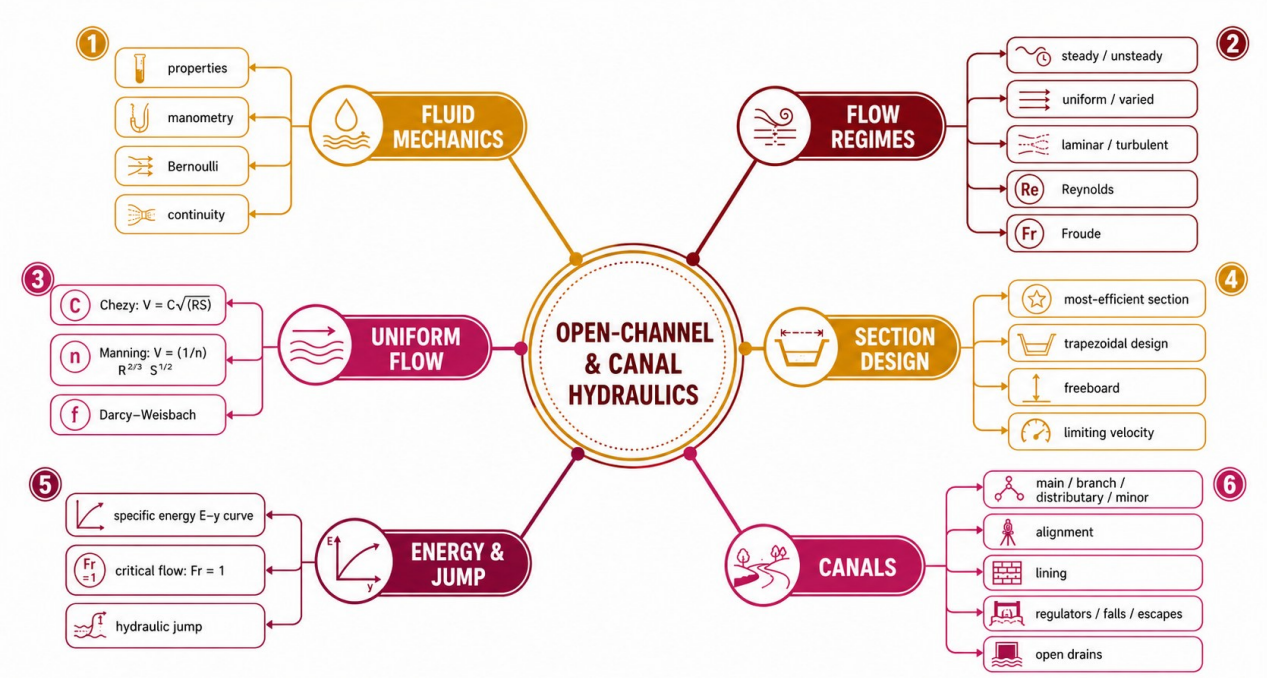


Fig. 4.0 Concept map of Chapter 4 — from fluid properties to canal network design.

1 SCOPE & THE FLUID–CHANNEL–CANAL SYSTEM

This chapter welds together three layers of the same subject. At the base sits ***fluid mechanics*** — the properties of water and the laws (continuity, Bernoulli, momentum) that govern any flow. Built on it is ***open-channel flow*** — the behaviour of water with a ***free surface***, which is how water actually moves in every canal, ditch and drain. The top layer is the engineering pay-off: the ***hydraulic design of canals and drains*** — choosing a cross-section, a slope and a lining that carry the required discharge safely and economically.

The single most important physical distinction for this chapter: in ***pipe flow*** the conduit runs full, there is no free surface and flow is driven by a pressure gradient; in ***open-channel flow*** the top surface is exposed to the atmosphere and flow is driven by gravity acting on the bed slope. Because the free surface can rise and fall, the flow depth becomes an unknown of the problem — this is what makes open-channel hydraulics richer than pipe hydraulics.

> ***Open-channel flow*** : flow of a liquid in a conduit with a **free surface** subject *to atmospheric pressure, in which the motive force is the component of gravity along the bed slope.*

HOW THE SYLLABUS THEMES WEIGH IN THE EXAM

From the past-question record for this chapter, four clusters dominate: ***Manning–Chezy channel hydraulics*** and the ***most-efficient section*** (the single largest block of marks and numericals), the ***hydraulic jump & specific energy*** pair (asked almost every year, up to 20 marks), the ***Reynolds/Froude flow-regime*** classification, and ***canal design, lining and network*** description questions. The sections below are ordered to build each idea before it is used, and every past question is reproduced in full at the point it applies.

2 FLUID MECHANICS FUNDAMENTALS

Every open-channel or pipe result in this chapter is a special case of a handful of fluid-mechanics laws. They are collected here so the later sections can call on them without interruption.

2.1 Properties of a Fluid

A ***fluid*** deforms continuously under shear, however small. Water — the working fluid of irrigation — is treated as ***incompressible*** and ***Newtonian***. The properties that recur are:

- ***Mass density ρ*** : mass per unit volume; for water ρ ≈ 1000 kg/m³ at 4 °C.
- ***Specific weight γ*** : weight per unit volume, γ = ρg ≈ 9.81 kN/m³ for water.
- ***Specific gravity*** : ratio of a fluid's density to that of water; dimensionless.
- ***Dynamic viscosity μ*** : resistance to shear; from ***Newton's law of viscosity***, the shear stress $\tau = \mu\ (du/dy)$, where du/dy is the velocity gradient. Unit: Pa·s.
- ***Kinematic viscosity ν*** : ν = μ/ρ; unit m²/s. It is ν that appears in the Reynolds number for channels.
- ***Surface tension & capillarity*** : cause the small rise/fall of water against solid walls; usually negligible at field scale but important in lab models and soil pores.
- ***Bulk modulus / compressibility*** : water's bulk modulus K ≈ 2.1 GPa — large, so water is taken as incompressible except in water-hammer analysis.

$$\gamma = \rho g \qquad \nu = \mu/\rho \qquad \tau = \mu\ (du/dy)$$

ρ = density (kg/m³) · g = 9.81 m/s² · μ = dynamic viscosity (Pa·s) · ν = kinematic viscosity (m²/s)

Newtonian fluid — *a fluid for which shear stress is* ***linearly*** *proportional to the rate of shear strain, the constant of proportionality being the dynamic viscosity μ. Water, air and most thin oils are Newtonian.*

2.2 Fluid Pressure & Manometry

Pressure at a point in a static liquid acts equally in all directions (***Pascal's law***) and increases linearly with depth. At depth h below the free surface the ***gauge pressure*** is p = ρgh. Absolute pressure = gauge pressure + atmospheric pressure.

$$p = \rho\, g\, h \qquad \text{(hydrostatic pressure at depth h)}$$

measured above atmospheric = gauge; add p_atm for absolute

PRESSURE-MEASURING DEVICES

- ***Piezometer*** : a simple open vertical tube; the liquid rises to a height h = p/ρg giving the gauge pressure directly. Suitable only for moderate positive pressures.
- ***U-tube manometer*** : a U-tube containing a heavier manometric liquid (*e.g.* mercury); pressure is read from the difference in levels of the two limbs.
- ***Differential manometer*** : connects two points and reads the ***difference*** of pressure between them — the basis of the venturi and orifice meters used to gauge canal and pipe flow.

For a U-tube reading a pressure p_A with manometric-liquid deflection x and density ρ_m over a working liquid of density ρ: $p_A = \rho_m\, g\, x - \rho\, g\, y$, where y is the height of working liquid in the connecting limb. Manometry converts an invisible pressure into a visible, measurable length.

2.3 Hydrostatic Force on Submerged Surfaces

The total hydrostatic thrust on a plane surface of area A whose centroid lies at a depth $\bar{h}$ below the free surface is $F = \rho g \cdot \bar{h} \cdot A$, acting normal to the surface at the ***centre of pressure***, which lies ***below*** the centroid by I_G /(A·$\bar{h}$). These results size canal gates, regulator shutters and the vertical faces of falls and drop structures.

$$F = \rho\, g\, \bar{h}\, A \qquad h_cp = \bar{h} + I_G\ /(A\, \bar{h})$$

$\bar{h}$ = depth of centroid · I_G = second moment of area about the centroidal axis

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2.4 The Continuity Equation

Conservation of mass for steady incompressible flow: the volume flow rate is the same at every section. For a stream tube between sections 1 and 2,

$$Q = A_1V_1 = A_2V_2 = \text{constant}$$

Q = discharge (m^3/s) · A = cross-sectional area (m^2) · V = mean velocity (m/s)

Continuity is the first equation written in almost every numerical of this chapter — it links the unknown depth (through A) to the velocity.

2.5 Bernoulli's Energy Equation

For steady, incompressible, non-viscous flow along a streamline, the total energy head is constant. Dividing the energy per unit weight into three heads:

$$z + p/\gamma + V^2/2g = \text{constant (H)}$$

z = elevation (datum) head · p/γ = pressure head · $V^2/2g$ = velocity head · H = total head (m)

Bernoulli's theorem follows by integrating ***Euler's equation*** of motion along a streamline. Its stated ***assumptions*** — steady flow, incompressible fluid, non-viscous (frictionless) flow, and flow along a streamline — matter because real canal flow is viscous, so a ***head-loss term h_L*** is added between two sections:

$$z_1 + p_1/\gamma + {V_1}^2/2g = z_2 + p_2/\gamma + {V_2}^2/2g + h_L$$

the working (energy) form used for channels and pipes

EVERYDAY APPLICATIONS

- ***Venturimeter & orifice meter*** : measure pipe discharge from the pressure drop at a contraction.
- ***Pitot tube*** : measures local velocity from the stagnation-pressure rise, $V = \sqrt{(2g \cdot \Delta h)}$.
- ***Specific energy*** : the open-channel specific-energy function of §6 is simply Bernoulli's head measured from the channel bed as datum.

3 FLOW REGIMES & DIMENSIONLESS NUMBERS

3.1 Classification of Open-Channel Flow

Open-channel flow is classified on ***two independent axes*** — variation with ***time*** and variation with ***space*** — and, separately, by the ratios of forces that decide whether the flow is laminar/turbulent (viscosity) and sub-/super-critical (gravity).

(A) VARIATION WITH TIME — STEADY VS UNSTEADY

- ***Steady flow*** : depth and velocity at a section do not change with time ($\partial/\partial t = 0$). Design flow in a canal is treated as steady.
- ***Unsteady flow*** : depth or velocity change with time — flood waves in rivers, surges on sudden gate operation.

(B) VARIATION WITH SPACE — UNIFORM VS NON-UNIFORM (VARIED)

- ***Uniform flow*** : depth, area and velocity are constant along the channel length; the water surface is parallel to the bed. Gravity exactly balances boundary friction. Occurs in a long prismatic channel of constant slope — the depth is then the ***normal depth***.
- ***Non-uniform (varied) flow*** : depth varies along the channel. It is ***gradually varied (GVF)*** when the change is slow and the surface curvature gentle (backwater/drawdown), and ***rapidly varied (RVF)*** when the depth changes abruptly over a short reach (*e.g.* the hydraulic jump and hydraulic drop).

- ***Spatially varied flow*** : discharge itself changes along the reach through lateral addition (side-channel spillway, drain receiving inflow) or withdrawal (irrigation channel feeding outlets).

(C) EFFECT OF VISCOSITY — LAMINAR VS TURBULENT

- ***Laminar flow*** : viscous forces dominate; fluid moves in orderly layers.
- ***Turbulent flow*** : inertial forces dominate; irregular mixing. Practically all canal flow is turbulent.

(D) EFFECT OF GRAVITY — SUB-CRITICAL, CRITICAL, SUPER-CRITICAL

Decided by the Froude number (§3.3): tranquil/streaming flow (Fr < 1), critical flow (Fr = 1) and shooting/torrential flow (Fr > 1).

PREVIOUS YEAR QUESTIONS

Explain the classifications of open channel flow with suitable examples.

[OPSC·CSE 2020–21 · P1/Q.1(c)(i) · 8M]

MODEL Q Answer on the two axes (time → steady/unsteady; space → uniform/GVF/RVF), then add the viscosity (laminar/turbulent) and gravity (sub/critical/super) classifications, one crisp example each — canal = steady uniform turbulent sub-critical; flood wave = unsteady; jump = RVF.***

PREVIOUS YEAR QUESTIONS

Steady and unsteady flow – Uniform and non-uniform flow – Laminar and turbulent flow – What is open channel flow? Explain various formulae / methods for its measurement.

[OPSC·CSE 2017–18 · P1/Q.1(d) · 15M]

MODEL Q Define each pair (½–¾ page), define open-channel flow, then list measurement methods: area–velocity (current meter / float), the uniform-flow formulae (Manning, Chezy), and control structures — weirs, flumes (Parshall), notches and orifices. Cross-refer to Chapter on flow measurement.***

3.2 Reynolds Number — the Viscosity Criterion

The ***Reynolds number*** is the ratio of inertial to viscous force. For open channels the characteristic length is the hydraulic radius R, so

$$Re = \rho VR/\mu = VR/\nu \quad \text{(open channel, length-scale = R)}$$

V = mean velocity · R = hydraulic radius · ν = kinematic viscosity

Regime	Open channel (length = R)	Pipe (length = D)
Laminar	Re < 500	Re < 2000
Transitional	500 – 2000	2000 – 4000
Turbulent	Re > 2000	Re > 4000

The limits differ because the pipe uses diameter D = 4R as its length-scale; dividing the pipe limits by about four recovers the channel limits.

3.3 Froude Number — the Gravity Criterion

The ***Froude number*** is the ratio of inertial to gravity force and is the master parameter of free-surface flow:

$$Fr = V / \sqrt{(g\,D)} \qquad D = A/T \ \text{(hydraulic depth)}$$

T = top width of flow · D = hydraulic mean depth · for a rectangle D = y

Fr	State	Description	Behaviour
< 1	Sub-critical	Tranquil / streaming	Depth large, velocity low; disturbances travel upstream

= 1	Critical	Critical flow	Specific energy minimum; surface unstable, waves stationary
> 1	Super-critical	Shooting / torrential	Depth small, velocity high; disturbances swept downstream

A surface disturbance travels at celerity c = √(gD). When V < c (Fr < 1) it can move upstream — downstream conditions therefore ***control*** a sub-critical reach; when V > c (Fr > 1) it cannot, so super-critical flow is controlled from ***upstream***. This is why the hydraulic jump (§7) can only take the flow from super- to sub-critical, never the reverse.

4 UNIFORM FLOW & RESISTANCE EQUATIONS

4.1 Uniform Flow & Normal Depth

In ***uniform flow*** the water surface, energy line and bed are all parallel, so the friction slope S_f equals the bed slope S_o. The constant depth is the ***normal depth***. A force balance on a slice of length L — the gravity component $\rho g \cdot A \cdot L \cdot S_o$ balancing the boundary shear $\tau_o \cdot P \cdot L$ — gives the average boundary shear $\tau_o = \rho g R S_o$, the seed of both resistance formulae below.

$$\tau_0 = \rho\, g\, R\, S_0 \quad \text{(average boundary shear in uniform flow)}$$

R = A/P = hydraulic radius · S_o = bed slope

4.2 Chézy's Equation (1769)

Equating the tractive force $\rho g R S_o$ to a turbulent resistance proportional to V^2 ($\tau_o = k V^2$) and absorbing the constants into one coefficient C gives ***Chézy's equation***:

$$V = C\sqrt{(R\,S)} \qquad Q = A\,C\sqrt{(R\,S)}$$

C = Chézy's coefficient (m^{1/2}/s) — not dimensionless; larger C = smoother boundary

4.3 Manning's Equation (1889)

The most-used uniform-flow formula in Indian practice expresses the velocity through ***Manning's roughness coefficient n***:

$$V = (1/n)\, R^{2/3}\, S^{1/2} \qquad Q = (1/n)\, A\, R^{2/3}\, S^{1/2}$$

n = Manning's roughness ($s \cdot m^{-1/3}$); n ≈ 0.012 lined concrete, 0.025 earthen, 0.03–0.04 weedy/natural

Comparing Chézy and Manning gives the ***Strickler relation*** $C = (1/n)\, R^{1/6}$, which is used constantly to convert between the two coefficients.

4.3 Darcy–Weisbach & Correlation of the Resistance Coefficients

The Darcy–Weisbach equation, written for pipes as $h_f = f\, L\, V^2/(2gD)$, applies to a channel by substituting the ***hydraulic diameter D = 4R***. With the head-loss slope $S = h_f / L$,

$$S = f\, V^2 / (8\, g\, R)$$

$$V = \sqrt{(8g/f)} \cdot \sqrt{(R\,S)}$$

f = Darcy–Weisbach friction factor (dimensionless)

Setting this equal to Chézy's $V = C\sqrt{(RS)}$ at once ties all three coefficients together — the exact content of the 15-mark comparison question:

$$C = \sqrt{(8g/f)} \qquad C = (1/n)\, R^{1/6}$$

$$f = 8\, g\, n^2 / R^{1/3}$$

the bridge relations between Chézy C, Manning n and Darcy f

Feature	Chézy	Manning	Darcy–Weisbach
Form	V = C√(RS)	V = (1/n)R^{2/3}S^{1/2}	$h_f = fLV^2/2gD$
Coefficient	C (dimensional)	n (dimensional)	f (dimensionless)
Depends on	boundary roughness, R	boundary roughness (≈const)	Re and relative roughness
Best suited to	early/empirical channel design	earthen & lined channels (standard)	pipe flow; rational, Re-based
Link	C = √(8g/f)	C = (1/n)R^{1/6}	$f = 8gn^2/R^{1/3}$

Physically: ***f is dimensionless and rational*** (it varies with Reynolds number and relative roughness through the Moody chart), whereas ***C and n are dimensional and empirical***; n is nearly constant for a given lining, which is exactly why Manning's form is preferred for routine canal design.

PREVIOUS YEAR QUESTIONS

Compare the Chezy's, Manning's and Darcy–Weisbach formula for design of earthen irrigation channel and correlate the resistance coefficients used in these formulae.

[OPSC·CSE 2016–17 · P1/Q.3(c) · 15M]

MODEL Q Give the three equations, the comparison table above, then derive the two bridge relations C = √(8g/f) and C = (1/n)R^{1/6}, and close with why n is the practical choice for earthen channels (constant n, direct discharge computation). ***

5 MOST-EFFICIENT (BEST-HYDRAULIC) SECTION & CHANNEL DESIGN

5.1 The Economical-Section Principle

A channel section is ***most economical*** (best-hydraulic, most-efficient) when it carries the ***maximum discharge for a given cross-sectional area***, slope and roughness. From Manning/Chézy, for fixed A, S and n the discharge Q rises with the hydraulic radius R = A/P; R is greatest when the ***wetted perimeter P is least***. So the most economical section is the one of ***minimum wetted perimeter*** — which also minimises excavation, lining area and cost. Of all shapes the ***semicircle*** has the least perimeter for a given area, but the trapezoid is used because it is far easier to construct and stand up in earth.

Most-efficient section : *the channel cross-section that, for a given area, slope and roughness, conveys the* ***maximum discharge*** *— equivalently, the section of minimum wetted perimeter. Its hydraulic radius equals half the flow depth* ($R = y/2$).

5.2 Rectangular Most-Efficient Section

For a rectangle of width b and depth y: A = by and P = b + 2y. Substituting b = A/y, P = A/y + 2y; setting dP/dy = 0 gives $-A/y^2 + 2 = 0$, so $A = 2y^2$, i.e. $b = 2y$ and $R = A/P = 2y^2/(4y) = y/2$. The best rectangular channel is twice as wide as it is deep.

5.3 Trapezoidal Most-Efficient Section — full derivation

Let b = bed width, y = depth and z = side slope (z horizontal : 1 vertical). Then

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

trapezoid area and wetted perimeter (z = horizontal run per unit vertical rise)

Keep A and z fixed and eliminate b using b = A/y − zy:

$$P = A/y - z\,y + 2y\sqrt{(1+z^2)}$$

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For the most economical section, minimise P with respect to y (dP/dy = 0):

$$dP/dy = -A/y^2 - z + 2\sqrt{(1+z^2)} = 0 \;\Rightarrow\; A = y^2(2\sqrt{(1+z^2)} - z)$$

Substitute this A back into A = by + zy² and solve for the bed width:

$$b = 2y(\sqrt{(1+z^2)} - z) \;\Rightarrow\; b + 2zy = 2y\sqrt{(1+z^2)}$$

The left side (b + 2zy) is the ***top water-surface width T***; the right side is ***twice the sloping side length*** y√(1+z²). Hence ***half the top width equals one sloping side*** — the required condition. Dividing the economical A by the economical P gives, after cancellation,

$$\tfrac{1}{2}(b + 2zy) = y\sqrt{(1+z^2)} \quad \text{and} \quad R = y/2$$

conditions for the most economical trapezoidal section

A second optimisation — minimising P with respect to the side slope z as well — gives the ***best side slope z = 1/√3 (θ = 60° with horizontal)***, for which the trapezoid becomes ***half of a regular hexagon*** and its hydraulic radius is still y/2.

PREVIOUS YEAR QUESTIONS

Show that, the most economical trapezoidal channel section is obtained when half of top width is equal to one of the sloping side.

[OPSC·CSE 2018–19 · P1/Q.3(b)(i) · 8M]

MODEL Q Reproduce the boxed derivation: write A and P, eliminate b, set dP/dy = 0, obtain A = y²(2√(1+z²)−z), back-substitute to get b + 2zy = 2y√(1+z²), and read off ½·T = sloping side. State R = y/2 as the corollary. ***

5.4 Design Procedure for a Trapezoidal Channel

The standard steps asked in the 10-mark procedure question:

1. ***Data*** : fix design discharge Q, bed slope S, side slope z (from soil stability) and Manning's n (from lining).
2. ***Velocity check*** : select a non-silting, non-scouring velocity — keep V between the ***limiting velocities*** for the soil/lining (≈0.6 m/s minimum to avoid silting; upper limit from the permissible-velocity table).
3. ***Area*** : from continuity A = Q/V.
4. ***Section*** : impose the most-economical condition (R = y/2) or a chosen B/D ratio, and solve A = by + zy² and P simultaneously for b and y.
5. ***Slope/velocity closure*** : verify with Manning V = (1/n)$R^{\{2/3\}}S^{\{1/2\}}$; adjust S or section until Q, V are both satisfied.
6. ***Freeboard*** : add freeboard (≈15–30% of depth, or 0.15–0.75 m by canal size) above the full-supply level.

PREVIOUS YEAR QUESTIONS

Explain the steps involved in designing the trapezoidal open channel.

[OPSC·CSE 2022–23 · P1/Q.7(b) · 10M]

MODEL Q List the six steps above; show the two section equations A = by+zy² and P = b+2y√(1+z²); mention limiting velocity and freeboard as the practical checks. ***

LIMITING (PERMISSIBLE) VELOCITIES — HANDY DESIGN DATA

Material	Clear water (m/s)	Water carrying colloidal silt (m/s)
Fine sand, colloidal	0.46	0.76
Sandy loam, non-colloidal	0.53	0.76

Silt loam, non-colloidal	0.61	0.92
Ordinary firm loam	0.76	1.07
Stiff clay / alluvial silt, colloidal	1.14	1.52
Coarse gravel, non-colloidal	1.22	1.83

5.5 Worked Numericals

◆ **WORKED NUMERICAL — *Most-efficient width, velocity & capacity*** [IFoS 2024 · P1/6(a) · 15M]

Problem. *Compute the most-efficient width for an open ditch/channel with flow depth 2·40 m in silt-loam soil. Find the velocity and channel capacity if the channel gradient is 0·09 % and Manning's n = 0·04. Side slope for silt loam = 1·5 : 1.*

Given. y = 2.40 m; z = 1.5; S = 0.09% = 0.0009; n = 0.04.

Find. most-efficient bed width b, velocity V, capacity Q.

Most-efficient condition. $b = 2y(\sqrt{(1+z^2)} - z);\ R = y/2.$

Bed width. $\sqrt{(1+1.5^2)} = \sqrt{3.25} = 1.803$; b = 2(2.40)(1.803 − 1.5) = **1.45 m.**

Area. A = by + zy² = (1.45)(2.40) + 1.5(2.40)² = 3.49 + 8.64 = 12.13 m².

Hydraulic radius. R = y/2 = 1.20 m.

Velocity (Manning). V = (1/0.04)(1.20)^{2/3}(0.0009)^{1/2} = 25 × 1.129 × 0.030 = **0.847 m/s.**

Capacity. Q = A V = 12.13 × 0.847 = **10.3 m³/s.**

Check. V = 0.847 m/s exceeds the 0.61 m/s silt-loam clear-water limit but is acceptable for the silt-carrying value (0.92 m/s) — non-silting and within the scouring limit. ✓

◆ **WORKED NUMERICAL — *Velocity & discharge of a lined trapezoidal channel*** [OPSC·CSE 2023–24 · P1/9(b) · 15M]

Problem. *Compute the mean velocity and discharge for a depth of flow of 0·30 m from a lined trapezoidal channel 0·6 m wide, side slope 1·5 H : 1 V. Manning's n = 0·012 and bed slope = 0·0003.*

Given. b = 0.60 m; y = 0.30 m; z = 1.5; n = 0.012; S = 0.0003.

Area. A = by + zy² = 0.60(0.30) + 1.5(0.30)² = 0.180 + 0.135 = 0.315 m².

Wetted perimeter. P = b + 2y√(1+z²) = 0.60 + 2(0.30)(1.803) = 1.682 m.

Hydraulic radius. R = A/P = 0.315/1.682 = 0.1873 m.

Velocity. V = (1/0.012)(0.1873)^{2/3}(0.0003)^{1/2} = 83.33 × 0.327 × 0.01732 = **0.473 m/s.**

Discharge. Q = A V = 0.315 × 0.473 = **0.149 m³/s.**

Note. Matches the standard AgriMoon Example 12.1 exactly.

◆ **WORKED NUMERICAL — *Most-efficient trapezoid in clay (drainage channel)*** [UK·PSC RFO 2021 · Q.3(iii) · 10M]

Problem. *Calculate the most-efficient bottom width for a trapezoidal drainage channel carrying flow 2·5 m deep in clay soil. Compute velocity and discharge capacity if the channel gradient is 0·04 %.*

Data note. the side slope and n were not stated in the question paper; adopting standard clay values z = 1 : 1 and n = 0.025 .

Given. y = 2.5 m; z = 1.0; n = 0.025; S = 0.04% = 0.0004.

Bed width. b = 2y(√(1+z²) − z) = 2(2.5)(√2 − 1) = 5(0.4142) = **2.07 m.**

Area & R. A = by + zy² = 2.07(2.5) + 1(2.5)² = 5.18 + 6.25 = 11.43 m²; R = y/2 = 1.25 m.

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Velocity. V = (1/0.025)(1.25)^{2/3}(0.0004)^{1/2} = 40 × 1.160 × 0.02 = **0.928 m/s.**

Discharge. Q = A V = 11.43 × 0.928 = **10.6 m³/s.**

◆ **WORKED NUMERICAL — *Design of a parabolic grassed waterway*** [OPSC·CSE 2023–24 · P1/15(b) · 20M]

Problem. *Design a parabolic grassed waterway to carry a peak flow of 6 m³/s on a 1 % slope on erodible sandy soil, with good grass cover and a permissible velocity of 1·5 m/s. Manning's n = 0·034.*

Given. Q = 6 m³/s; S = 1% = 0.01; V_perm = 1.5 m/s; n = 0.034; parabolic section.

Method. permissible-velocity (non-erodible) design: fix V at the permissible value, size the area from continuity, get R from Manning, then the parabola geometry.

Required area. A = Q/V = 6/1.5 = 4.0 m².

Hydraulic radius (Manning). R^{2/3} = Vn/√S = (1.5×0.034)/√0.01 = 0.510 ⇒ R = 0.510^{1.5} = 0.364 m.

Parabola geometry. for a parabola $A = \frac{2}{3} T D$ and (wide, shallow section) $R \approx \frac{2}{3} D$, so $D \approx 1.5 R$.

Depth. D = 1.5 × 0.364 = **0.55 m.**

Top width. T = 1.5 A/D = 1.5 × 4.0 / 0.55 = **11.0 m.**

Freeboard. add ≈0.15 m: total depth ≈ 0.70 m; top width at that depth T′ = T√((D+f)/D) = 11.0√(0.70/0.55) ≈ 12.4 m.

Result. **parabolic waterway, water-section top width ≈ 11 m and depth ≈ 0.55 m (≈12.4 m × 0.70 m including freeboard), carrying 6 m³/s at 1.5 m/s — non-erosive on grassed sandy soil. ✓**

6 SPECIFIC ENERGY, CRITICAL FLOW & THE FROUDE CRITERION

6.1 Specific Energy

The ***specific energy*** E is the total energy per unit weight measured with the ***channel bed as datum*** — Bernoulli's head with z = 0:

$$E = y + V^2/2g = y + Q^2/(2\,g\,A^2)$$

y = depth · V = mean velocity · A = flow area (a function of y)

For a fixed discharge, plotting E against y gives the ***specific-energy curve***: two limbs meeting at a nose. For any E greater than the minimum there are ***two possible depths*** — a large sub-critical ***alternate depth*** (upper limb, y > y_c) and a small super-critical one (lower limb, y < y_c). The nose, where the two merge, is the ***critical*** state of minimum specific energy.

6.2 Criterion for Critical Flow — derivation

Critical flow is the depth at which E is minimum for a given Q. Differentiate E with respect to y, noting that dA/dy = T (the top width):

$$dE/dy = 1 - (Q^2/g\,A^3)(dA/dy) = 1 - Q^2T/(g\,A^3)$$

Set dE/dy = 0 for the minimum:

$$Q^2\,T\,/\,(g\,A^3) = 1 \quad \Rightarrow \quad V^2/(g\,D) = 1 \quad (Fr = 1)$$

the general critical-flow criterion; D = A/T is the hydraulic mean depth

So at critical flow the ***Froude number is exactly 1*** — this is why Fr is the master parameter. Above the critical depth Fr < 1 (sub-critical); below it Fr > 1 (super-critical).

6.3 Rectangular Channel — critical depth and E_c = 1.5 y_c

For a rectangle of width b, put A = by, T = b, and discharge per unit width q = Q/b. The criterion $Q^2T/gA^3 = 1$ becomes $q^2/(g\,y_c^3) = 1$, so

$$y_c = (q^2 / g)^{1/3} \qquad V_c = \sqrt{(g\,y_c)}$$

critical depth and critical velocity for a rectangular channel

At critical depth the velocity head is $V_c^2/2g = g\,y_c/2g = y_c/2$, therefore

$$E_c = y_c + V_c^2/2g = y_c + y_c/2 = 1.5\,y_c$$

minimum specific energy of a rectangular channel

Thus at the critical state of a rectangular channel on level ground the specific-energy head equals ***1.5 times the depth of flow*** — the exact statement asked in the 10-mark derivation. The result underpins the design of flumes, spillway crests and critical-depth flumes, where a control section is deliberately forced to critical flow.

PREVIOUS YEAR QUESTIONS

- Define specific energy in a channel section. With the concept of specific energy, derive the criterion of critical state of flow (velocity-distribution coefficient = 1.0). Also show that at the critical state of flow the specific-energy head in a rectangular channel laid on level ground equals 1.5 times the depth of flow.

[OPSC·CSE 2018–19 · P1/Q.2(a)(i) · 10M]

★ **MODEL Q** Define $E = y + V^2/2g$; differentiate, set $dE/dy = 0$ to get $Q^2T/gA^3 = 1 \Leftrightarrow Fr = 1$; specialise to a rectangle to obtain $y_c = (q^2/g)^{1/3}$ and $E_c = 1.5\,y_c$. Sketch the E–y curve with y_c at the nose.

◆ **WORKED NUMERICAL — *Critical depth & specific energy (rectangular)*** **[AgriMoon Ex 12.2 (model)]**

Problem. *Compute the critical depth and minimum specific energy for a discharge of 6·0 m^3/s in a rectangular channel 2·4 m wide.*

Given. Q = 6.0 m^3/s; b = 2.4 m.

Unit discharge. $q = Q/b = 6.0/2.4 = 2.5\ m^2/s$.

Critical depth. $y_c = (q^2/g)^{1/3} = (2.5^2/9.81)^{1/3} = (0.637)^{1/3} =$ **0.860 m.**

Minimum specific energy. $E_c = 1.5\,y_c = 1.5 \times 0.860 =$ **1.29 m.**

Specific-energy (E–y) curve

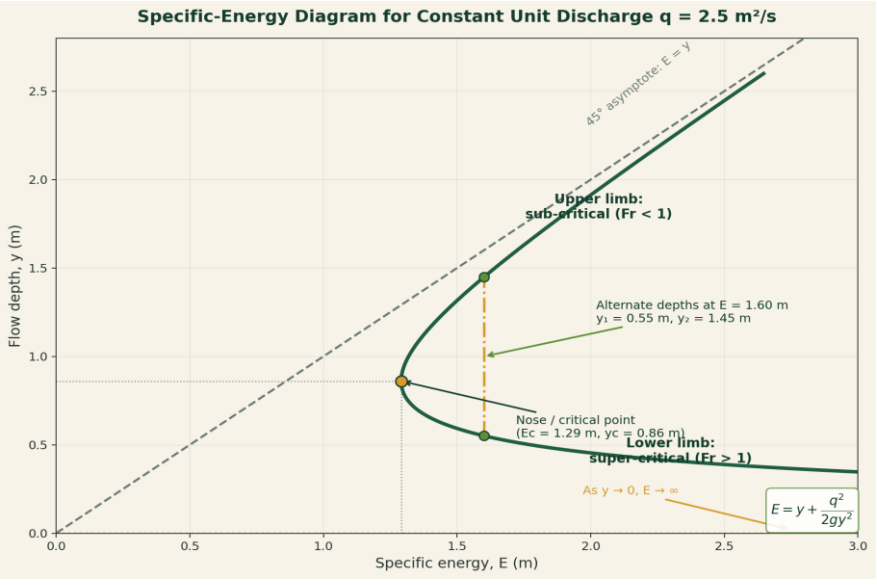


Fig. 4.1 Specific-energy curve — two alternate depths for E > E c; critical depth at the nose.

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It helps to see the two everyday states of flow side by side:

Feature	Sub-critical (Fr < 1)	Super-critical (Fr > 1)
Common name	Tranquil / streaming	Shooting / torrential
Depth & velocity	Large depth, low velocity	Small depth, high velocity
Relative to critical	y > y_c	y < y_c
Control section	From downstream	From upstream
Surface disturbance	Travels both up- & downstream	Swept downstream only
Typical location	Main canal, reservoir reach	Chute, steep fall, below a gate

7 HYDRAULIC JUMP

The hydraulic jump is the chapter's most heavily examined single topic. Master the definition, the sequent-depth relation, the energy loss, the Froude-number classification and the applications, and every jump question falls.

7.1 Definition & Occurrence

Hydraulic jump *— a sudden, turbulent transition of flow from the* ***super-critical*** *state (Fr > 1, shallow, fast) to the* ***sub-critical*** *state (Fr < 1, deep, slow), accompanied by a rolling surface and a large dissipation of energy.*

A jump forms wherever a fast super-critical stream must meet a slower, deeper tail-water — at the toe of a spillway or ogee, below a sluice gate, at the foot of a chute or steep drop, or where a steep channel flattens. Because surface disturbances cannot travel upstream in super-critical flow, the return to sub-critical ***cannot*** be gradual; it happens through this abrupt, dissipative jump.

7.2 Sequent (Conjugate) Depths — momentum derivation

Across the short, turbulent jump friction on the bed is negligible, so the ***momentum (not energy) equation*** is applied between the pre-jump depth y_1 and post-jump depth y_2. Equating the specific force (pressure + momentum flux) on the two sides, for a rectangular channel:

$$y_2/y_1 = \tfrac{1}{2}\left[\sqrt{(1 + 8\,Fr_1^{\,2})} - 1\right]$$

sequent-depth (Bélanger) equation · $Fr_1 = V_1/\sqrt{(g\,y_1)}$ = Froude number before the jump

y_1 and y_2 are the ***sequent (conjugate) depths***. Given the incoming super-critical depth and Froude number, the equation fixes the tail-water depth the jump will rise to — the key quantity for setting the floor level and length of a stilling basin.

7.3 Energy Dissipated in the Jump

Applying the energy equation across the jump, the head lost is

$$E_L = (y_2 - y_1)^3 / (4\,y_1\,y_2)$$

head loss in a hydraulic jump (rectangular channel) — always positive for a real jump

The loss grows rapidly with the height of the jump, which is why the jump is the preferred energy dissipator below high-head structures. The ***efficiency*** (fraction of energy retained) falls as Fr_1 rises.

7.4 Classification of Jumps by Froude Number

The form and effectiveness of the jump depend almost entirely on the incoming Froude number Fr_1:

Fr_1	Type of jump	Surface / action	Energy dissipated
1.0	(no jump — critical)	Flow is critical; no jump forms	—
1.0 – 1.7	Undular jump	Standing surface undulations	≈ 5%
1.7 – 2.5	Weak jump	Small surface rollers; smooth downstream	< 20%
2.5 – 4.5	Oscillating jump	Jet oscillates bed-to-surface; irregular waves	20 – 45%
4.5 – 9.0	Steady jump	Stable, well-balanced; best performance	45 – 70%
> 9.0	Strong jump	Rough, violent, strong downstream waves	up to 85%

The ***steady jump (Fr_1 = 4.5–9)*** is the designer's target — its position is least sensitive to tail-water and its dissipation is high without the violence of a strong jump. The oscillating range (2.5–4.5) is avoided where possible because its travelling surface waves can erode banks far downstream.

PREVIOUS YEAR QUESTIONS

- What is the phenomenon of hydraulic jump and explain the types of jumps in rectangular channels based on the values of Froude number?

  [OPSC·CSE 2023–24 · P1/Q.4(b) · 15M]

- Explain about the hydraulic jump and types of flows based on Froude number.

  [OPSC·CSE 2022–23 · P1/Q.5(b) · 10M]

MODEL Q Define the jump (super→sub-critical), give the sequent-depth and energy-loss equations, then the six-row Froude-number classification table with dissipation percentages. Name the steady jump as the design optimum. ***

◆ **WORKED NUMERICAL — *Sequent depth, jump type & energy loss*** [model numerical · jump]

Problem. *Water flows in a wide rectangular channel at a discharge intensity $q = 4{\cdot}0\ m^2/s$ with a pre-jump depth of $0{\cdot}5$ m. Find the sequent depth, the type of jump and the energy dissipated.*

Given. q = 4.0 m^2/s; y_1 = 0.5 m (wide rectangular channel).

Pre-jump velocity & Froude no. $V_1 = q/y_1 = 8.0$ m/s; $Fr_1 = V_1/\sqrt{(g\ y_1)} = 8/\sqrt{(9.81\times0.5)} = 3.61$ (super-critical).

Sequent depth. $y_2 = (y_1/2)[\sqrt{(1+8\cdot Fr_1^2)} - 1] = 0.25[\sqrt{105.3} - 1] = 0.25(10.26 - 1) =$ **2.32 m.**

Type of jump. $Fr_1 = 3.61$ lies in 2.5–4.5 → an **oscillating jump.**

Energy loss. $E_L = (y_2-y_1)^3/(4y_1y_2) = (1.82)^3/(4\times0.5\times2.32) = 6.03/4.64 =$ **1.29 m.**

Check. $E_1 = y_1+V_1^2/2g = 3.76$ m; $E_2 = 2.47$ m; $E_1-E_2 = 1.29$ m = E_L ✓ (≈34% of E_1 dissipated).

7.4 Practical Applications of the Hydraulic Jump

- ***Energy dissipation*** : its chief use — kill the high kinetic energy of water leaving a spillway, weir, sluice or chute in a ***stilling basin***, protecting the downstream bed from scour.
- ***Raising downstream water level*** : to recover head for a canal, or to drown a second control.
- ***Mixing of chemicals*** : the intense turbulence mixes coagulants/chlorine in water-treatment channels.
- ***Aeration*** : entrains air used to re-aerate water downstream of dams and in effluent channels.
- ***Removing air pockets*** : from supply pipelines and inverted siphons.
- ***Flow measurement / control*** : the jump location can indicate discharge and act as a control section.

PREVIOUS YEAR QUESTIONS

- What is a hydraulic jump? Explain different practical applications of the phenomenon of hydraulic jump.
  [OPSC·Forest Service 2015–16 · P1/Q.1(b) · 20M]
- What do you mean by hydraulic jump? Write the applications of hydraulic jump.
  [OPSC·CSE 2020–21 · P1/Q.2(c)(i) · 8M]
- Define hydraulic jump. How is it applicable in irrigation works? [OPSC·CSE 2018–19 · P1/Q.2(b)(i) · 8M]

MODEL Q For the 20-mark version: definition + neat sketch (y_1, y_2, roller, E_L), the sequent-depth and energy-loss equations, one line on the Froude classification, then the six applications above, leading with energy dissipation in stilling basins below spillways/weirs — the dominant irrigation use.

Hydraulic jump on a horizontal floor

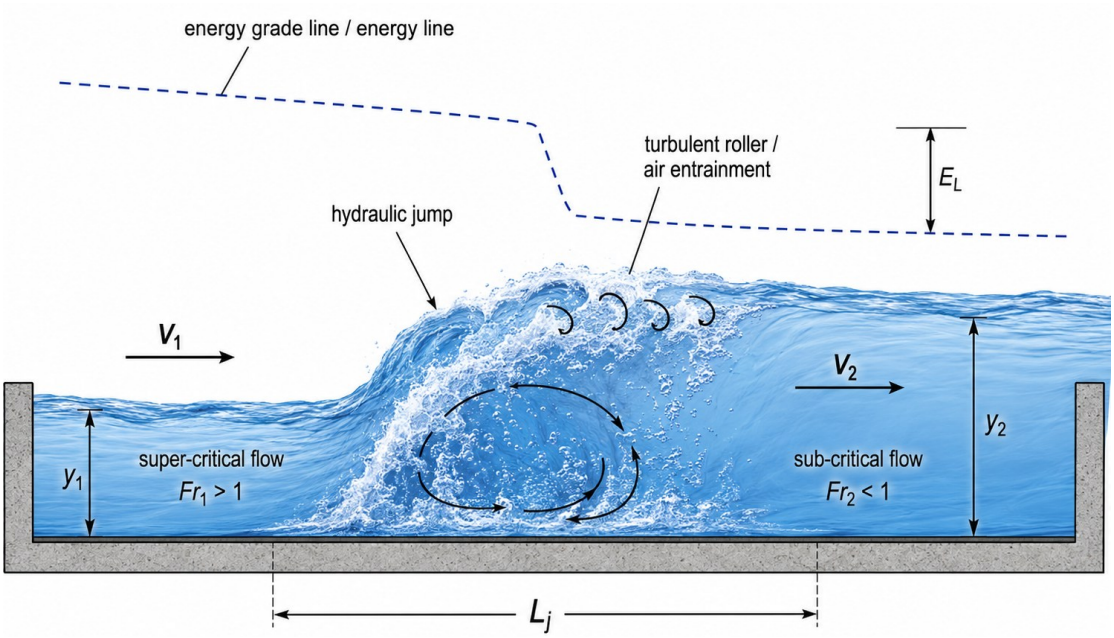


Fig. 4.2 Hydraulic jump — super-critical inflow rises to sub-critical tail-water through a turbulent roller (energy loss E_L).

8 GRADUALLY VARIED FLOW & SURFACE PROFILES

When the depth of a steady flow changes slowly along a long channel a backwater behind a weir, a drawdown towards a free fall the flow is ***gradually varied (GVF)***. The governing equation, from the energy gradient, is

$$dy/dx = (S_0 - S_f) / (1 - Fr^2)$$

S_0 = bed slope · S_f = friction (energy) slope · Fr = Froude number

The sign of dy/dx (rising or falling surface) follows from the signs of the numerator (whether the actual depth is above or below normal depth y_n) and denominator (above or below critical depth y_c). Classifying a channel by its bed slope relative to critical gives five families of ***surface profiles***:

Slope type	Condition	Profiles	Typical example
Mild (M)	y_n > y_c	M1, M2, M3	Backwater behind a weir on a mild canal
Steep (S)	y_n < y_c	S1, S2, S3	Flow down a steep chute
Critical (C)	y_n = y_c	C1, C3	Rare transitional reach
Horizontal (H)	$S_0 = 0$	H2, H3	Flow approaching a free overfall
Adverse (A)	$S_0 < 0$	A2, A3	Short rising-bed reach

The ***M1 backwater curve*** (sub-critical flow deepening upstream of an obstruction) is the one most used in canal practice it fixes how far upstream a regulator or weir raises the water level, and hence the land that may be submerged.

9 PIPE FLOW

Pressurised (full-bore) pipe flow governs underground pipeline distribution, inverted siphons, culverts and the pump and sprinkler/drip mains of later chapters. The two working equations are continuity and the energy equation with friction.

9.1 Continuity & Energy in Pipes

Continuity $Q = A_1V_1 = A_2V_2$; the energy equation is Bernoulli's with a loss term (§2.5). The line joining the piezometric heads ($z + p/\gamma$) is the ***hydraulic grade line (HGL)***; adding the velocity head gives the ***total energy line (TEL)***, which always falls in the direction of flow by the head lost.

9.2 Darcy–Weisbach Equation & Friction Factor

$$h_f = f\,L\,V^2 / (2\,g\,D)$$

h_f = head loss to friction · f = friction factor · L = length · D = diameter · V = mean velocity

- ***Laminar flow (Re < 2000)*** : f = 64/Re (Hagen–Poiseuille); f is independent of roughness.
- ***Turbulent flow (Re > 4000)*** : f depends on Re and relative roughness ε/D through the ***Colebrook–White equation***, read graphically from the ***Moody chart***.

The older ***Hazen–Williams*** formula is also used for water mains, but Darcy–Weisbach is the rational, dimensionally-consistent choice.

9.3 Major & Minor Losses

- ***Major loss*** : continuous friction along the pipe length — the Darcy–Weisbach h_f above; usually the dominant loss in long mains.
- ***Minor (local) losses*** : at entrances, exits, bends, valves, contractions and expansions; each is written $h = k \cdot V^2/2g$. Sudden-expansion loss = $(V_1 - V_2)^2/2g$. Important in short pipelines and fittings-heavy layouts.

$$h_{minor} = k\,V^2/2g \qquad h_{total} = h_f + \Sigma\, h_{minor}$$

k = loss coefficient of the fitting

10 CANAL DESIGN, NETWORK, LINING & OPEN-DRAIN DESIGN

10.1 Components of a Canal Network

In a large irrigation project water is delivered through a ***branching hierarchy*** of channels, each smaller than its parent, classified by function:

- ***Main canal*** : takes off directly from the river/reservoir head-works or a feeder; largest capacity; generally ***not*** used for direct irrigation it feeds branches and major distributaries.
- ***Branch canal*** : takes off from the main canal (usually > 5 cumec); mainly feeds distributaries, with limited direct irrigation.
- ***Major distributary (Rajbaha)*** : 0.25–5 cumec; supplies water through outlets to water-courses and to minor distributaries; direct irrigation.
- ***Minor distributary (minor)*** : < 0.25 cumec; feeds water-courses.
- ***Water-course / field channel*** : small channel from an outlet to the fields; built and maintained by the cultivators.

Canals are further classified by ***alignment*** — ***ridge/watershed canal*** (on the ridge, irrigates both sides, no cross-drainage works needed), ***contour canal*** (parallel to contours, irrigates one side, needs cross-drainage works), and ***side-slope canal*** (down the slope, steep, no cross-drainage works) — and by function (***productive vs protective***), soil (***alluvial vs non-alluvial***) and whether ***lined or unlined***. ***Regulation and control structures*** complete the network: ***head regulator*** (controls supply into an off-taking canal), ***cross regulator*** (controls level/supply in the parent canal), ***canal falls*** (step the bed down where ground slope exceeds canal slope, dissipating energy by a jump), ***escapes*** (dispose of surplus water safely), ***outlets/modules*** (deliver a set discharge to a water-course), and ***cross-drainage works*** — aqueduct, super-passage, syphon — where a canal meets a natural drain.

CANAL NETWORK HIERARCHY

MAIN CANAL
Off-take: river / reservoir head-works · Largest capacity

↓

BRANCH CANAL
Off-take from Main Canal · > 5 cumec

↓

MAJOR DISTRIBUTARY (RAJBAHA)
0.25 – 5 cumec · feeds water-courses & minors · direct irrigation

↓

MINOR DISTRIBUTARY
< 0.25 cumec · feeds water-courses

↓

WATER-COURSE / FIELD CHANNEL
Built & maintained by cultivators

CLASSIFIED BY ALIGNMENT	REGULATION & CONTROL STRUCTURES
Ridge / Watershed canal — on the ridge, irrigates both sides, no cross-drainage works Contour canal — along contours, irrigates one side, needs cross-drainage works Side-slope canal — down the slope, steep, no cross-drainage works	Head regulator · Cross regulator · Canal falls Escapes · Outlets/modules Cross-drainage works — aqueduct, super-passage, syphon

PREVIOUS YEAR QUESTIONS

Explain the components of canal network in a large irrigation project using diagram.
[IFoS 2019 · P1/Q.5(a) · 8M]

MODEL Q Draw the branching schematic river → head-works → main → branch → major distributary → minor → water-course → field, mark head & cross regulators, a fall, an escape and an outlet, then describe each component in one line with its discharge band. Add alignment types (ridge/contour/side-slope) if space allows.

Layout of a canal network in a large project

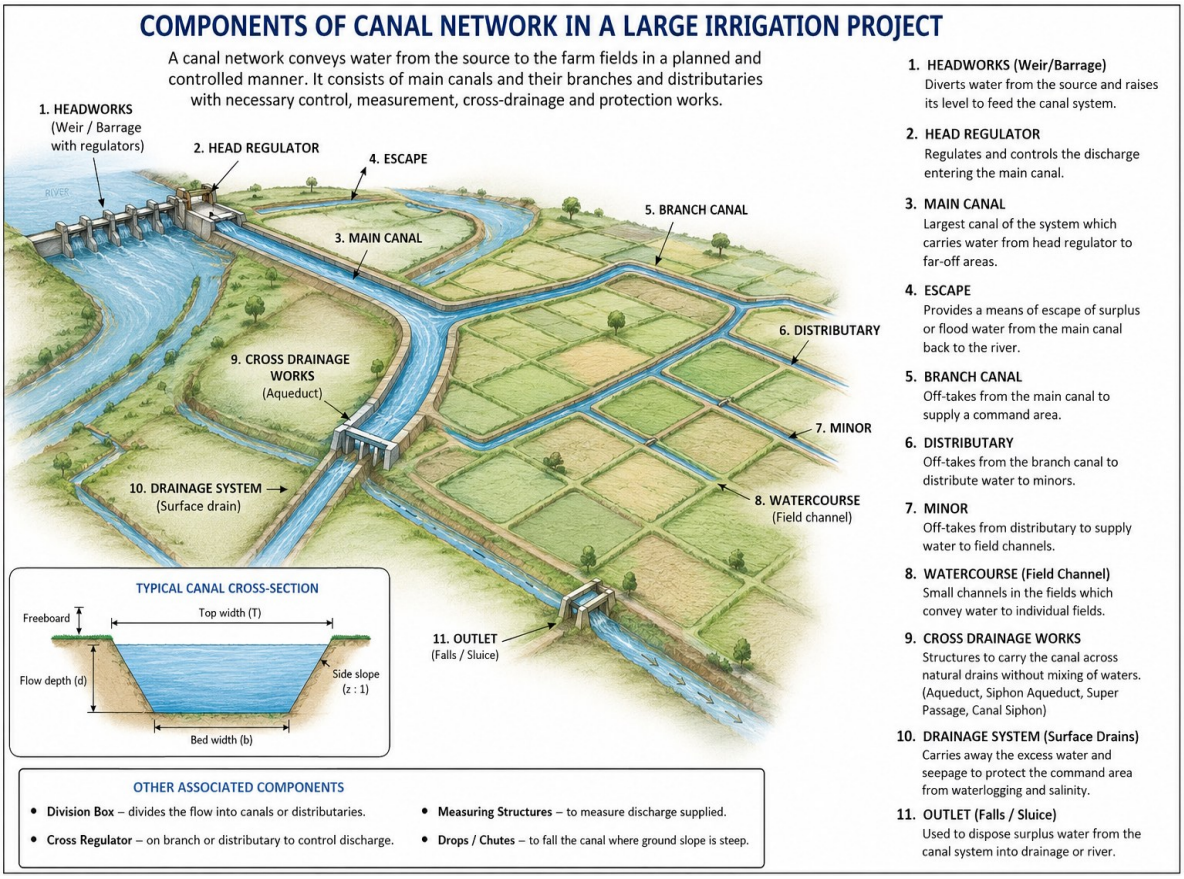


Fig. 4.3 Components of a canal network — main, branch, distributary, minor and water-course with regulation structures.

10.2 Regulation Structures, Falls & Cross-Drainage Works

The syllabus names regulators, escapes and falls explicitly. ***Regulators*** control supply and level — a ***head regulator*** at a canal off-take sets the discharge admitted, while a ***cross regulator*** on the parent canal holds the water level up so upstream off-takes draw their share and silt entry is controlled. ***Escapes*** are safety outlets that dispose of surplus or emergency water into a natural drain (a surplus-water escape for routine spill; a tail escape at the canal end).

CANAL FALLS (DROPS)

A ***fall*** lowers the canal bed where the ***natural ground slope is steeper than the permissible canal slope***, so the surplus head is destroyed safely by a hydraulic jump (§7) instead of producing scouring velocities. Principal types:

- ***Ogee fall*** : smooth ogee profile; a gentle transition used for small drops.
- ***Vertical-drop (Sarda-type) fall*** : water drops vertically onto a cushioned floor; simple and robust.
- ***Glacis fall (straight / parabolic)*** : flow glides down a sloping glacis and the jump forms on it; the modern standard, and can be combined with a regulator or metering flume.

CROSS-DRAINAGE (CD) WORKS

Where a canal and a natural drain cross, a ***cross-drainage work*** carries one across the other:

- ***Aqueduct*** : canal carried in a trough over the drain; the drain passes below at low stage (canal bed well above drain).
- ***Syphon aqueduct*** : as above, but in floods the drain runs under pressure (syphons) beneath the canal trough.

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- ***Super-passage*** : the drain is carried over the canal — the reverse of an aqueduct.
- ***Canal syphon / level crossing*** : the canal passes under the drain (syphon), or the two are mixed at a regulated level crossing.

10.3 Canal Lining

A ***lining*** is an impervious (or protective) layer on the bed and banks. Its chief purpose is to cut ***seepage loss*** (a quarter to a third of the diverted water in unlined canals, and up to a half in sandy reaches); it also allows ***higher, non-scouring velocities*** — so a smaller section — prevents water-logging, checks weed growth and reduces maintenance.

TYPES OF CANAL LINING

- ***Hard-surface / rigid linings***: cement concrete (cast in-situ or pre-cast), stone or brick masonry, brick/concrete tile, shotcrete and asphaltic concrete. Durable, low-seepage, allow high velocity; costlier and can crack on expansive soils.
- ***Earth-type (flexible) linings*** : compacted earth, soil-cement, and bentonite–clay blankets. Cheap, locally available; lower velocity limit and shorter life.
- ***Synthetic / buried-membrane linings*** : LDPE film, rubber or synthetic sheets, usually buried under a protective soil cover. Excellent seepage control; needs careful laying and protection.

Selection factors: availability and cost of material at site, labour cost, degree of water-tightness required, design velocity of flow, useful life and maintenance cost.

PREVIOUS YEAR QUESTIONS

What do you mean by lining of channel? Discuss about the types of canal lining used for channel.

[OPSC·CSE 2022–23 · P1/Q.8(a) · 5M]

MODEL Q Define lining and its purpose (seepage control), then the three families — rigid/hard-surface, earth-type, synthetic membrane — with one example each; finish with the selection factors.

10.4 Hydraulic Design of Open Drains

Surface (open) drains remove excess irrigation and storm water to prevent water-logging. They are of two kinds: ***shallow surface drains*** (dispose of surface/storm water, little sub-drainage) and ***deep open drains*** (lower the water table, relieve already-waterlogged land, and serve as outlets for tile-drain systems).

DESIGN FACTORS

- ***Layout*** : align along the natural drainage lines; every drain must have an ***outfall*** into a larger drain or natural stream, positioned to give the required bed slope.
- ***Capacity*** : designed for the ***storm runoff*** (which dwarfs seepage and surface irrigation flows); estimated from hydrology — e.g. the Sarda Canal system used ≈0.109 cumec per km² of catchment. Uneconomical to design for extreme storms.
- ***Section*** : trapezoidal, designed on the ***same Manning/most-economical principles as irrigation channels***; a small central ***cunnette*** carries the low seepage flow at a self-cleaning velocity so the full section works only in storms. Typical deep-drain depth 0.6–1.5 m and bed width 0.3–1.2 m by soil.
- ***Maintenance*** : weed growth is the main problem (low silt-free flows) — controlled by keeping a higher velocity and periodic clearing.

So the hydraulic computation is exactly the trapezoidal Manning design of §5: fix the design storm discharge, choose a non-scouring velocity for the soil, get $A = Q/V$, and solve $A = by + zy^2$ with $P = b + 2y\sqrt{(1+z^2)}$ for the section then add the cunnette and freeboard.

PREVIOUS YEAR QUESTIONS

Discuss in detail about the hydraulic design of open drains.[IFoS 2023 · P1/Q.6(c) · 10M]

MODEL Q Define open drains (shallow vs deep), give the four design factors (layout, capacity from storm runoff, trapezoidal section with cunnette, maintenance), then show the Manning/most-economical section computation (A = Q/V; solve A = by+zy², P = b+2y√(1+z²)) with freeboard — cross-refer to §5.***

11 FORMULA SHEET · SUMMARY · LAST-NIGHT REVISION

11.1 Consolidated Formula Sheet

$\tau = \mu(du/dy)$ · $\gamma = \rho g$ · $\nu = \mu/\rho$
Fluid properties

$p = \rho g h$ · $F = \rho g \bar{h} A$ · $Q = A_1V_1 = A_2V_2$
Hydrostatics & continuity

$z + p/\gamma + V^2/2g = \text{constant}$
Bernoulli (add h_L for real flow)

$Re = VR/\nu$ · $Fr = V/\sqrt{(gD)}$
Regime numbers (channel: R; D = A/T)

$V = C\sqrt{(RS)}$ · $V = (1/n)R^{2/3}S^{1/2}$
Chézy & Manning uniform flow

$C = (1/n)R^{1/6}$ · $C = \sqrt{(8g/f)}$ · $f = 8gn^2/R^{1/3}$
Coefficient correlations

Trapezoid: $A = by + zy^2$ · $P = b + 2y\sqrt{(1+z^2)}$
Section geometry

Most-efficient: $b = 2y(\sqrt{(1+z^2)} - z)$ · $\frac{1}{2}T = y\sqrt{(1+z^2)}$ · $R = y/2$
Best-hydraulic trapezoid

$E = y + V^2/2g$ · $Q^2T/gA^3 = 1$ (Fr=1) · y_c=$(q^2/g)^{1/3}$ · E_c=1.5y_c
Specific energy & critical flow

$y_2/y_1 = \frac{1}{2}[\sqrt{(1+8Fr_1^2)} - 1]$ · $E_L = (y_2-y_1)^3/(4y_1y_2)$
Hydraulic jump

$dy/dx = (S_0 - S_f)/(1 - Fr^2)$ · $h_f = fLV^2/2gD$
GVF & pipe friction

11.2 Chapter Summary

Open-channel flow is gravity-driven flow with a free surface; its depth is an unknown, which makes the ***Froude number*** (gravity) and ***Reynolds number*** (viscosity) the two classifiers of state. Uniform flow is computed with ***Manning*** (routine) or ***Chézy***, the two tied to Darcy's f by C = (1/n)R^{1/6} = √(8g/f). The ***most-efficient section*** minimises the wetted perimeter — for a trapezoid, half the top width equals a sloping side and R = y/2 — and is the backbone of every channel- and drain-sizing numerical. ***Specific energy*** E = y + V²/2g is minimum at critical flow (Fr = 1, E_c = 1.5y_c for a rectangle); a super-critical stream returns to sub-critical only through a ***hydraulic jump***, whose sequent depths follow from momentum and whose dissipation (5%→85%) and form are set by Fr_1 — the steady jump (4.5–9) being the design ideal for stilling basins. On the engineering side,

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canals form a ***main→branch→distributary→minor→water-course*** hierarchy with regulators, falls and escapes; ***lining*** controls seepage; and ***open drains*** are simply trapezoidal Manning channels sized for storm runoff.

11.3 Last-Night Revision — one page

- ***Pipe vs OCF*** : free surface, gravity-driven, depth unknown → Froude governs.
- ***Reynolds (channel)*** : Re = VR/v; laminar < 500, turbulent > 2000.
- ***Froude*** : Fr = V/√(gD); <1 sub-critical (deep/slow, d/s control), >1 super-critical (shallow/fast, u/s control).
- ***Manning*** : V = (1/n)R^{2/3}S^{1/2}; n ≈ 0.012 concrete, 0.025 earth, 0.03–0.04 weedy.
- ***Correlations*** : C = (1/n)R^{1/6}; C = √(8g/f); f = 8gn²/R^{1/3}.
- ***Most-efficient trapezoid*** : b = 2y(√(1+z²)−z); ½ top width = sloping side; R = y/2; best slope 60°.
- ***Design steps*** : Q,S,z,n → limiting V → A=Q/V → solve section → Manning check → freeboard.
- ***Specific energy*** : E = y+V²/2g; Fr=1 at E_min; rectangle y_c=(q²/g)^{1/3}, E_c=1.5y_c.
- ***Hydraulic jump*** : super→sub-critical; $y_2/y_1=½[\sqrt{(1+8Fr_1^2)}-1]$; $E_L=(y_2-y_1)^3/4y_1y_2$.
- ***Jump types*** : undular(<5%), weak(<20%), oscillating(20–45%), steady(45–70%, best), strong(≤85%).
- ***Jump uses*** : energy dissipation (stilling basin), raise d/s level, mixing, aeration, remove air pockets.
- ***Canal hierarchy*** : main→branch→major distributary→minor→water-course; ridge/contour/side-slope alignment.
- ***Structures*** : head & cross regulators, falls (energy by jump), escapes, outlets, CD works.
- ***Lining*** : cuts seepage (¼–⅓ of supply); rigid / earth / synthetic; allows higher velocity.
- ***Open drains*** : shallow vs deep; design for storm runoff; trapezoidal Manning section + cunnette.

CHAPTER

5

GROUNDWATER, WELLS & PUMPS

Groundwater & aquifers · Well hydraulics · Pumping & recuperation tests · Well construction & screens · Centrifugal, submersible & reciprocating pumps · Cavitation · Power & energy cost

SYLLABUS (Paper I | Soil & Water Conservation): Groundwater hydrology — subsurface vertical distribution of water, vadose zone, water table, perched water, capillary fringe. Aquifer types — confined, unconfined, semi-confined/leaky, perched — and characteristics: specific yield, specific retention, storage coefficient, transmissibility/transmissivity, hydraulic conductivity. Well hydraulics — steady-state and unsteady flow to wells; Thiem and Theis equations; drawdown, cone of depression, radius of influence; pumping test and recuperation test for aquifer parameters; specific capacity of wells. Well construction — open/dug wells, tube wells, dug-cum-bore, cavity, driven, filter-point, borewells; well screens, well development; tube-well design parameters. Pumps — centrifugal, reciprocating, submersible, jet, axial-flow, air-lift; characteristics, efficiency, effects of speed and impeller diameter; cavitation and its prevention; pump selection and installation; horsepower (WHP/BHP) and energy-cost calculations.

Chapter Outline

1. **Scope & Groundwater in the Hydrologic Cycle**
2. **Occurrence & Vertical Distribution of Subsurface Water**
3. **Aquifer Types & Characteristics**
4. **Aquifer Properties & Darcy's Law**
5. **Groundwater Movement & Steady Flow to Wells**
6. **Unsteady Flow & Pumping / Recuperation Tests**
7. **Groundwater Investigation & Recharge Estimation**
8. **Wells: Types & Construction**
9. **Well Screens, Development & Tube-well Design**
10. **Groundwater Management, Recharge & Quality**
11. **Pumps: Classification & Centrifugal Pumps**
12. **Pump Performance, Cavitation, Selection & Power**

Chapter 5 Concept Map

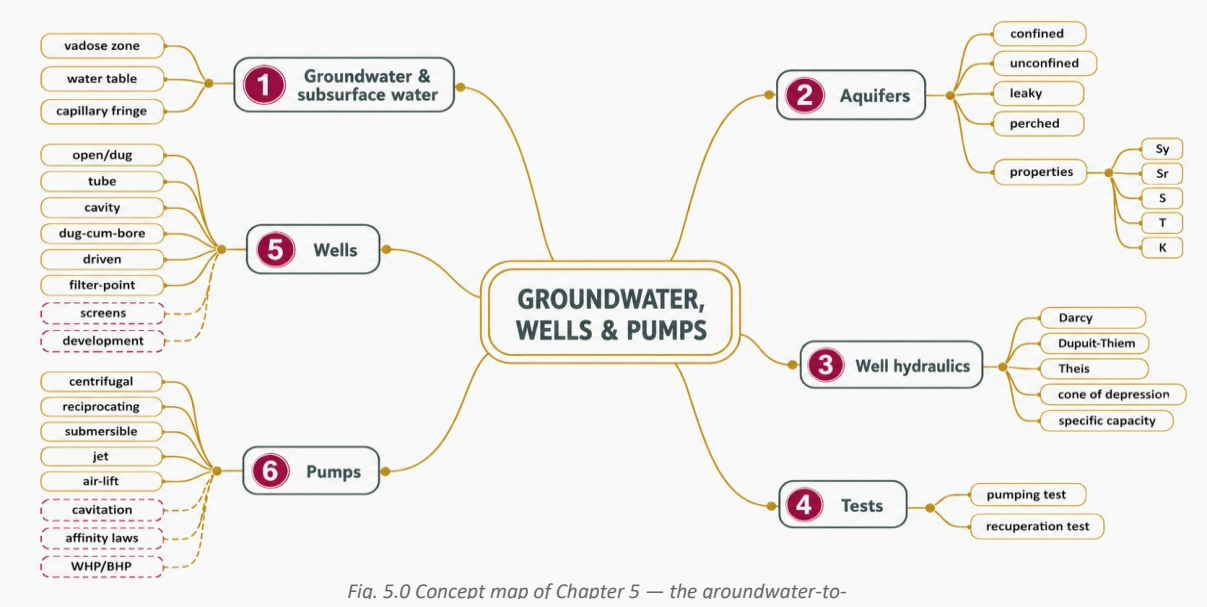


Fig. 5.0 Concept map of Chapter 5 — the groundwater-to-

1 SCOPE & GROUNDWATER IN THE HYDROLOGIC CYCLE

Groundwater is the single largest source of usable freshwater and supplies about ***60% of India's irrigated area***. This chapter follows the natural chain where water sits underground, how aquifers store and transmit it, how wells draw it, how we test aquifers, how wells are built, and how pumps lift the water each link carrying its own bank of previous-year questions.

Groundwater : the water present in the ***zone of saturation*** below the water table, which can be collected through wells, tunnels or drainage galleries or flows naturally to the surface via seeps and springs. Only ***free (gravitational) water*** that moves under gravity into wells is groundwater.

GROUNDWATER IN THE WATER CYCLE

Of the water infiltrating the land surface, part is retained in the vadose zone, part is transpired, and the rest percolates to the saturated zone as ***recharge***. Natural recharge is from precipitation, streamflow, lakes and reservoirs; ***artificial recharge*** is from canal seepage, return flow from irrigation, and percolation/check-dam structures. Discharge occurs as baseflow to streams and springs, evapotranspiration from shallow water tables, and the major artificial discharge pumping of wells.

IMPORTANCE OF GROUNDWATER

It is about 98% of the liquid freshwater readily available for human use; a reliable, good-quality supply in humid and arid regions alike; a drought and emergency reserve that sustains river baseflow; and the mainstay of India's irrigation and rural drinking water.

GROUNDWATER DEPLETION IN ARID / SEMI-ARID INDIA — FACTORS & THE ENGINEER'S RESPONSE

Factors : over-abstraction by a growing number of energised wells (free/subsidised power); low and erratic monsoon recharge; falling water tables (2-3 m/yr in the north-west); reduced natural recharge from urbanisation and canal lining; and quality loss from over-draft (salinity, fluoride, arsenic).

Engineer's solutions : artificial recharge and managed aquifer recharge (percolation tanks, check dams, recharge shafts, rooftop recharge); watershed treatment to raise infiltration; micro-irrigation (drip/sprinkler) and better on-farm efficiency to cut demand; conjunctive use of canal and groundwater; participatory groundwater management and metering; and rejuvenating traditional water harvesting.

PREVIOUS YEAR QUESTIONS

- Groundwater is fast depleting in most of the arid and semi-arid regions of our country. What are the factors responsible for it and what solution would you like to offer to combat this situation as an engineer? [OPSC·Forest (Main) 2015-16 | P1/8(d) | 10M]

Groundwater In The Hydrologic Cycle

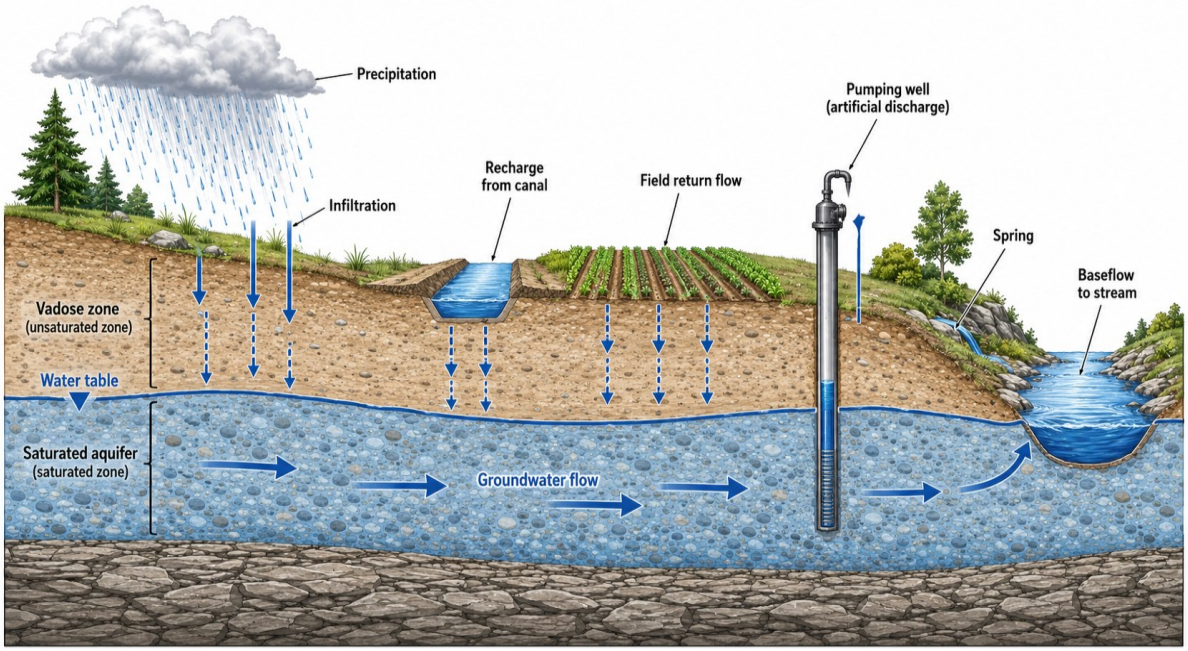


Fig. 5.1 Recharge and discharge pathways linking groundwater to the water cycle.

2 OCCURRENCE & VERTICAL DISTRIBUTION OF SUBSURFACE WATER

Below the ground, water is distributed in two broad zones separated by the ***water table*** — the zone of aeration above and the zone of saturation below. Reading this vertical profile correctly is the basis for every later idea (aquifers, wells, pumping).

THE VERTICAL PROFILE (TOP TO BOTTOM)

Zone / sub-zone	State of the pores	Water & its pressure
Zone of aeration (vadose zone)	pores hold both air and water	held below atmospheric pressure; not free to enter a well
Soil-water zone	near surface, roots active	held by capillarity & adsorption; feeds ET
Intermediate zone	between soil water and capillary fringe	pellicular / gravity water in transit
Capillary fringe	voids largely water-filled above water table	held by capillarity at < atmospheric pressure
Water table	the free surface	water at atmospheric pressure
Zone of saturation (aquifer)	all voids completely water-filled	at > atmospheric pressure; this is groundwater

Water table – the ***free surface*** at which pore-water pressure equals atmospheric pressure; the upper boundary of the zone of saturation and of an unconfined aquifer.

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Vadose zone – the whole unsaturated region between the ground surface and the water table (soil-water zone + intermediate zone + capillary fringe); water here is ***vadose water*** held below atmospheric pressure, so it cannot flow into a well.

TYPES OF SUBSURFACE WATER

By position relative to the water table, subsurface water is either ***vadose (suspended) water*** above it — soil water, intermediate/pellicular water and capillary water — or ***groundwater (phreatic water)*** below it in the zone of saturation. Genetic types occasionally met are connate, magmatic/juvenile and metamorphic water.

Perched water / perched water table – a local body of saturated water held in the vadose zone above the main water table by an ***impervious lens*** (e.g. a clay layer) that impedes downward percolation; its upper surface is the perched water table. It supports only small, seasonal dug wells.

PREVIOUS YEAR QUESTIONS

- Discuss the subsurface vertical distribution of groundwater with an emphasis on different types of subsurface water. [IFoS 2025 | P1/5(b) | 8M]

MODEL Q Draw the vertical profile; define each zone by pore-state and pressure; name the water table as the atmospheric-pressure surface; then classify subsurface water into vadose (soil/intermediate/capillary) and phreatic (groundwater), adding perched water as the special case. ***

Vertical Distribution Of Subsurface Water

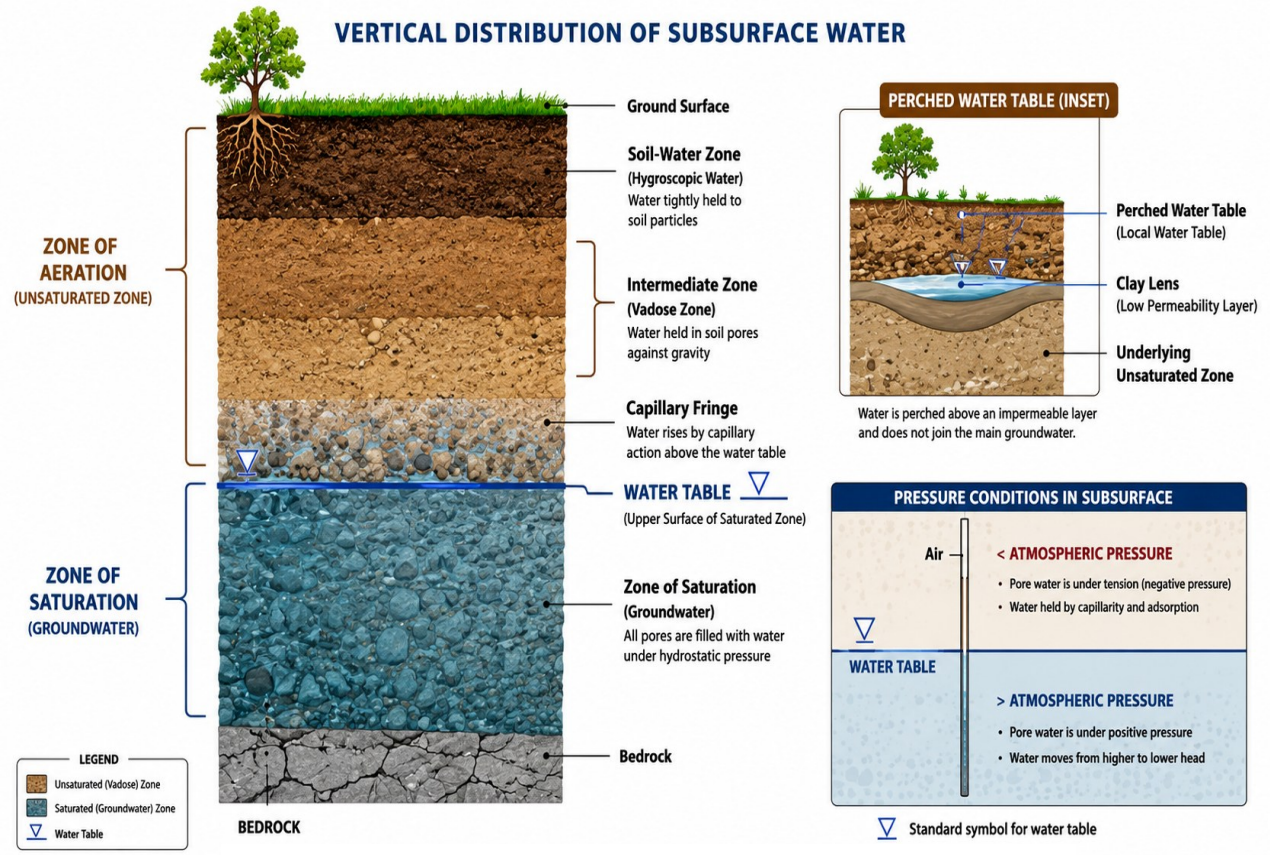


Fig. 5.2 Hydrologic zones below the ground and the position of the water table.

3 AQUIFER TYPES & CHARACTERISTICS

This is the most heavily examined area of the chapter. A ***geologic formation*** is judged by two abilities to store water and to transmit it — and that judgement fixes both the aquifer type and the yield of any well sunk into it.

Formation	Stores water?	Transmits water?	Example
Aquifer	yes	yes — in usable quantity	sand, gravel, sandstone
Aquitard	yes	slowly — leaks	sandy clay, silt
Aquiclude	yes (much)	no — negligible	clay
Aquifuge	no	no	solid, unfractured granite

THE FOUR TYPES OF AQUIFER

Unconfined (water-table / phreatic) : bounded above by the water table (at atmospheric pressure) and below by an aquiclude; recharged directly from the surface; the well water level stands at the water table.

Confined (artesian / pressure) : sandwiched between two impervious layers; water is under pressure, so in a well it rises above the aquifer top to the ***piezometric level***. If that level is above the ground, the well flows on its own (a flowing / artesian well).

Leaky (semi-confined) : a confined or unconfined aquifer that gains or loses water through an adjacent leaky aquitard; the commonest real case.

Perched : a small unconfined body held in the vadose zone on an impervious lens, above the main water table; supports only minor dug wells.

Piezometric (Potentiometric) Surface : the imaginary surface to which water rises in wells tapping a ***confined*** aquifer; it represents the confined-aquifer head. Where it lies above ground, wells flow freely (artesian condition).

KEY DIFFERENTIATIONS (FREQUENTLY ASKED)

Basis	Unconfined aquifer	Confined aquifer
Upper boundary	water table (free surface)	overlying impervious layer
Water pressure	atmospheric at water table	greater than atmospheric
Level in well	stands at the water table	rises to piezometric level above aquifer top
Recharge	direct from surface above	mainly via outcrop / leakage
Water released by	dewatering of pores (Sy)	compression + water expansion (S)
Storativity	high — Sy 0.01-0.30	low — S 5×10^{-5} to 5×10^{-3}

Basis	Semi-confined (leaky) aquifer	Perched water table
Location	main saturated aquifer	local saturation in vadose zone, above main WT
Bounding layer	leaky aquitard (transmits leakage)	impervious lens (holds water up)
Extent & yield	regional, dependable yield	local, small, often seasonal
Recharge	vertical leakage from adjacent aquifer	trapped downward percolation

Basis	Piezometric surface	Pumping water level
Defined	static level of confined water	level in the well while pumping
Condition	no pumping (static)	during pumping (dynamic)
Drawdown	the datum (zero drawdown)	lowered from static by the drawdown
Tells us	confined-aquifer head	drawdown, specific capacity

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AQUIFER CHARACTERISTICS THAT INFLUENCE WELL YIELD

Yield rises with the aquifer's ***transmissivity T (= K·b)*** and hydraulic conductivity, its saturated thickness and areal extent, and its storativity (Sy for unconfined, S for confined); it is reduced by fine grain size, partial penetration and well losses. Coarse, thick, extensive, high-K aquifers give the best wells.

PREVIOUS YEAR QUESTIONS

- Discuss the different types of aquifers. [IFoS 2022 | P1/5(b) | 8M]
- What are the characteristics of the aquifer that influence yield of wells? Explain in brief [IFoS 2024 | P1/5(b) | 8M]
- Discuss the important aquifer characteristics influencing yields of wells. [IFoS 2027 | P1/6(b) | 10M]
- Differentiate between: (I) Semi-confined aquifer and Perched water table; (II) Transmissibility and Storage coefficient; (III) Piezometric surface and Pumping water level; (IV) Single-acting pump and Double-acting pump. [pairs II, IV tabled in §4 and §11] [IFoS 2020 | P1/7(a·ii) | 8M]
- Explain the characteristics of saturated underground formations such as aquifer (confined and unconfined), aquiclude and aquifuge. Also explain Darcy's law for well hydraulics. [Darcy's law in §4] [UK ·PSC RFO (Main) 2012| Q3(iv) | 10M]

Types Of Aquifers

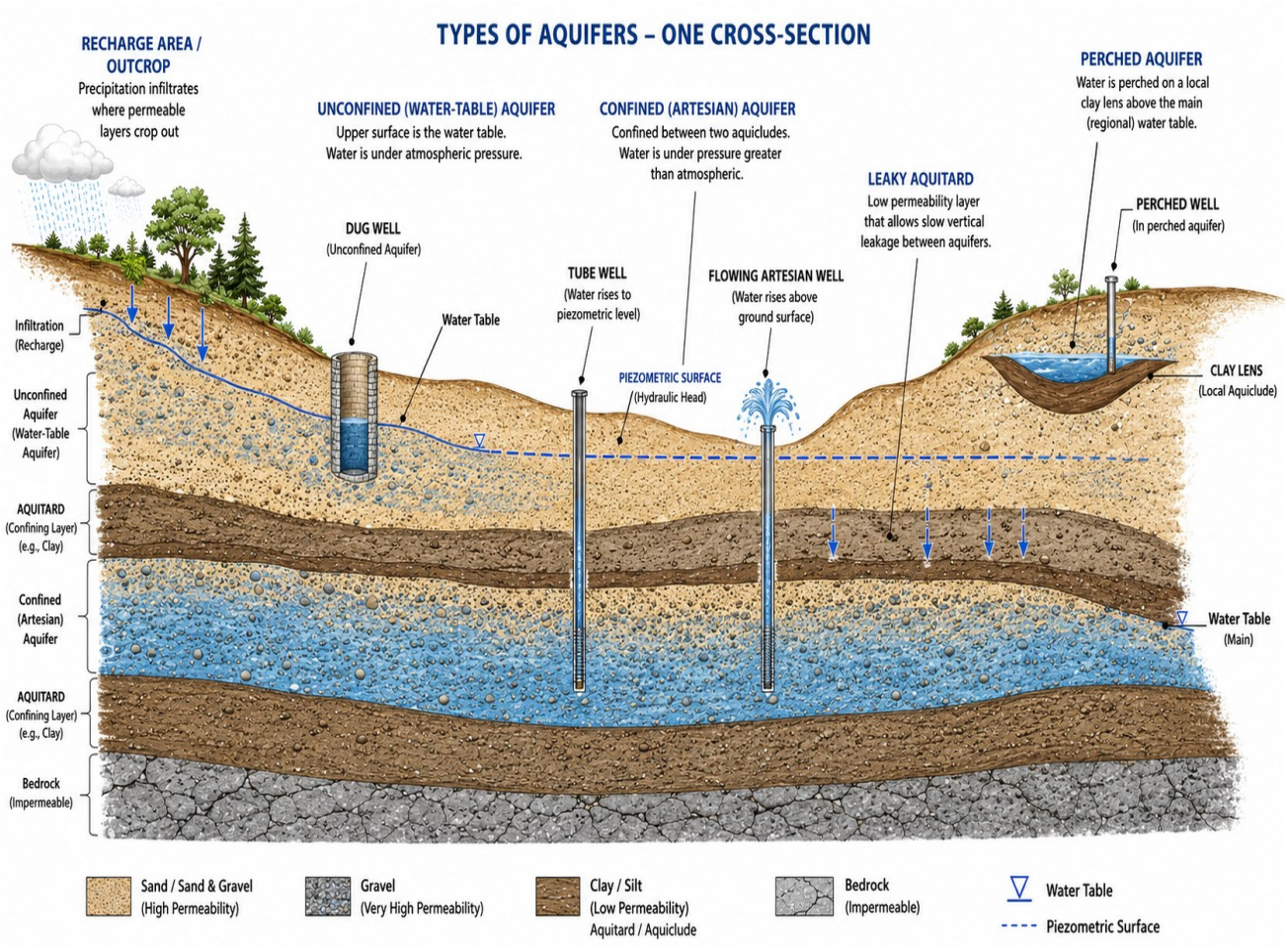


Fig. 5.3 Unconfined, confined (artesian), leaky and perched aquifers in one

4 AQUIFER PROPERTIES & DARCY'S LAW

Aquifer properties are of two families — ***storage parameters*** (how much water an aquifer holds and releases) and ***transmission parameters*** (how readily it lets water flow). Together they drive every well-yield and pumping-test calculation.

STORAGE PARAMETERS

Porosity (n) — ratio of void volume to total volume, $n = Vv/V$; effective porosity is the interconnected fraction available for flow.

Specific yield (Sy) & specific retention (Sr) — Sy is the water that ***drains under gravity*** per unit bulk volume; Sr is the water ***retained*** against gravity. They partition the porosity: $n = Sy + Sr$.

Storage coefficient / storativity (S) — volume of water released from (or taken into) storage per unit ***plan area*** per unit change in head; $S = Ss \cdot b$ (Ss = specific storage, b = saturated thickness). For unconfined aquifers S ≈ Sy.

TRANSMISSION PARAMETERS & DARCY'S LAW

Hydraulic conductivity (K) & transmissivity (T) — K measures the ease of flow through the medium for water (m/day); transmissivity is its depth-integrated value, $T = K \cdot b$ (m²/day) — the rate an aquifer transmits water over its full thickness.

$$v = K \cdot i \qquad Q = K \cdot i \cdot A = K \cdot A \cdot (dh/dL)$$

Darcy's law: v = Darcy (apparent) velocity (m/day); K = hydraulic conductivity (m/day); i = dh/dL = hydraulic gradient (–); A = flow area (m²); Q = discharge (m³/day)

$$n = Sy + Sr \qquad S = Ss \cdot b \qquad T = K \cdot b$$

n porosity; Sy specific yield; Sr specific retention; S storativity (–); Ss specific storage (m⁻¹); b saturated thickness (m); T transmissivity (m²/day)

TYPICAL VALUES (FOR REVISION)

Material	Porosity %	Specific yield %
Coarse gravel	28	23
Coarse sand	39	27
Fine sand	43	23
Silt	46	8
Clay	42	3
Sandstone (medium)	37	27
Limestone	30	14

KEY DIFFERENTIATIONS (FREQUENTLY ASKED)

Basis	Transmissibility (T)	Storage coefficient (S)
Meaning	rate aquifer transmits water	water released per unit area per unit head drop
Formula	T = K·b	S = Ss·b
Dimension	L^2/T (m²/day)	Dimensionless
Governs	well yield & drawdown	volume of water in storage
Typical	10-10 000 m²/day	confined 5×10^{-5}-5×10^{-3}; unconfined = Sy

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Basis	Specific yield (Sy)	Specific retention (Sr)
Definition	drainable water / bulk volume	water held against gravity / bulk volume
Partition	n = Sy + Sr	n = Sy + Sr
Large for	coarse sand & gravel	fine silt & clay
Significance	usable storage	unusable retained water

Basis	Specific capacity of well	Specific yield of aquifer
Belongs to	the well	the aquifer material
Definition	discharge per unit drawdown, Q/s	drainable fraction, Vd/V
Unit	m^3/day per m (≈ m^2/day)	dimensionless
Depends on	T, S, well radius, time, well loss	pore size & drainage

◆ **WORKED NUMERICAL — *Specific yield & porosity from a basin water balance*** [OPSC·CSE (Main) 2018-19 · Paper-I Q.5(a)(ii) · 10M]

Problem. *In an alluvial basin of 100 km², 85 Mm³ of groundwater was pumped in a year and the groundwater table dropped by about 5 m during the year. Assuming no replenishment, estimate the specific yield of the aquifer. If the specific retention is 14%, what is the porosity of the soil?*

Given. A = 100 km^2 = 100×10^6 m^2; V = 85 Mm^3 = 85×10^6 m^3; water-table drop Δh = 5 m; Sr = 0.14.

Formula. $V = A \cdot \Delta h \cdot Sy \;\Rightarrow\; Sy = V/(A\cdot\Delta h);\; n = Sy + Sr$

Substitution. $Sy = (85\times10^6)/(100\times10^6 \times 5) = (85\times10^6)/(500\times10^6) = 0.170$

$n = 0.170 + 0.140 = 0.310$

Result. Specific yield Sy = 0.170 (17.0%); porosity n = 0.310 (31%).

Check. Sy < n and Sy + Sr = n both hold; values are typical of alluvium.

PREVIOUS YEAR QUESTIONS

- Specific yield and specific retention [OPSC ·CSE (Main) 2020 -21 | P1/5(d) (v) | 5M]
- Define 'Transmissibility' and 'Storage Coefficient' of an aquifer. [OPSC ·CSE (Main) 2018 -19 | P1/5(a) (i) | 5M]
- What is aquifer? Write the types and properties of aquifer. [OPSC ·CSE (Main) 2022 -23 | P1/13(a) | 8M]
- Differentiate between: (i) Specific capacity of well and Specific yield of aquifer; (ii) Open wells and Tubewells; (iii) Pumping test and Recuperation test of a well; (iv) Confined and Unconfined aquifers. [pairs (ii) §8, (iii) §6, (iv) §3] [IFOS 2018 | P1/5(b) | 8M]
- Define confined and unconfined aquifer, recharge well, perched water table, drainable porosity and groundwater exploration. [OPSC ·CSE (Main) 2016 -17 | P1/5(b) | 20M]

5 GROUNDWATER MOVEMENT & STEADY FLOW TO WELLS

When a well is pumped, the water table (or piezometric surface) is drawn down into an inverted ***cone of depression***. Steady-state (equilibrium) well hydraulics relates the pumping rate to this cone and yields the aquifer parameters.

BASIC TERMS

Drawdown (s) : the lowering of the water level at any point due to pumping. **Cone of depression —** the 3-D drawdown surface around the well. **Radius of influence (R) —** the radial distance at which drawdown becomes negligible. **Specific capacity —** well discharge per unit drawdown, Q/sw.

DUPUIT-FORCHHEIMER ASSUMPTIONS

The classical steady formulae assume: flow is steady and radial to a fully-penetrating well; the aquifer is homogeneous, isotropic and of infinite areal extent; the well is pumped at constant Q; and (Dupuit) for unconfined flow the hydraulic gradient equals the slope of the water table and is small, with flow essentially horizontal.

Confined (Thiem): $Q = 2\pi Kb\,(s_1 - s_2) / \ln(r_2/r_1) = 2\pi Kb \cdot sw / \ln(R/rw)$

Q discharge (m^3/s); K conductivity (m/s); b aquifer thickness (m); s drawdown (m); r radial distance (m); R radius of influence; rw well radius. T = Kb.

Unconfined (Dupuit-Thiem): $Q = \pi K\,(h_2^2 - h_1^2) / \ln(r_2/r_1)$

$= \pi K\,(H^2 - hw^2) / \ln(R/rw)$

h = saturated depth (head) at radius r (m); H = initial saturated thickness; hw = depth of water in well.

Specific capacity: $Sc = Q / sw$ Darcy / flow-net velocity: $v = K \cdot i$, actual $v_a = K \cdot i / n_e$

Sc (m^2/day); i = hydraulic gradient; n_e = effective porosity. Flow-net discharge per unit width $q = K \cdot H \cdot (Nf/Nd)$.

FLOW NETS (OPSC 2016)

A flow net is a grid of orthogonal flow lines and equipotential lines. With Nf flow channels and Nd potential drops across a head H, seepage per unit width is $q = K \cdot H \cdot (Nf/Nd)$; the Darcy velocity is v = K·i and the true (seepage) velocity is v/n_e — the equation used to trace groundwater movement.

◆ **WORKED NUMERICAL — *Hydraulic properties of a confined aquifer (two observation wells)*** **[IFoS 2024 · P1/7(a) · 15M]**

Problem. *A well penetrating an aquifer which is underlain and overlain by impermeable layers was tested with a uniform discharge of 1000 litres/min. The steady-state drawdowns measured in two observation wells at 1.0 m and 10.0 m radial distances from the centre of the pumped well were 13.40 m and 4.20 m respectively. Determine the hydraulic properties of the aquifer if its saturated thickness is 10.0 m.*

Given. Confined aquifer; Q = 1000 L/min = 0.01667 m^3/s; r_1 = 1.0 m, s_1 = 13.40 m; r_2 = 10.0 m, s_2 = 4.20 m; b = 10.0 m.

Formula. $Q = 2\pi T(s_1 - s_2)/\ln(r_2/r_1)$

$\Rightarrow T = Q \cdot \ln(r_2/r_1) / [2\pi(s_1 - s_2)]$, $K = T/b$

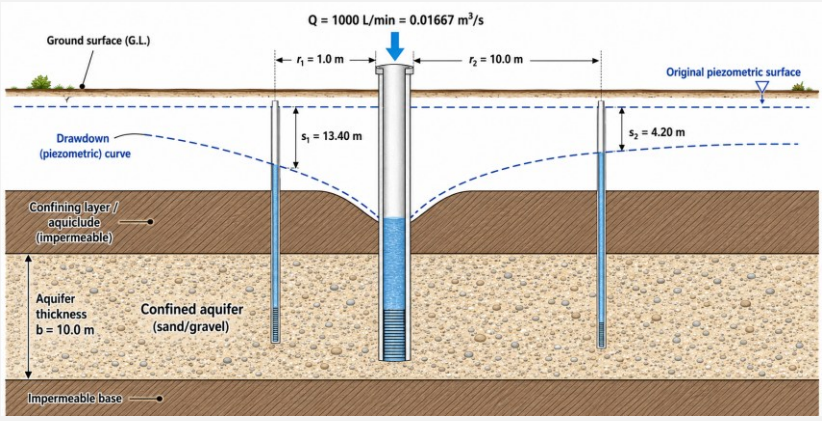
Substitution. $T = 0.01667 \times \ln(10) / [2\pi \times (13.40 - 4.20)]$

$= 0.01667 \times 2.3026 / (2\pi \times 9.20)$

$= 6.64 \times 10^{-4}$ m^2/s

$T = 6.64 \times 10^{-4} \times 86\,400 = 57.4$ m^2/day;

$K = T/b = 57.4/10 = 5.74$ m/day (6.64×10^{-5} m/s)



Result. Transmissivity T ≈ 57.4 m^2/day; hydraulic conductivity K ≈ 5.74 m/day. (Storativity S needs unsteady data.)

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◆ **WORKED NUMERICAL — *Hydraulic conductivity of an unconfined aquifer*** [IFoS 2017 · P1/7(b) · 10M]

Problem. *A 25 cm diameter well is pumped at a uniform rate of 50 l/s. The drawdowns observed at 1 m and 100 m from the centre of the well are 8 m and 4.0 m respectively. Determine the hydraulic conductivity of the water-bearing strata. Take the saturated thickness of the aquifer as 25 m.*

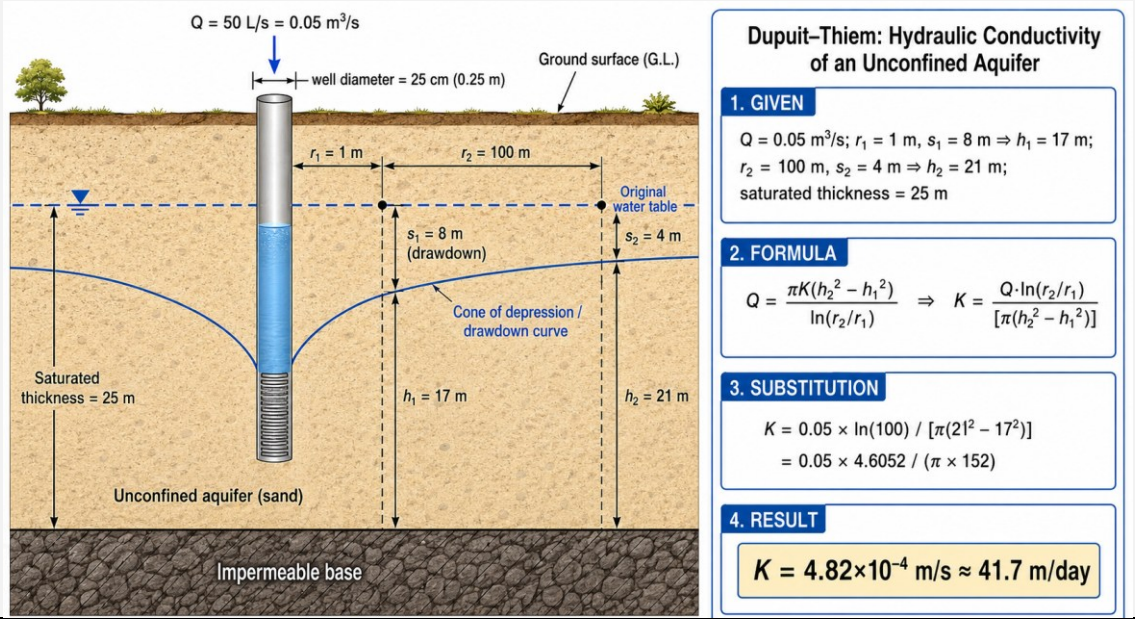
Given. Q = 50 L/s = 0.05 m^3/s; r_1 = 1 m, s_1 = 8 m ⇒ h_1 = 17 m; r_2 = 100 m, s_2 = 4 m ⇒ h_2 = 21 m.

Formula. $Q = \pi K(h_2^2 - h_1^2)/\ln(r_2/r_1)$

$$\Rightarrow K = Q \cdot \ln(r_2/r_1) \,/\, [\pi(h_2^2 - h_1^2)]$$

Substitution. $K = 0.05 \times \ln(100) / [\pi(21^2 - 17^2)] = 0.05 \times 4.6052 / (\pi \times 152) = 4.82\times10^{-4}$ m/s

Result. $K = 4.82\times10^{-4}$ m/s ≈ 41.7 m/day.



PREVIOUS YEAR QUESTIONS

- A well penetrating an aquifer, underlain and overlain by impermeable layers, was tested with a uniform discharge of 1,000 L/min. Steady-state drawdowns in two observation wells (1 m and 10 m from the pumped well) were 13.4 m and 4.2 m. Determine the hydraulic conductivity and transmissibility if the saturated thickness is 10 m. [OPSC ·CSE (Main) 2016 -17 | P1/6(a) | 30M]
- Calculate the discharge from a tube well of 30 cm diameter penetrating fully into a confined aquifer 30 m thick, permeability 40 m/day; drawdown 3 m, zero drawdown at 300 m. If the diameter is doubled, find the percentage increase in yield. [OPSC ·CSE (Main) 2018 -19 | P1/6(c) | 20M]
- A 10 cm diameter well penetrates a 10 m thick confined aquifer. Steady drawdowns were 2.5 and 0.05 m at 10 m and 40 m from the centre, at a constant discharge of 125 L/min for 12 hours. Using the Dupuit-Thiem equation, calculate the transmissibility and hydraulic conductivity. [OPSC ·CSE (Main) 2019 -20 | P1/5(b) | 20M]
- Explain how flow nets can be used to determine groundwater flow. Also derive the equation for estimation of groundwater flow velocity. [OPSC ·CSE (Main) 2016 -17 | P1/7(b) | 15M]
- A 10 m diameter well penetrates 8 m thick water-bearing strata; constant discharge 100 L/min for 12 hours; steady drawdowns 3 and 0.05 m at 10 m and 50 m from the centre. Using the Dupuit-Thiem equation, calculate the transmissibility and hydraulic conductivity. [OPSC ·CSE (Main) 2015 -16 | P1/6(b) | 20M]

★ **MODEL Q** For every two-observation-well problem: confined ⇒ $Q = 2\pi T(s_1 - s_2)/\ln(r_2/r_1)$; unconfined ⇒ $Q = \pi K(h_2^2 - h_1^2)/\ln(r_2/r_1)$. Solve for T or K, then K = T/b. Watch the litre-to-m³ and per-minute-to-per-second conversions.

Cone Of Depression & Steady Radial Flow

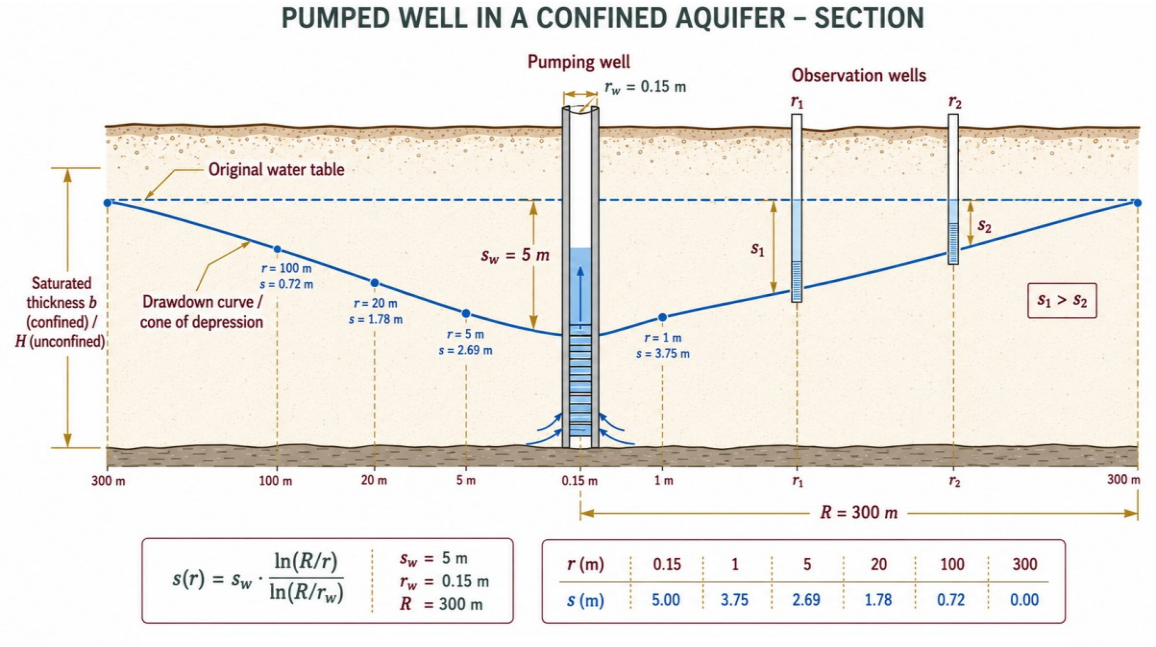


Fig. 5.4 Cone of depression around a pumped well and the drawdowns at two observation

6 UNSTEADY FLOW & PUMPING / RECUPERATION TESTS

Before steady state is reached the flow is ***unsteady (transient)***, and drawdown grows with time. The Theis solution and its Cooper-Jacob simplification describe this and let a pumping test yield both T and the storativity.

Theis: $s = (Q / 4\pi T) \cdot W(u)$, $u = r^2 S / (4Tt)$

s drawdown (m); Q discharge (m³/s); T transmissivity (m²/s); S storativity (–); r distance (m); t time since pumping began (s); W(u) = well function (exponential integral).

Cooper-Jacob ($u < 0.01$): $s = (2.303\ Q / 4\pi T) \cdot \log_{10}(2.25\ T\ t / r^2 S)$

A straight line of s vs log t; slope gives T, intercept gives S. Valid at small u (large t / small r).

PUMPING TEST — STEP-BY-STEP PROCEDURE (IFOS 2017)

1. Construct a fully-penetrating pumping well and two or more observation wells at known radial distances.
2. Record the static water level in every well before pumping.
3. Pump at a constant, accurately-measured discharge Q (measured by orifice/weir/flow-meter).
4. Record drawdown against time in the observation wells — to steady state for the equilibrium (Thiem) test, or at close intervals for the non-equilibrium (Theis) test.
5. On stopping the pump, record the recovery (residual drawdown) with time — the recovery test.
6. Reduce the data: steady ⇒ Thiem for T, K; unsteady ⇒ Theis type-curve or Cooper-Jacob straight-line for T and S.

RECUPERATION (RECOVERY) TEST — FOR OPEN / DUG WELLS

Where an aquifer is too poor for a normal pumping test (dug wells), the well is pumped to a depression and its ***recovery*** of level is timed. The constant of the well and the safe yield follow:

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$C = (2.303 / t) \cdot \log_{10} (h_1 / h_2)$ Safe yield $Q = C \cdot A \cdot Hs$

C = constant of recuperation (h^{-1}); h_1, h_2 = depression heads at start and after time t; A = area of well (m^2); Hs = permissible working depression head (m).

Basis	Pumping test	Recuperation test
Suited to	tube wells; confined & unconfined aquifers	open (dug) wells in poor aquifers
What is measured	drawdown vs discharge (and time)	recovery of level after pumping stops
Gives	T, K and S (aquifer parameters)	constant of the well & safe yield
Wells needed	pumping well + observation wells	the single dug well itself

◆ **WORKED NUMERICAL — *Transmissibility & drawdown in the pumped well*** [OPSC-CSE (Main) 2020-21 · Paper-I Q.5(a)(ii) · 12M]

Problem. *A 30 cm well fully penetrates a confined aquifer 30 m deep. After a long period of pumping at 1200 lit/min, the drawdowns in wells at 20 and 45 m from the pumping well are 2.2 and 1.8 m respectively. Determine the transmissibility of the aquifer. What is the drawdown in the pumped well?*

Given. Confined, b = 30 m, rw = 0.15 m; Q = 1200 L/min = 0.02 m^3/s; r_1 = 20 m, s_1 = 2.2 m; r_2 = 45 m, s_2 = 1.8 m.

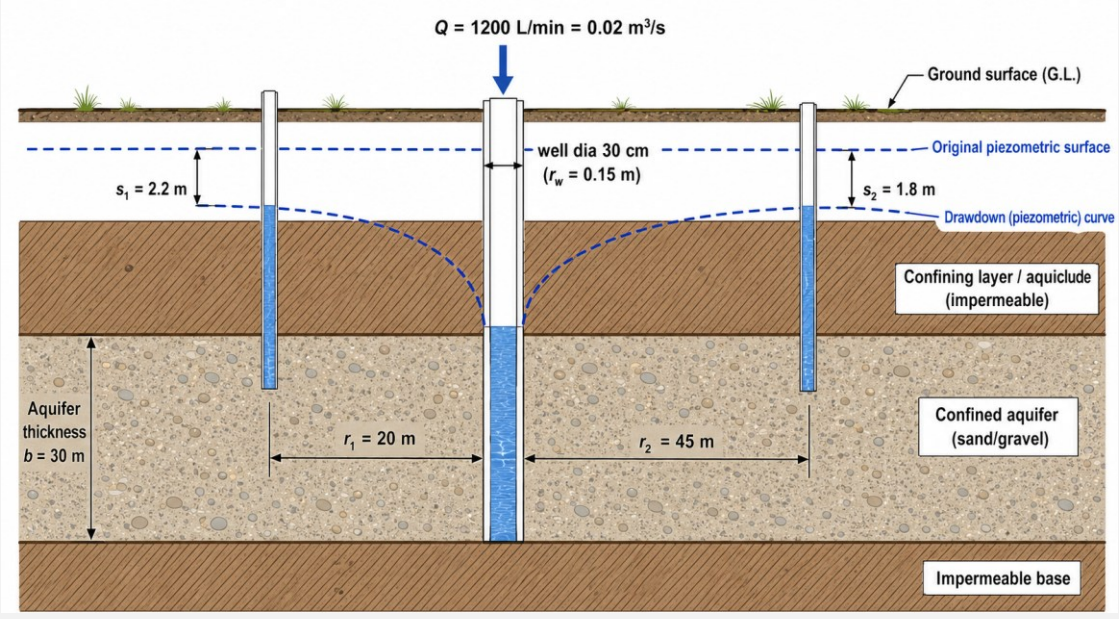
Formula. $T = Q \cdot \ln(r_2/r_1)/[2\pi(s_1 - s_2)]$;

$$sw = s_1 + [Q/(2\pi T)] \cdot \ln(r_1/rw)$$

Substitution. T = 0.02 × ln(45/20) / (2π × 0.4) = 0.02 × 0.8109 / 2.513 = 6.45×10^{-3} m^2/s = 557 m^2/day

sw = 2.2 + [0.02/(2π×6.45×10^{-3})]·ln(20/0.15) = 2.2 + 0.493 × 4.893 = 4.61 m

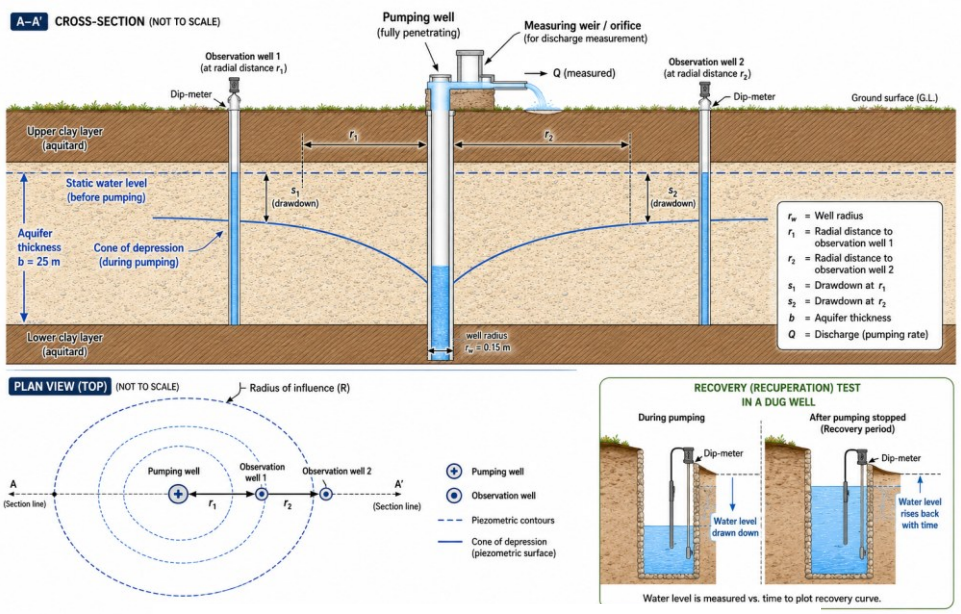
Result. Transmissibility T ≈ 557 m^2/day (6.45×10^{-3} m^2/s); drawdown in the pumped well ≈ 4.61 m.



PREVIOUS YEAR QUESTIONS

- Discuss the Pumping Test of wells. Explain the step-by-step procedure adopted for conducting pumping tests of wells. [IFOS 2017 | P1/7(c) | 10M]
- Differentiate between Pumping test and Recuperation test of a well. [IFOS 2018 | P1/5(b)(iii) | 8M]

Pumping-Test Layout



Pumping-test layout with observation wells; inset: recuperation

7 GROUNDWATER INVESTIGATION & RECHARGE ESTIMATION

Before a well is sunk, the aquifer must be located and appraised. Methods are ***surface*** (indirect) or ***subsurface*** (direct).

SURFACE (INDIRECT) METHODS

Geologic & hydrogeologic : study of landforms, outcrops, springs and existing well data. **Remote sensing / GIS** — satellite imagery for lineaments and recharge zones. **Geophysical** — electrical-resistivity (most used), seismic-refraction, gravity and magnetic surveys.

ELECTRICAL-RESISTIVITY METHOD

Current is passed through outer electrodes and the potential drop read across inner electrodes; the ***apparent resistivity*** distinguishes saturated (low resistivity) from dry or clayey ground. In the Wenner array the four electrodes are equally spaced 'a':

Wenner: $\rho a = 2\pi\, a\, (\Delta V / I)$

ρa apparent resistivity (Ω·m); a electrode spacing (m); ΔV potential difference (V); I current (A). Increasing 'a' probes greater depth (vertical electrical sounding).

SUBSURFACE (DIRECT) METHODS

Test drilling with lithologic logging, and geophysical well logging — electrical (SP & resistivity), gamma-ray, and caliper logs — to identify and test aquifer horizons directly.

GROUNDWATER RECHARGE & DISCHARGE COMPONENTS OF A BASIN (APPSC 2018)

Recharge (inflow)	Discharge (outflow)
rainfall infiltration	well pumping / abstraction
influent seepage from rivers, canals, tanks	baseflow (effluent seepage to streams)
return flow from irrigation	evapotranspiration from shallow water table
inflow from adjacent aquifers; artificial recharge	spring flow; subsurface outflow

GW balance: $\text{Recharge} - \text{Discharge} = \Delta\text{Storage} = Sy \cdot A \cdot \Delta h$ Water-table-fluctuation recharge: $R = Sy \cdot A \cdot \Delta h$

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Sy specific yield; A area (m²); Δh water-table rise/fall (m). Other estimation methods: GW balance, chloride mass-balance, tracer/injection, and rainfall-infiltration-factor (GEC) norms.

PREVIOUS YEAR QUESTIONS

- Explain about groundwater investigation methods. [OPSC ·CSE (Main) 2022 -23 | P1/14(b) | 12M]
- Explain the surface method of groundwater exploration with a suitable sketch. [OPSC ·CSE (Main) 2020 -21 | P1/6(a)(i) | 8M]
- Explain the groundwater recharge estimation methods. [OPSC ·CSE (Main) 2021 -22 | P1/7(e) | 12M]
- Discuss groundwater recharge and discharge components for a basin. [AP ·PSE (Main) 2018 | 7(b) | 6M]

Electrical-Resistivity Survey (Wenner Array)

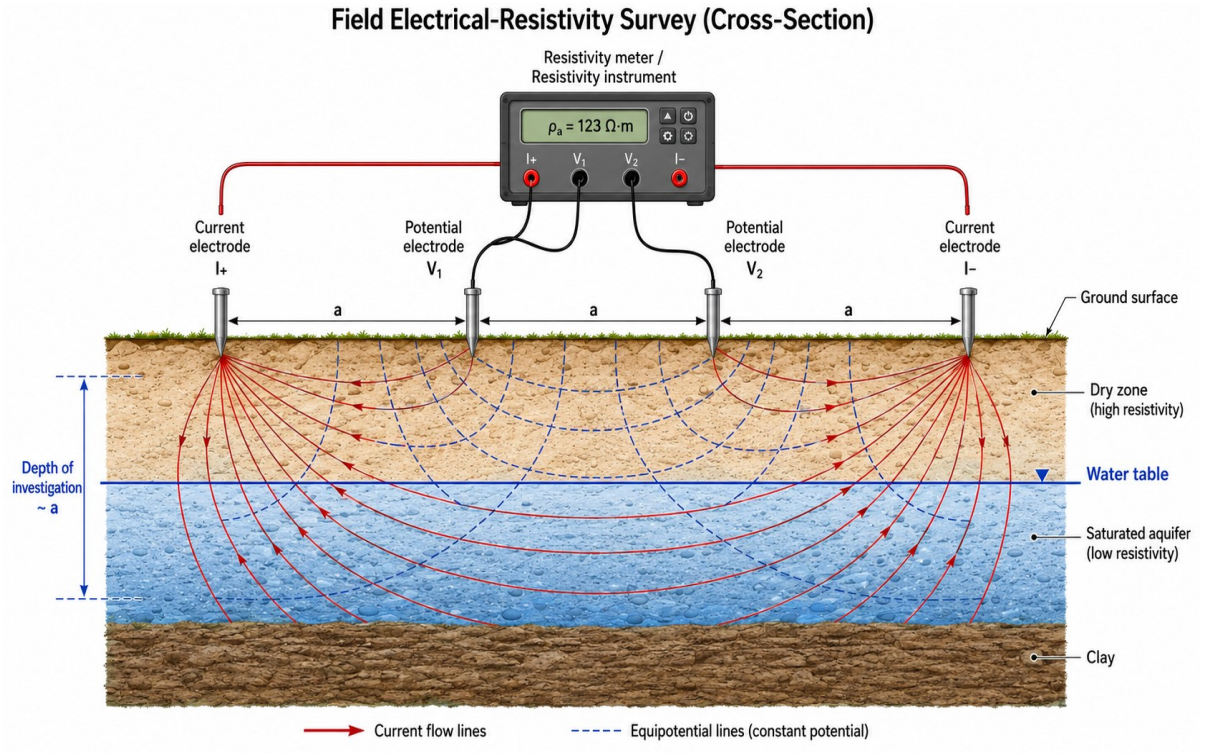


Fig. 5.6 Wenner electrode array for vertical electrical sounding of an aquifer.

8 WELLS: TYPES & CONSTRUCTION

A well is the structure that taps the aquifer. Broadly there are ***open (dug) wells*** and ***tube wells***, with several special forms; the construction method is chosen to suit the formation.

OPEN (DUG) WELLS

Large-diameter (2-9 m) shallow wells that store water in the well itself; suited to low-yield, shallow, unconfined aquifers. Two types — ***unlined (kutcha)*** and ***lined/steined (pucca)***. A special dug well in fine strata taps water through a bottom cavity.

TUBE WELLS AND SPECIAL WELLS

Tube well : a bored/drilled well with a pipe casing and a screen against the aquifer; shallow (strainer) or deep, small diameter, high yield. **Cavity tube well —** draws from a cavity formed below a stiff clay roof in a confined aquifer, without a screen.

Dug-cum-bore well : a dug well deepened by a bore hole at its bottom to reach a deeper aquifer — combines storage of a dug well with the yield of a bore. **Driven well —** a well-point/pipe driven into shallow soft strata (no drilling). **Filter point —** a small driven tube well with a perforated, screened point for shallow sandy aquifers. **Collector (Ranney) well —** a large caisson with horizontal radial laterals for high yield near rivers.

CONSTRUCTION / DRILLING METHODS AND THEIR SUITABILITY

Method	How it works	Best suited to
Hand boring / auger	auger cuts and lifts soil	shallow soft soils, small tube wells
Driving	well-point driven in	shallow loose sand
Jetting (hydraulic)	high-pressure water jet cuts	soft sand & silt, shallow
Percussion (cable-tool)	heavy bit pounds & crushes	consolidated rock, boulders, all formations
Hydraulic rotary	rotating bit + drilling mud	deep tube wells in unconsolidated strata
Reverse-circulation rotary	large-diameter, mud up the pipe	large deep wells in soft formations

OPEN WELLS VS TUBE WELLS (FREQUENTLY ASKED)

Basis	Open (dug) well	Tube well
Diameter / depth	large dia (2-9 m), shallow	small dia, shallow to deep
Taps	shallow unconfined aquifer	deep/confined or shallow aquifers
Yield	low; stores water in the well	high; draws directly from aquifer
Water enters	bottom & sides	through the screen
Life & cost	long life, low tech	costlier, needs pump & power

PREVIOUS YEAR QUESTIONS

- Write short notes (with sketches where required): (i) Cavity tube wells (ii) Dug-cum-bore wells (iii) Driven wells (iv) Filter points. [IFOS 2019 | P1/ 5(b) | 8 M]
- Describe in detail the various methods used for tube-well drilling. Discuss the suitability of each method with respect to soil and site conditions. [UK·PSC ACF/RFO (Mains) 2025| Q.2(ii) | 15M]
- Differentiate between Open wells and Tubewells. [IFOS 2018 | P1/ 5(b)(ii) | 8 M]

Types Of Wells

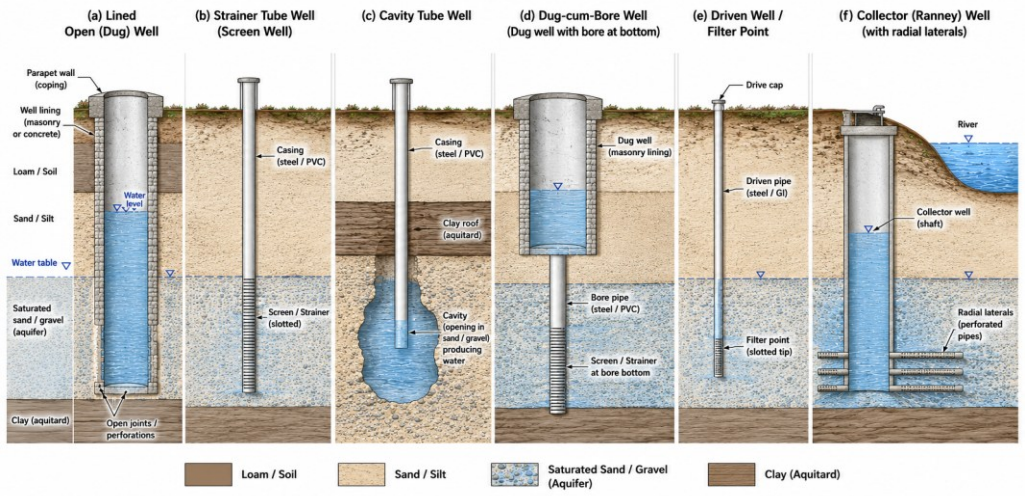


Fig. 5.7 Principal well types used in Indian irrigation

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9 WELL SCREENS, DEVELOPMENT & TUBE-WELL DESIGN

The screen admits water while keeping sand out, development makes the well efficient, and design ties discharge, diameter, depth and screen together.

WELL SCREEN — FUNCTION, REQUIREMENTS & TYPES

The screen (strainer) is the intake section against the aquifer. Its ***basic requirements*** (IFoS 2020) are: a high percentage of ***open area*** with adequate strength; a slot size that retains the aquifer/gravel yet passes water freely; a low entrance (approach) velocity (≤ 3 cm/s) to minimise head loss, incrustation and corrosion; resistance to corrosion and incrustation; a non-clogging slot shape that is easy to develop; and sufficient collapse and column strength.

Types : slotted pipe, bridge-slot, louvre/shutter, wire-wound continuous-slot (Johnson), and agricultural strainers (Cook, Tej, coir/bamboo). Continuous-slot gives the greatest open area and the best development.

GRAVEL PACK

A graded gravel envelope placed around the screen in fine, uniform aquifers to stabilise the formation and allow a larger slot. Design: pack-to-aquifer grain-size ratio $D50(pack)/D50(aquifer) \approx 4\text{–}6$, uniform gravel, thickness 15-20 cm, with the slot sized to retain ~90% of the pack.

WELL DEVELOPMENT — OBJECTIVES & METHODS

Objectives : remove fines and drilling mud from around the screen, increase permeability and yield, reduce well loss, and stabilise the formation to prevent sand pumping.

Methods : over-pumping; back-washing / surging with a surge block; ***compressed-air*** surging and air-lift pumping; high-velocity jetting; and chemical treatment (acidization, polyphosphate dispersants).

Compressed-air method : compressed air is injected to surge water in and out of the screen, loosening fines, and is then used to air-lift-pump the well to bring the loosened sand and mud to the surface; repeated until the water runs clear.

TUBE-WELL DESIGN PARAMETERS (IFOS 2023)

1. **Design discharge** from the command area and crop water requirement.
2. **Aquifer data:** depth, thickness and a sieve analysis of formation samples.
3. **Well diameter:** fixed by the pump bowl to be housed, not by yield (yield rises only marginally with diameter).
4. **Depth & screen length/position:** screen set against the most permeable strata.
5. **Slot size & open area:** from grain-size; entrance velocity ≤ 3 cm/s.
6. **Gravel pack:** grain-size ratio and 15-20 cm thickness.
7. **Development & sanitary seal.**

◆ **WORKED NUMERICAL — *Command area of a tube well*** [OPSC·Forest (Main) 2015-16 · Paper-I Q.8(a) · 10M]

Problem. *A tube well having a capacity of 4000 lp/Min operates 20 hours each day during the irrigation season. How much area can it command if the irrigation interval is 20 days and the depth of irrigation is 7 cm?*

Given. Q = 4000 L/min; operation = 20 h/day; interval = 20 days; depth d = 7 cm = 0.07 m.

Formula. Volume per interval = Q × (min/day) × days;

$$\text{Area} = \text{Volume} / d$$

Substitution. $V = 4000 \times (20\times60) \times 20 = 9.6\times10^{7}$ L $= 9.6\times10^{4}$ m³

$$A = 9.6\times10^{4} / 0.07 = 1.371\times10^{6} \text{ m}^2$$

Result. Command area ≈ 1.37×10^{6} m² = 137 ha.

PREVIOUS YEAR QUESTIONS

- What are the parameters to be considered in designing of tube wells? Explain. [IFOS 2023 | P1/ 7(b) | 10 M]
- Discuss the basic requirements for any well screen. [IFOS 2020 | P1/ 7(c) | 10 M]
- Write a detailed note on the various types of well screen. [OPSC·CSE (Main) 2015-16 | P1/ 7(a)(i) | 10 M]
- Discuss the various methods used for well development. [UK·PSC ACF/RFO (Mains) 2025 | Q.1(iv) | 10 M]
- What is well development? List various methods of well development and briefly describe the compressed-air method of well development. [UK·PSC RFO (Mains) 2021 | Q.3(ii) | 10 M]
- Briefly explain the steps in designing a tube well. [OPSC·CSE (Main) 2023-24 | P1/ 13(b)| 20 M]
- What are the steps involved in the design of a tube well? [AP·PSC RFO (Mains) 2012 | Q.1(F) | 4 M]

Well Screen & Gravel Pack

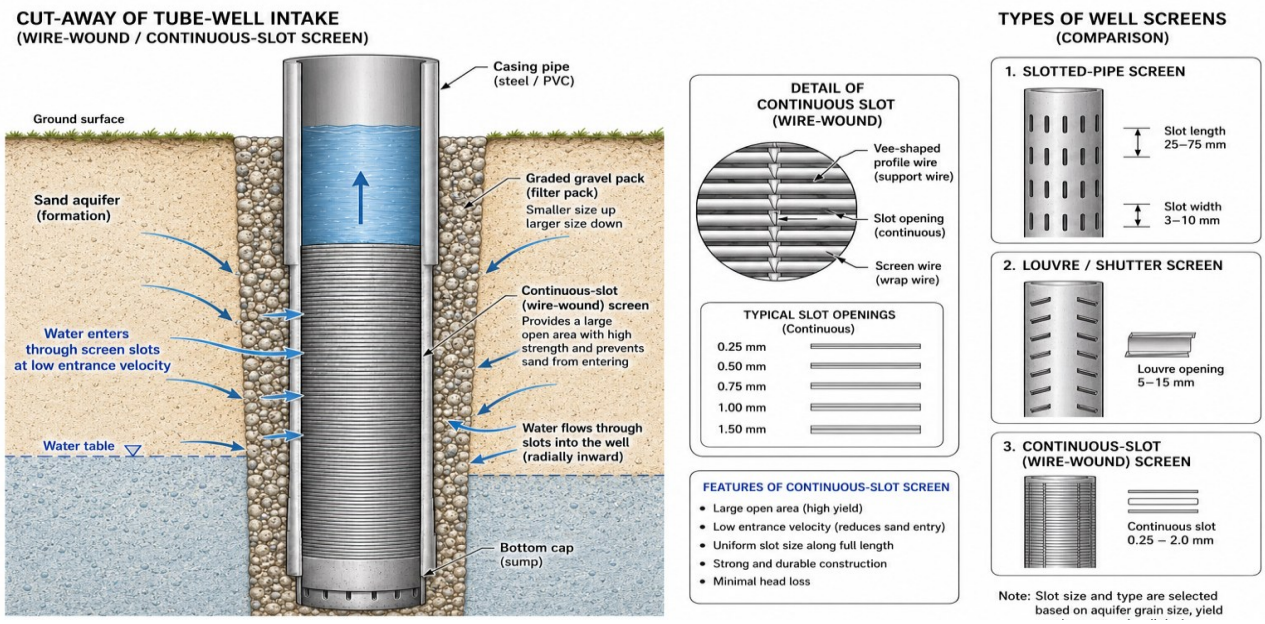


Fig. 5.8 Continuous-slot screen with gravel pack; inset: common screen types.

10 GROUNDWATER MANAGEMENT, RECHARGE & QUALITY

Sustained over-draft lowers water tables and degrades quality, so groundwater must be managed as a renewable but finite resource — balancing draft against recharge and protecting quality.

OVER-EXPLOITATION & CGWB CATEGORISATION

The ***stage of groundwater development*** = (annual GW draft / annual net GW availability) × 100. Units are graded — ***Safe* (< 70%)**, Semi-critical (70-90%), Critical (90-100%) and ***Over-exploited* (> 100%)** — also weighing long-term water-level trends. Safe yield is the draft that can be sustained without unacceptable depletion or quality loss.

ARTIFICIAL RECHARGE & BASIN-WIDE DEVELOPMENT

Artificial recharge deliberately augments the aquifer: spreading basins and flooding, check dams and percolation tanks, recharge wells/shafts and pits, rooftop rainwater recharge, and subsurface dykes. It differs from natural recharge only in being ***engineered and controlled***. Basin-wide development combines recharge, demand management (micro-irrigation, crop shift), conjunctive use, metering and participatory regulation.

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COASTAL AQUIFERS — SEAWATER INTRUSION

Over-pumping near the coast lets denser seawater displace fresh groundwater. The fresh-salt interface follows the ***Ghyben-Herzberg*** relation; intrusion is checked by cutting coastal draft, recharge barriers, injection wells and subsurface dykes, and saline horizons are sealed off with casing and cement grouting.

Ghyben-Herzberg: $hs = \rho f / (\rho s - \rho f) \cdot hf \approx 40\ hf$

hs = depth of fresh-salt interface below sea level (m); hf = water-table height above sea level (m); ρf, ρs = fresh & salt water densities. Irrigation-quality indices: EC, TDS, SAR, RSC, %Na.

GROUNDWATER QUALITY & POLLUTION (APPSC 2018)

Irrigation suitability is judged by salinity (EC, TDS), sodium hazard (SAR, %Na) and RSC. ***Aquifer pollution is far harder to correct than surface-water pollution*** because groundwater moves very slowly (so pollutants disperse little and flush out over decades), the aquifer is inaccessible for treatment, and contaminants adsorb onto the matrix. The main agricultural pollutants are ***nitrates from fertilizers***, pesticides, and salts from return flow.

PREVIOUS YEAR QUESTIONS

- What is artificial recharge? How does it differ from groundwater recharge? Explain with practical examples.

  [OPSC·CSE (Main) 2016-17 | P1/ 5(b) | 15 M]
- How do you seal brackish and saline aquifer horizons? When does sea-water intrusion take place in coastal areas? Explain with example.

  [OPSC·CSE (Main) 2016-17 | P1/ 5(c) | 15 M]
- Explain, in brief, the measures for basin-wide groundwater development.

  [OPSC·CSE (Main) 2016-17 | P1/ 5(d) | 15 M]
- Why is aquifer pollution much more difficult to correct than surface-water pollution? What are the primary pollutants from agriculture that have contributed to aquifer pollution?

  [AP·PSC RFO (Mains) 2018 | Q.7(c)(d) | 3 M + 3M]

11 PUMPS: CLASSIFICATION & CENTRIFUGAL PUMPS

A pump adds energy to lift groundwater to the surface. Pumps are ***positive-displacement*** (reciprocating, rotary) or ***rotodynamic*** (centrifugal, mixed-flow, axial/propeller), with special forms — jet, air-lift, submersible and deep-well turbine.

Class	Examples	Suited to
Rotodynamic — centrifugal	volute, turbine (diffuser), submersible	open wells, tube wells; medium head, large Q
Rotodynamic — axial	propeller, mixed-flow	very large Q, low head
Positive displacement	reciprocating, rotary	small Q, high head; low yield wells
Special	jet, air-lift, deep-well turbine	deep/small bores, sandy or gassy water

Centrifugal Pump : a rotodynamic pump in which a rotating ***impeller*** imparts kinetic energy to the water, which the volute/diffuser casing converts to pressure head; the commonest irrigation pump.

WORKING PRINCIPLE, PARTS & PRIMING

The primed casing is filled with water; the impeller spins, throwing water outward by centrifugal action and creating a low pressure at the eye that draws more water up the suction pipe; the volute converts velocity to pressure at the delivery. Main parts — ***impeller*** (adds energy), ***casing/volute*** (converts velocity to pressure), suction pipe with ***foot valve & strainer***, delivery pipe with a delivery valve, and the drive shaft.

> ***Priming*** — filling the pump casing and suction pipe with water to expel air before starting, because a centrifugal pump handling ***air*** (low density) develops too little pressure to lift water.

Why frequent priming is needed (OPSC 2019) — an air leak in the suction line, a worn/defective foot valve that lets water drain back between runs, a high suction lift, or worn wearing rings — each lets the casing lose its prime.

TYPES OF CENTRIFUGAL PUMPS (BY CRITERIA)

Criterion	Types
Casing	volute; diffuser (turbine)
Impeller	open, semi-open, closed; radial, mixed-flow, axial
No. of stages	single-stage; multistage (high head)
Suction / entry	single-suction; double-suction
Shaft position	horizontal; vertical (incl. submersible, deep-well turbine)

REASONS A CENTRIFUGAL PUMP MAY FAIL TO OPERATE (IFOS 2016)

Not primed or air-bound; suction lift too high (cavitation); clogged/leaking foot valve or strainer; wrong direction of rotation; speed too low; worn or clogged impeller; required head above the pump's capacity; leaking or blocked pipes; insufficient submergence.

RECIPROCATING PUMP — SINGLE VS DOUBLE ACTING

Basis	Single-acting	Double-acting
Water delivered	one side of piston; 1 stroke/rev	both sides; 2 strokes/rev
Theoretical Q	Q = A·L·N/60	Q ≈ 2·A·L·N/60
Delivery	once per rev (pulsating)	twice per rev (steadier)
Valve pairs	one	two

◆ **WORKED NUMERICAL — *Slip, coefficient of discharge & power of a reciprocating pump*** **[OPSC-CSE (Main) 2018-19 · Paper-I Q.1(b)(ii) · 12M]**

Problem. *A single-acting reciprocating pump lifts water at 2.5 m³ per minute to a tank 20 m above the sump. The pump has a bore of 30 cm and a stroke of 40 cm. Find the slip, coefficient of discharge and horsepower required if the suction pipe diameter is 10 cm and the pump runs at 80 rpm. Assume an overall efficiency of 80%.*

Given. Single-acting; Qact = 2.5 m³/min; H = 20 m; bore D = 0.30 m; stroke L = 0.40 m; N = 80 rpm; η_o = 0.80.

Formula. $Qth = A \cdot L \cdot N$ (per min),

$$A = \pi D^2/4;$$

$$slip = Qth - Qact;$$

$$Cd = Qact/Qth;$$

$$P = \rho g Q_{act} H/\eta_o$$

Substitution. A = π/4 × 0.30² = 0.0707 m²;

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Q^{th} = 0.0707 × 0.40 × 80 = 2.262 m^3/min

slip = 2.262 − 2.5 = −0.238 m^3/min (−10.5%); Cd = 2.5/2.262 = 1.105

P = 1000 × 9.81 × (2.5/60) × 20 = 8175 W = 8.18 kW; input = 8.18/0.80 = 10.2 kW = 13.9 hp

Result. Slip = −0.238 m^3/min (negative slip, −10.5%); Cd = 1.105; power ≈ 10.2 kW (13.9 hp).

Note. Negative slip (Qact > Qth) is real for a long suction pipe at high speed (delivery valve opens before stroke-end); the 10 cm suction-pipe size is not needed for slip/Cd/power.

Centrifugal Pump & Submersible Pump

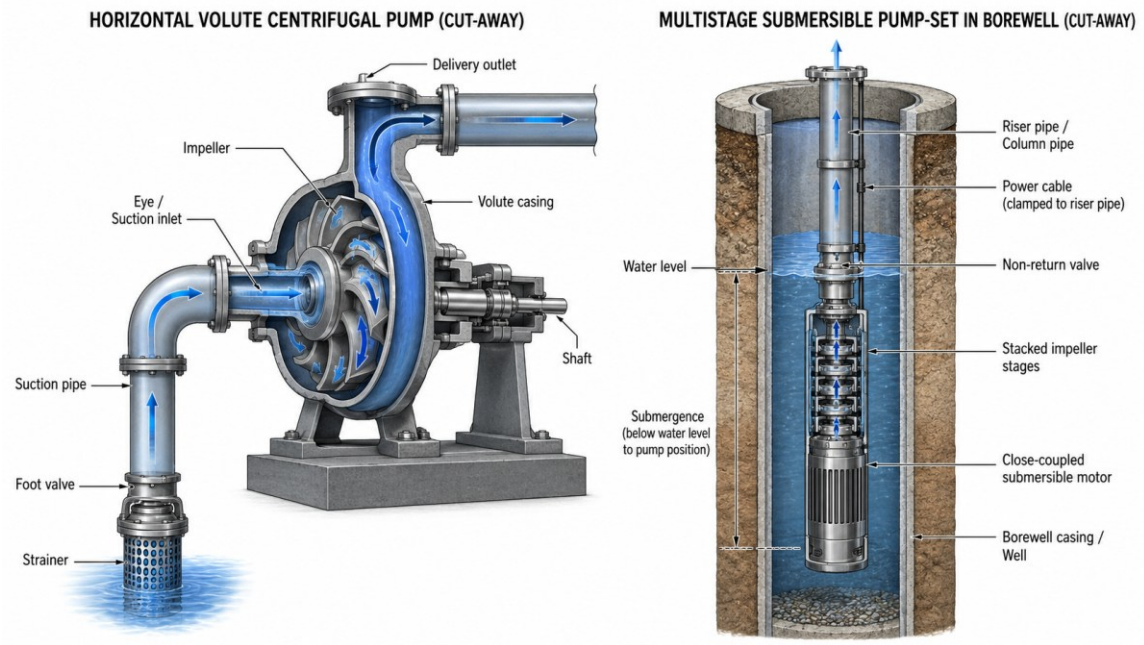


Fig. 5.9 Volute centrifugal pump (left) and a borewell submersible pump-set (right).

PREVIOUS YEAR QUESTIONS

- Write in brief about different types of centrifugal pumps based on various criteria.
  [IFOS 2019 | P1/ 6(b) | 10M]
- Define a centrifugal pump. Discuss the probable reasons when the centrifugal pump may fail to operate. [IFOS 2016 | P1/ 5(c) | 10M]
- With the help of a neat diagram, explain the working of a centrifugal pump
  [AP·PSC RFO (Mains) 2012 | Q.3(a) | 8M]
- Explain the working principle of different types of centrifugal pump set for irrigation purpose and discuss the functions of its various parts. [UK·PSC RFO (Mains) 2012 | Q.2(iv)| 10M]
- What is priming? Give reasons for the requirement of frequent priming in a centrifugal pump.
  [OPSC·CSE (Main) 2019-20 | P1/ 5(c) | 0 M]

12 PUMP PERFORMANCE, CAVITATION, SELECTION & POWER

Selecting and running a pump well means matching its head-discharge behaviour to the system, guarding against cavitation, and sizing the prime mover and energy cost correctly.

HEADS & TOTAL DYNAMIC HEAD

$$H = (hs + hd) + hf + v^2/2g \text{ (static lift + friction + velocity head)}$$

hs static suction lift; hd static delivery head; hf pipe/fitting friction; $v^2/2g$ velocity head. Manometric head Hm ≈ H; total dynamic head TDH = H.

CHARACTERISTIC CURVES & OPERATING POINT

At constant speed a pump's **H-Q** (head falls as discharge rises), efficiency-Q (peak at the design point) and power-Q curves are plotted; the intersection of the H-Q curve with the rising ***system-head curve*** is the operating point. A pump is selected so this point sits at peak efficiency for the required head and discharge.

EFFECT OF SPEED & IMPELLER DIAMETER — THE AFFINITY LAWS (IFOS 2024, 2021)

$$Q \propto N \propto D \qquad H \propto N^2 \propto D^2 \qquad P \propto N^3 \propto D^3$$

N = speed (rpm); D = impeller diameter. For a given pump, discharge varies directly, head as the square, and power as the cube of speed (or diameter).

So raising speed or trimming/enlarging the impeller shifts the whole H-Q curve; discharge changes in proportion, head as the square and — critically — ***power as the cube***, so a small speed rise sharply increases the power demand. Example: raising speed 1450 → 1750 rpm multiplies Q by 1.21, H by 1.46 and P by 1.76.

CAVITATION & NPSH (IFOS 2023, 2017)

Cavitation — the formation and violent collapse of ***vapour bubbles*** where the local pressure at the impeller eye falls below the water's vapour pressure; the collapse pits the metal and causes noise, vibration and a drop in head, discharge and efficiency.

Prevention : keep the available NPSH above the required NPSH by limiting suction lift and placing the pump close to the water; avoid excessive speed; use a larger, shorter suction pipe (less friction/velocity); avoid throttling the suction; and use cavitation-resistant materials.

$$NPSHa = (p_atm - p_v)/\gamma - hs - hfs \geq NPSHr \qquad Ns = N\sqrt{Q} / H^{(3/4)}$$

NPSHa available, NPSHr required net positive suction head (m); p_v vapour pressure; hs suction lift; hfs suction friction; Ns specific speed.

SUBMERSIBLE PUMP INSTALLATION (IFOS 2017)

Check the borewell (straightness, depth, water level) and select the pump for the head and discharge; assemble the multistage pump with its close-coupled submersible motor and a non-return valve; splice and waterproof the motor cable; lower the set on the riser (column) pipe, clamping at each joint with the cable strapped alongside; keep it fully submerged above the well bottom to avoid sand; connect the surface plate, delivery and a protected control panel (star-delta/DOL, overload); then test insulation, direction, current and yield, and record static and pumping levels.

POWER & ENERGY COST

$$WP = \rho gQH \qquad BP\ (shaft) = WP/\eta p \qquad Electrical\ input = WP/(\eta p \cdot \eta d) \qquad Energy = input(kW) \times hours$$

WP water power (W); ηp pump eff.; ηd drive/motor eff. Metric: WHP = γQH/75 (γ = 1000 kgf/m³, Q in m³/s). 1 unit = 1 kWh.

◆ **WORKED NUMERICAL — *Water hp, prime mover & monthly energy cost*** **[IFoS 2019 · P1/8(d) · 10M]**

Problem. *A pump lifts 95000 litres of water per hour against a total head of 20 m. Compute the water hp. If the pump efficiency is 75%, what size of prime mover is required? If a direct-drive electric motor of 85% efficiency is used, compute the cost of electrical energy in a month of 30 days, the pump running 12 hours per day. Cost of electrical energy is ₹5 per unit.*

Given. Q = 95000 L/h = 0.02639 m³/s; H = 20 m; ηp = 0.75; ηm = 0.85; 12 h/day × 30 d; ₹5/unit.

Formula. $WP = \rho gQH;\ WHP = WP/735.5;\ shaft = WP/\eta p;\ input = WP/(\eta p \cdot \eta m);\ cost = input \times h \times rate$

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Substitution. WP = 1000×9.81×0.02639×20 = 5178 W = 5.178 kW;

WHP = 5.178/0.7355 = 7.04 hp

Prime mover = 5.178/0.75 = 6.90 kW = 9.39 hp → provide a 10 hp motor

Electrical input = 5.178/(0.75×0.85) = 8.12 kW; energy = 8.12×12×30 = 2924 units (kWh)

Result. Water power ≈ 7.04 hp; prime mover ≈ 9.4 hp (use 10 hp); monthly cost = 2924 × ₹5 ≈ ₹14,619.

◆ **WORKED NUMERICAL — *BHP of an engine-driven centrifugal pump (with friction allowance)*** [IFoS 2016 · P1/5(d) · 10M]

Problem. *An engine-driven centrifugal pump in an open well delivers 16000 litres of water per hour. The static water level is 15 m and the pumping water level is 18 m from ground level. Friction losses in pipe and accessories may be assumed 15% of the total static head. If the pump efficiency is 55% and drive efficiency is 70%, calculate the BHP of the engine required to drive the pump.*

Given. Q = 16000 L/h = 0.004444 m³/s; pumping lift = 18 m; friction = 15% of static head; ηp = 0.55; ηd = 0.70.

Formula. $H = \text{static} + \text{friction};\ WP = \rho gQH;\ BHP = WP/(\eta p \cdot \eta d)$

Substitution. H = 18 + 0.15×18 = 20.7 m; WP = 1000×9.81×0.004444×20.7 = 902.5 W = 0.9025 kW

BHP = 0.9025/(0.55×0.70) = 0.9025/0.385 = 2.344 kW = 3.19 hp

Result. BHP of the engine ≈ 3.19 hp (≈ 2.34 kW). (Total static head taken as the 18 m pumping lift.)

PREVIOUS YEAR QUESTIONS

- Discuss the effect of pump speed and impeller diameter on the performance of a centrifugal pump. [IFOS 2024 | P1/ 6(b) | 10M]
- Discuss the effect of speed and impeller diameter on pump performance. [IFOS 2021 | P1/ 6(c) | 10M]
- What is cavitation? How does it affect the performance of a pumping system? [IFOS 2023 | P1/ 6(b) | 10M]
- What is cavitation? How does it affect the performance of a pumping system? How is it prevented in a centrifugal pump? [IFOS 2017 | P1/ 5(d) | 8M]
- What are submersible pumps? Explain the complete procedure to install a submersible pump in a borewell including initial preparations, installation and testing. [IFOS 2017 | P1/ 7(d) | 10M]
- A pump lifts 93600 lph against a total head of 21 m. Compute the water horsepower. If pump efficiency is 72%, what prime mover is required? For a directly-driven motor of 80% efficiency, compute the monthly (30-day) energy cost at 75 paise/unit, pump running 12 h/day. [OPSC·CSE (Main) 2022-23 | P1/ 9(b) | 10 M]
- A centrifugal pump discharges 10 l/s; suction water level 15 m and pumping level 18 m from ground; friction losses 15% of total suction head. If pump efficiency is 60% and drive efficiency 80%, calculate the BHP of the engine. [UK·PSC RFO (Mains) 2015 | Q.2(ii)| 10M]
- A centrifugal pump lifts 1500 litres per minute against a total head of 15 m. Compute the water horsepower. What prime mover is required if pump efficiency is 75%? For a direct-drive motor of 82% efficiency, compute the annual energy cost — pump operated 8 hours daily for 240 days at ₹3.10 per unit. [OPSC·CSE (Main) 2018-19 | P1/ 4(b)(ii) | 12 M]
- What is cavitation? How does it affect the performance of a pumping system? [OPSC·CSE (Main) 2023-24 | P1/ 10(a) | 15 M]

★ **MODEL Q** Power chain: WP = ρgQH → prime mover = WP/ηp → electrical input = WP/(ηp·ηmotor) → units = input(kW)×hours → cost = units×rate. Keep Q in m³/s and H in m; 1 unit = 1 kWh.

Characteristic Curves & The Operating Point

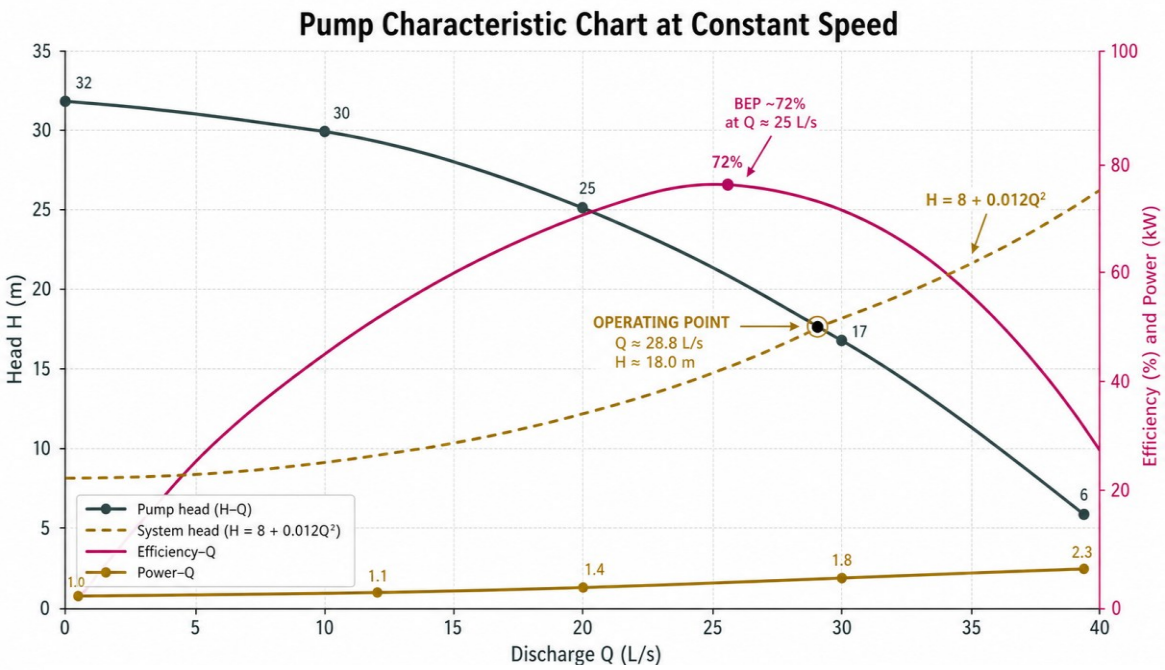


Fig. 5.10 Centrifugal-pump characteristic curves and the operating point at the best-efficiency point.

FORMULA SHEET — CHAPTER 5

Quantity	Formula
Darcy's law	$v = K \cdot i$; $Q = K \cdot i \cdot A$
Porosity split	$n = Sy + Sr$
Storativity & transmissivity	$S = Ss \cdot b$; $T = K \cdot b$
Confined well (Thiem)	$Q = 2\pi Kb(s_1 - s_2)/\ln(r_2/r_1)$
Unconfined well (Dupuit-Thiem)	$Q = \pi K(h_2^2 - h_1^2)/\ln(r_2/r_1)$
Specific capacity	$Sc = Q/sw$
Theis	$s = (Q/4\pi T) \cdot W(u)$, $u = r^2S/4Tt$
Cooper-Jacob	$s = (2.303Q/4\pi T) \cdot \log_{10}(2.25Tt/r^2S)$
Recuperation test	$C = (2.303/t) \cdot \log_{10}(h_1/h_2)$; $Q = C \cdot A \cdot Hs$
Water-table recharge	$R = Sy \cdot A \cdot \Delta h$
Resistivity (Wenner)	$\rho a = 2\pi a(\Delta V/I)$
Ghyben-Herzberg	$hs = \rho f/(\rho s - \rho f) \cdot hf \approx 40\ hf$
Water power	$WP = \rho gQH$
Shaft & input power	$BP = WP/\eta p$; input $= WP/(\eta p \cdot \eta d)$
Affinity laws	$Q \propto N \propto D$; $H \propto N^2 \propto D^2$; $P \propto N^3 \propto D^3$
NPSH & specific speed	$NPSHa \geq NPSHr$; $Ns = NvQ/H\text{^}(3/4)$
Reciprocating pump	$Qth = A \cdot L \cdot N/60$; slip $= Qth - Qact$; $Cd = Qact/Qth$

SUMMARY

- Groundwater is the free water in the zone of saturation below the water table; the vadose zone above holds water below atmospheric pressure.
- Aquifers store and transmit water; ranked aquifer > aquitard > aquiclude > aquifuge; types — unconfined, confined (artesian), leaky, perched.

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- Storage: n = Sy + Sr; storativity S = Ss·b (confined 5×10^{-5}-5×10^{-3}, unconfined ≈ Sy); transmission: T = K·b; Darcy v = K·i.
- Steady flow to wells: confined $Q = 2\pi Kb(s_1-s_2)/\ln(r_2/r_1)$; unconfined $Q = \pi K(h_2^2-h_1^2)/\ln(r_2/r_1)$; doubling well diameter barely raises yield.
- Unsteady flow: Theis $s = (Q/4\pi T)W(u)$; Cooper-Jacob straight-line; specific capacity = Q/sw.
- Pumping test gives T, K, S (tube wells); recuperation test gives safe yield (dug wells).
- Investigation: geologic, remote sensing and electrical-resistivity (Wenner $\rho a = 2\pi a\cdot\Delta V/I$); recharge from water-table fluctuation $R = Sy\cdot A\cdot\Delta h$.
- Wells: open/dug, tube (strainer, cavity), dug-cum-bore, driven, filter-point, collector; drilling by boring, jetting, percussion or rotary to suit the formation.
- Screen needs high open area, low entrance velocity (≤ 3 cm/s), correct slot; gravel pack ratio 4-6; develop the well (compressed-air etc.).
- Manage draft vs recharge (CGWB safe→over-exploited); artificial recharge and conjunctive use; Ghyben-Herzberg guards coastal aquifers.
- Pumps: centrifugal (needs priming), reciprocating, submersible, jet, air-lift; affinity laws $Q\propto N$, $H\propto N^2$, $P\propto N^3$.
- Power WP = ρgQH; prime mover = WP/ηp; energy cost = WP/(ηp·ηmotor) × hours × rate; avoid cavitation by keeping NPSHa ≥ NPSHr.

LAST-NIGHT REVISION

Must-remember	Value / formula
Aquifer types	unconfined · confined · leaky · perched
Storage formations	aquifer > aquitard > aquiclude > aquifuge
Porosity split	n = Sy + Sr (Sy: coarse high; Sr: clay high)
Storativity	confined 5×10^{-5}-5×10^{-3}; unconfined = Sy (0.01-0.30)
Confined well yield	$Q = 2\pi Kb(s_1-s_2)/\ln(r_2/r_1)$
Unconfined well yield	$Q = \pi K(h_2^2-h_1^2)/\ln(r_2/r_1)$
Theis u	$u = r^2S/4Tt$
Screen entrance velocity	≤ 3 cm/s
Gravel-pack ratio	D50(pack)/D50(aquifer) ≈ 4-6
CGWB stage of development	Safe<70 · Semi-crit 70-90 · Crit 90-100 · Over-exploited>100 %
Affinity laws	$Q\propto N$ · $H\propto N^2$ · $P\propto N^3$
Water power / unit	WP = ρgQH · 1 unit = 1 kWh
Cavitation guard	NPSHa ≥ NPSHr
Priming	fill casing/suction; centrifugal can't pump air

CHAPTER

6

DRAINAGE ENGINEERING, SALINITY & SOIL RECLAMATION

Drainage coefficient · Surface & subsurface drains · Hooghoudt spacing · Mole · Interceptor · Vertical & Bio-drainage · Salinity · ESP–SAR · Reclamation · Leaching requirement

SYLLABUS (Paper I | Soil & Water Conservation): Agricultural drainage — definition, objectives, sources & ill-effects; importance of drainage networks in canal-command areas. Drainage hydrology — drainage coefficient, drainable porosity, pore-space/void-ratio relationships. Surface drainage — open drains, layout, advantages & limitations. Subsurface drainage — tile, mole, pipe, pipeless drains; design parameters; tile spacing by Hooghoudt's equation; supplemental structures for long-life tile drainage. Specialised drains — interceptor, relief, vertical, bio-drainage. Sanitary drainage & sewage handling. Soil salinity & reclamation — saline, sodic and saline-sodic soils; ESP & SAR relationship and significance; saline-soil management; reclamation measures; seawater intrusion. Leaching requirement — concept, estimation, design implications. Waterlogging & salt accumulation — causes, effects, management.

Chapter Outline

1. **Scope: Agricultural Drainage — Definition, Objectives & Ill-effects**
2. **Waterlogging & Salt Accumulation**
3. **Drainage Hydrology: Coefficient, Drainable Porosity & Void Ratio**
4. **Surface Drainage**
5. **Subsurface Drainage: Types & Design**
6. **Tile-Drain Spacing — Hooghoudt's Equation**
7. **Tile Hydraulic Design & Supplemental Structures**
8. **Mole Drainage & Pipeless Drains**
9. **Specialised Drains: Interceptor, Relief, Vertical & Bio-drainage**
10. **Sanitary Drainage & Sewage Handling**
11. **Soil Salinity & Salt-Affected Soils**
12. **Hydrographs & Unit Hydrograph**
13. **Reclamation of Salt-Affected Soils & Leaching Requirement**

▣ ***MIND-MAP — Chapter 6 concept map***

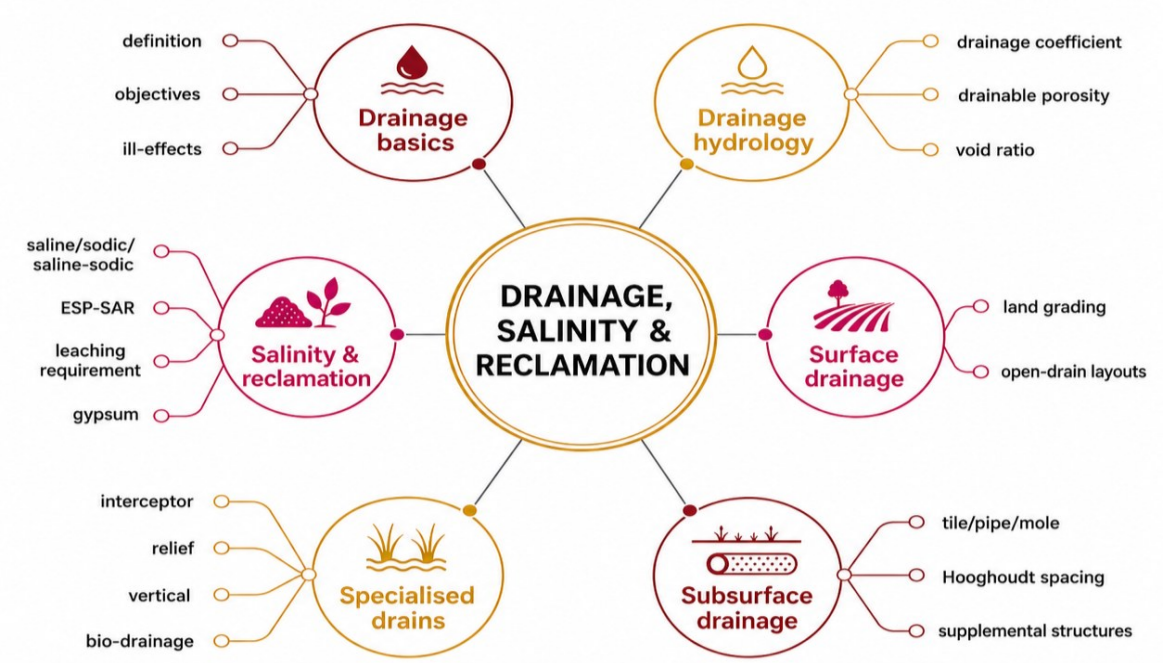


Fig. 6.0 Concept map of Chapter 6 — from drainage design to salt reclamation.

1 SCOPE: AGRICULTURAL DRAINAGE — DEFINITION, OBJECTIVES & ILL-EFFECTS

Drainage is the ***reverse of irrigation*** — the removal of excess water (and salts) from land. In India's canal commands, decades of irrigation without matching drainage have raised water tables and salinised soils, so drainage is now central to sustaining productivity.

> ***Agricultural (land) drainage*** — (ICID, 1979) the removal of excess ***surface and subsurface water*** from the land to enhance crop growth, ***including the removal of soluble salts*** from the soil. It is both a preventive and a curative measure against soil degradation.

OBJECTIVES OF DRAINAGE

Keep the root zone aerated (ideal moisture FC to ~50% FC; only rice/jute need standing water); prevent water-table rise and salt build-up in the root zone; reclaim land lost to waterlogging and salinity; and improve trafficability, tilth, the growing season and crop yield.

SOURCES OF EXCESS WATER & ILL-EFFECTS

Sources : rainfall (chief), snowmelt, over-irrigation and deep percolation, canal and reservoir seepage, surface inflow/runoff, floods and a high regional water table.

Ill-effects of poor drainage : waterlogging (poor aeration, denitrification), secondary salinisation/alkalisation of the root zone, delayed field operations, reduced germination and yield, and eventual loss of arable land (detailed in Section 2).

IMPORTANCE OF THE DRAINAGE NETWORK IN CANAL COMMANDS & LARGE PROJECTS

A drainage network is the ***safety valve*** of an irrigation project: it disposes of excess rain, canal seepage and irrigation return flow, controls the water table, prevents waterlogging and salinity, leaches salts, and thereby protects the huge investment in the command. Surface and subsurface drainage must be planned together with the irrigation system, not as an afterthought.

BENEFITS / ADVANTAGES OF DRAINAGE

Better aeration and root growth; a longer growing season and more field-working days; improved soil structure and trafficability; salinity/alkalinity control; higher, more stable yields; and reduced disease and mosquito nuisance.

PREVIOUS YEAR QUESTIONS

- Define agricultural drainage. What are the sources and ill effects of drainage? [IFOS 2016 | P1/7(a) | 10M]
- What is the importance of drainage network in canal command and large irrigation projects? List all the information required for design and installation of subsurface drainage systems. [design information in §5] [IFOS 2018 | P1/6(b) | 10M]
- What is agricultural drainage? Explain various benefits of drainage. A drainage channel drains 500 hectare land with a discharge of 0.40 m^3/s. Compute the drainage coefficient. [numerical solved in §3] [UK ·PSC FRO(Mains) 2012 | Q.1(iii) | 10M]
- Define the term 'Agricultural Drainage'. Name and discuss different surface and sub-surface drainage systems. [systems in §4-§5] [AP ·PSC FRO (Mains) 2012 | Q.3(c) | 8M]

Components Of An Agricultural Drainage System

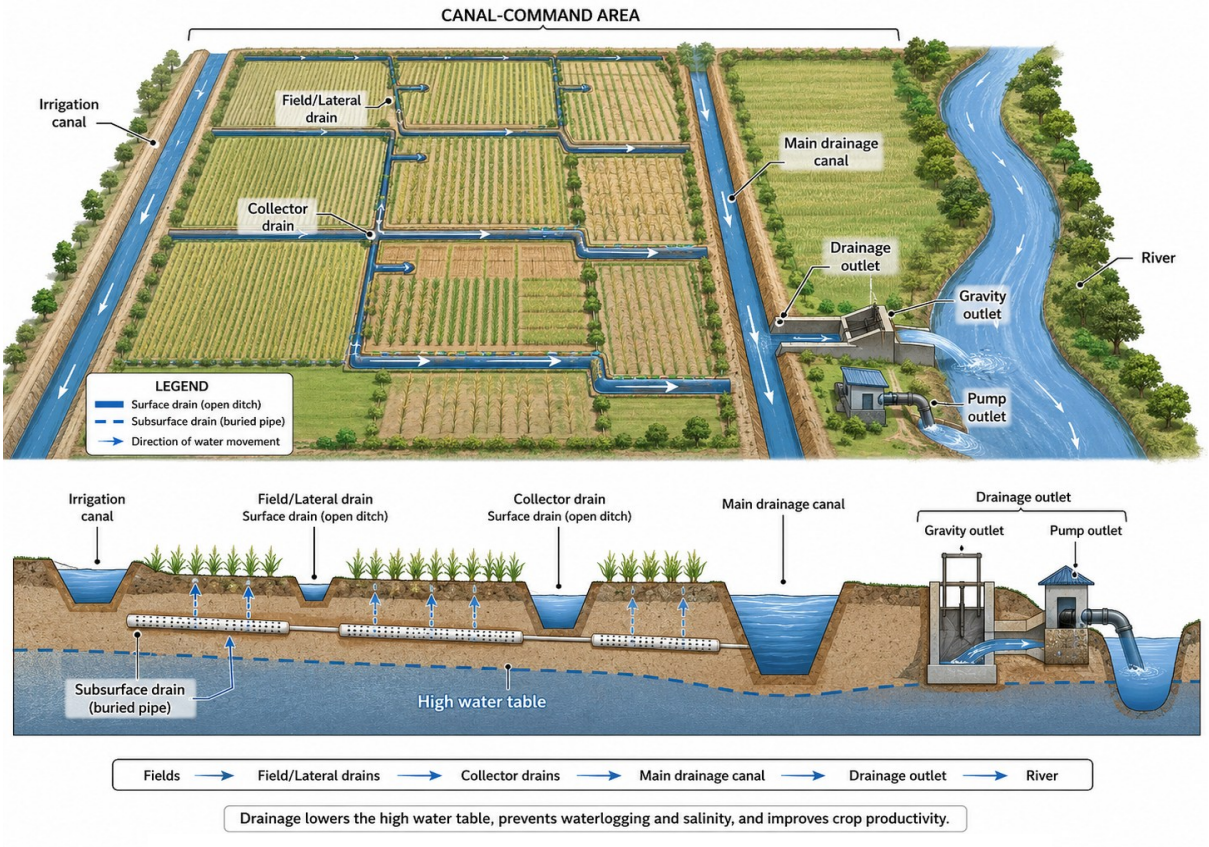


Fig. 6.1 Field drains → collectors → main drain → outlet, integrated with the canal command.

2 WATERLOGGING & SALT ACCUMULATION

Waterlogging and salinization are the twin evils that drainage exists to fight — usually the direct result of irrigating without adequate drainage.

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Waterlogging **:** the condition in which the ***water table rises into or near the root zone*** (soil pores saturated), so that aeration falls below the level crops need and productivity declines.

CAUSES

Over-irrigation and poor on-farm water management; seepage from unlined canals, reservoirs and field channels; inadequate natural or artificial drainage; heavy rainfall on flat, low-lying land; a rising regional water table; impervious sub-layers; and irrigation return flow — all raising the water table faster than it can discharge.

CATEGORISATION OF WATERLOGGED LAND (MOWR)

Category	Depth to water table	Status
Waterlogged	within 2 m of surface	aeration/salinity affected — needs drainage
Potentially waterlogged	2 – 3 m	at risk; monitor
Safe	below 3 m	no drainage problem

SALT ACCUMULATION

Where the water table is shallow, capillary rise brings salts to the surface and evaporation concentrates them (secondary salinisation). It is aggravated by poor-quality (saline) irrigation water, over-irrigation without leaching, and the absence of drainage to carry salts away.

ADVERSE EFFECTS ON AGRICULTURAL LAND (IFOS 2024)

Poor root aeration and denitrification; salt toxicity and osmotic stress lowering water uptake; delayed sowing/harvest and fewer working days; shallow rooting and lodging; reduced germination and yield; and, ultimately, land going out of cultivation.

MANAGEMENT

Adequate surface & subsurface drainage; canal lining to cut seepage; conjunctive use and vertical (tube-well) drainage to lower the water table; controlled, efficient irrigation with leaching; bio-drainage; and reclamation of already-affected land (Sections 11-12).

PREVIOUS YEAR QUESTIONS

- How does waterlogging and salt accumulation affect the agricultural land adversely? Explain in brief. [IFOS 2016 | P1/5(c) | 8M]
- What are the causes of waterlogging and soil salinity in an irrigated agricultural field? [IFOS 2019 | P1/5(c) | 8M]
- What are the reasons for waterlogging? How is categorization of waterlogged land done? [OPSC·CSE (Main) 2020-21 | P1/4(b) (i) | 8M]
- What is waterlogging? Explain the adverse effect of waterlogging. [OPSC·CSE (Main) 2022-23 | P1/10(a) | 5M]
- What are the causes of waterlogging and advantages of drainage? [advantages in §1] [OPSC·CSE (Main) 2015-16 | P1/1(c) | 20M]
- State various harmful effects of waterlogging on crops. [AP·PSC RFO (Mains) 2012 | Q.1(k) | 4M]

Waterlogging & Secondary Salinization

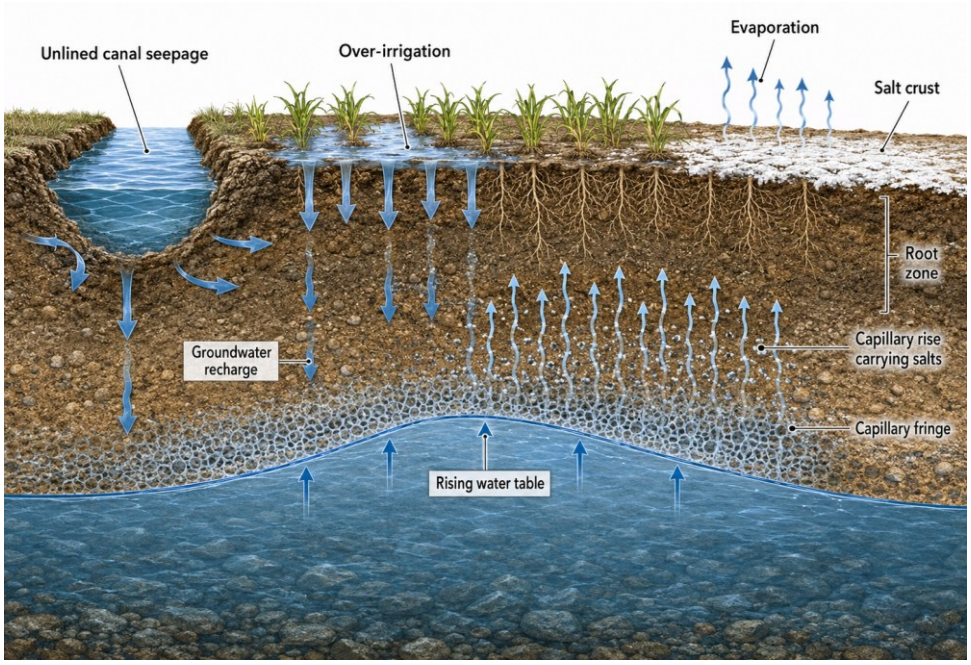


Fig. 6.2 How irrigation without drainage causes waterlogging and secondary salinization.

3 DRAINAGE HYDROLOGY: COEFFICIENT, DRAINABLE POROSITY & VOID RATIO

The hydraulic design of any drain rests on three quantities — the ***drainage coefficient*** (how much water to remove), ***drainable porosity*** (how much a soil yields on draining) and the ***pore-space / void-ratio*** relations that connect them.

Drainage coefficient (DC) **:** the depth of surplus water to be removed from the ***whole drainage area in 24 hours*** so that crops are not damaged; units cm/day or mm/day (also m^3/s per km^2 or L/s/ha). Note ***1 mm/day = 0.116 L/s/ha***.

Drainable porosity (μ) **:** the volume of water drained by gravity per unit volume of saturated soil (= ***effective porosity / specific yield***); typically 2-10% for field soils. It is the porosity minus the moisture retained after gravity drainage.

$$n = Vv/V \quad e = Vv/Vs \quad n = e/(1+e)\ e = n/(1-n)\ \mu = n - \theta r \quad V_{drain} = \mu \cdot A \cdot D$$

n porosity; e void ratio; Vv voids, Vs solids (-); θr moisture retained after drainage (v/v); μ drainable porosity; A area (m^2); D root/soil depth (m).

◆ **WORKED NUMERICAL — Void ratio, drainable porosity & drainable water volume** [IFoS 2025 · P1/5(d) · 8M]

Problem. *An agricultural area of 1 hectare needs to be drained of excess water. The soil contains 47% pore space and the soil moisture content after gravitational drainage is 39% (by volume). Find the void ratio, drainable porosity and drainable water volume from the area. The effective root-zone depth is 0.9 m.*

Given. A = 1 ha = 10^4 m^2; porosity n = 0.47; retained moisture θr = 0.39; root-zone depth D = 0.9 m.

Formula. $e = n/(1-n)$; $\mu = n - \theta r$; $V_{drain} = \mu \cdot A \cdot D$

Substitution. e = 0.47/(1 − 0.47) = 0.47/0.53 = 0.887

μ = 0.47 − 0.39 = 0.08; V = 0.08 × 10^4 × 0.9 = 720 m^3

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Result. Void ratio e = 0.887; drainable porosity = 0.08 (8%); drainable water volume = 720 m³.

◆ **WORKED NUMERICAL — *Drainage coefficient from a water balance*** [IFoS 2016 · P1/7(b) · 20M]

Problem. *Runoff water from a watershed enters into a drainage area for 8 hours at the rate of 3 m³/s. The total rainfall during a 24-hour period is 12 cm and the total infiltration during the period is 4 cm. If the total drainage area is 200 ha and the crop can tolerate a ponding of 10 cm, calculate the drainage coefficient of the land.*

Given. Inflow Q = 3 m³/s for 8 h; P = 12 cm, infiltration f = 4 cm (24 h); A = 200 ha = 2×10^6 m²; permissible ponding = 10 cm.

Formula. Water to remove = inflow volume + (P − f)·A − ponding·A;

DC = (volume to remove)/A cm or mm /per day

Substitution. inflow = 3 × 8 × 3600 = 86 400 m³;

rain excess = (0.12 − 0.04) × 2×10^6 = 160 000 m³;

ponding = 0.10 × 2×10^6 = 200 000 m³

volume to remove = inflow + rain excess - ponding

volume to remove = 86400 + 160000 − 200 000 = 46 400 m³ (in 24 h)

DC = 46 400 / (2×10^6) = 0.0232 m/day

Result. Drainage coefficient = 2.32 cm/day (≈ 23.2 mm/day).

◆ **WORKED NUMERICAL — *Drainage coefficient from discharge & area*** [OPSC·CSE (Main) 2016-17 · Paper-I Q.4(b) · 15M]

Problem. *Define Drainage Coefficient. A drainage canal discharges 0.2 m³/s and drains 250 ha. What is the drainage coefficient of this land?*

Given. Q = 0.2 m³/s; A = 250 ha = 2.5×10^6 m².

Formula. DC = Q × 86 400 / A

Substitution. DC = 0.2 × 86 400 / (2.5×10^6) = 17 280 / 2.5×10^6 = 0.00691 m/day

Result. DC ≈ 6.91 mm/day (0.69 cm/day). Check: 1 mm/day = 0.116 L/s/ha.

◆ **WORKED NUMERICAL — *Water removed over a period*** [OPSC·CSE (Main) 2020-21 · Paper-I Q.3(b)(ii) · 12M]

Problem. *A drainage ditch draining 10 ha of land flows at a design capacity for three days following a storm. If the system is designed using a drainage coefficient of 2 cm, how much water will be removed during this period?*

Given. A = 10 ha = 10^5 m²; DC = 2 cm/day = 0.02 m/day; t = 3 days.

Formula. V = DC × A × t

Substitution. V = 0.02 × 10^5 × 3 = 6000 m³

Result. Water removed = 6000 m³.

Estimating The Design Drainage Coefficient

On steep land (>1-2% slope) the peak runoff (rational/SCS methods) governs; on flat land a design storm of chosen return period is drained in a safe period (≈2 days).

Empirical formulae: ***Cypress Creek*** $Q = C\cdot A^{(5/6)}$ (C from CN-runoff; slope ≤0.45%) and the

Boston Society $Q = C\cdot A^{(5/6)}$

(cusec, A in sq. miles). Drainage periods (Pai-Hukkeri): paddy/sugarcane 7 d, millet/cotton 3 d, sorghum/maize 2 d, vegetables 1 d.

PREVIOUS YEAR QUESTIONS

- What is the drainage coefficient? Discuss its usage. A command area of 2500 ha is to be provided with surface drainage in heavy clay soil of coastal Odisha; max 24-h rainfall 220 mm, runoff coefficient 0.80, crop tolerates 48 h ponding. Determine the drainage coefficient (mm/day) and the required capacity of the main drain draining the whole 2500 ha. [OPSC·CSE (Main) 2024-25 | P1/5 | 15M]
- Runoff water enters a drainage area for 5 hours at 24 m^3/s. Total 24-h rainfall is 10 cm and infiltration 2 cm. If the drainage area is 500 ha and the crop tolerates 14 cm ponding, calculate the drainage coefficient of the land. [OPSC·CSE (Main) 2023-24 | P1/11(a) | 15M]
- Compute the drainage coefficient for design of an open-ditch surface drainage system draining a 1500 ha watershed with the given information. [OPSC·CSE (Main) 2022-23 | P1/3(a)(ii) | 10M]
- What is the drainage coefficient? Explain its role/importance in designing the drainage system of an agricultural area. [OPSC·CSE (Main) 2017-18 | P1/1(e) | 15M]
- What are the causes of waterlogging and advantages of drainage? [advantages in §1] [OPSC·CSE (Main) 2015-16 | P1/1(c) | 20M]
- Explain: Drainage coefficient; Leaching requirement; Drainable porosity; Hooghoudt's equation; Transmissivity. And explain soil-reclamation methods for different problem soils. [reclamation in §12]. [OPSC·CSE (Main) 2022-23 | P1/11(b) | 10M]

★ **MODEL Q** Water-balance DC: volume to drain = surface inflow + (rainfall − infiltration) A − permissible-ponding·A; DC = that volume ÷ A ÷ days. Simple DC = Q·86400/A. Always convert cm↔m and remember 1 mm/day = 0.116 L/s/ha.

Drainage Coefficient From A Runoff Hydrograph

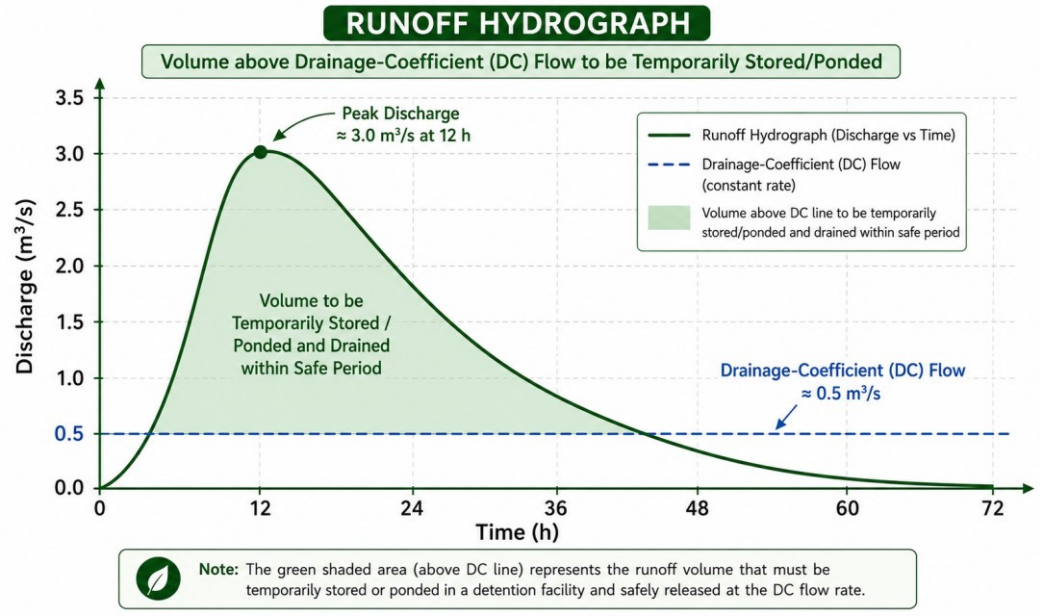


Fig. 6.3 The drainage coefficient is a flow rate below the hydrograph peak; excess is drained within the crop-safe period.

4 SURFACE DRAINAGE

Surface drainage removes ***ponded water from the land surface*** before it damages the crop — the first line of defence on flat, heavy or low-infiltration land.

Surface drainage — (ICID) the orderly removal of excess surface water by improved natural or constructed

channels, aided by ***land forming/grading*** to guide sheet flow to the drains without causing erosion.

LAND FORMING / GRADING

Reshaping the field micro-topography so water moves to the drains. ***Plane (least-squares) method*** fits a best plane through the field centroid for balanced cut-and-fill; the ***profile method*** sets grades along survey lines (flat land). Land smoothing removes minor irregularities.

OPEN-DRAIN / FIELD LAYOUTS

Layout	Where used
Random field drain	scattered depressions/pot-holes; cut ≤ 1 m
Bedding (dead furrows)	flat, slowly-permeable soils; slope < 1.5%
Parallel field drain	uniformly flat land needing regular removal
Parallel lateral (open) ditch	deeper ditches; also lower the water table
Cross-slope ditch	sloping land ≤ 4%; also checks erosion (W-drain = twin ditch)

ADVANTAGES & LIMITATIONS OF SURFACE (OPEN) DRAINS

Advantages	Limitations
low initial cost; simple to build	take land out of cultivation; split fields
carry both surface runoff & some seepage	obstruct farm machinery
easy to inspect	high recurring maintenance (weeds, silting, bank erosion)
provide surface storage in high rainfall	breeding of weeds/mosquitoes

DESIGN — HYDROLOGIC THEN HYDRAULIC

Hydrologic — fix the design drainage coefficient (Section 3). **Hydraulic** — size the open channel by Manning's equation for the design discharge, keeping the velocity below the soil's permissible (non-erosive) value.

$V = (1/n)\cdot R^{(2/3)}\cdot S^{(1/2)}$ $Q = A\cdot V$ $R = A/P$ Trapezoid: $A = (b + z\cdot y)\cdot y$, $P = b + 2y\sqrt{(1+z^2)}$

V velocity (m/s); n Manning roughness; R hydraulic radius (m); S bed slope; A flow area (m²); P wetted perimeter (m); b bed width; y depth; z side slope (H:V).

◆ **WORKED NUMERICAL — *Trapezoidal drain — permissible-velocity check*** **[OPSC·CSE (Main) 2020-21 · Paper-I Q.3(c)(ii) · 12M]**

Problem. *Design a trapezoidal drainage canal to drain 550 ha having a drainage coefficient of 2.5 cm. Soil is silt loam (permissible velocity 0.6 m/s); side slope 1.5 H:1 V; depth of flow 1.2 m; bottom width 0.75 m; bed slope 0.1%; Manning n = 0.04. Find whether the flow velocity when carrying the drainage discharge is below the permissible velocity.*

Given. DC = 2.5 cm/day = 0.025 m/day; A = 550 ha = 5.5×10^6 m²; b = 0.75 m; y = 1.2 m; z = 1.5; S = 0.001; n = 0.04; v_perm = 0.6 m/s.

Design Q. $Q = DC\cdot A/86\,400 = 0.025 \times 5.5\times10^6 / 86\,400 = 1.59$ m³/s

Geometry. $A = (0.75 + 1.5\times1.2) \times 1.2 = 3.06$ m²;

$P = 0.75 + 2\times1.2\sqrt{(1+1.5^2)} = 5.08$ m;

$R = 3.06/5.08 = 0.603$ m

Velocity. $V = (1/0.04) \times 0.603^{(2/3)} \times 0.001^{(1/2)} = 25 \times 0.714 \times 0.0316 = 0.564$ m/s

Result. V = 0.564 m/s < permissible 0.6 m/s → SAFE. Capacity A·V = 3.06×0.564 = 1.73 m³/s > 1.59 m³/s, so it runs just below full depth.

PREVIOUS YEAR QUESTIONS

- What is surface drainage? Explain the steps in surface-drainage design in an elaborate way.
  [OPSC·CSE (Main) 2023-24 | P1/11(b) | 15M]
- Discuss causes of waterlogging in the Indian scenario. Design the main open drain with a bed slope of 0.1% for a catchment area of 6 sq. km using the given data.
  [MH·PSC Forest Services (Mains) 2024 | Q.4(b) | 15M]
- Design a trapezoidal open ditch to drain 500 ha having a drainage coefficient of 3 cm/day; soil silt loam (side slope 1.5, permissible velocity 0.5 m/s) and maximum permissible channel-bed slope 0.1%.
  [OPSC·CSE (Main) 2016-17 | P1/1(c) | 20M]
- Explain the hydrologic and hydraulic design of surface and sub-surface drainage systems. [subsurface in §5-§7] [OPSC·CSE (Main) 2016-17 | P1/4(c) | 15M]

Surface-Drainage Field Layouts

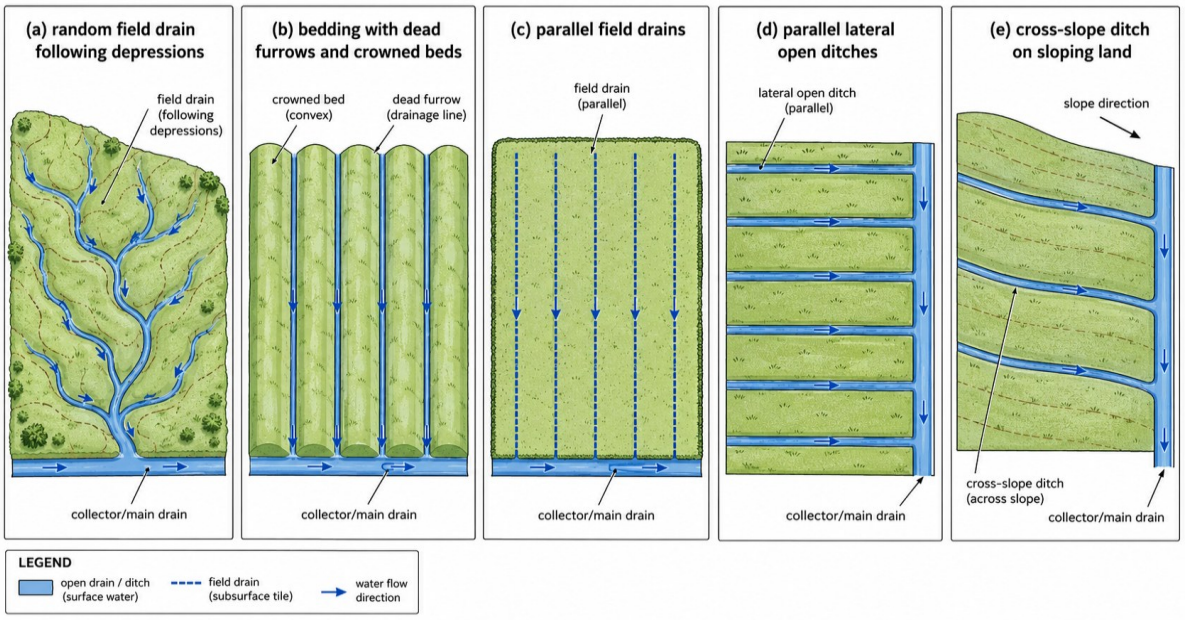


Fig. 6.4 Common surface-drainage layouts for different topographies.

5 SUBSURFACE DRAINAGE: TYPES & DESIGN

Subsurface drainage lowers a high ***water table*** by intercepting groundwater with buried drains — the standard cure for waterlogging and salinity in irrigated commands.

PURPOSE, BENEFITS & TYPES

Purpose/benefits : control the water table, aerate the root zone, remove salts, lengthen the growing season, improve tilth and trafficability, and raise yields.

Types : open ditches, buried ***tile / pipe drains***, ***mole drains*** and pipeless drains, and vertical (tube-well) drains. When field pipe drains discharge to an open collector the system is ***singular***; when to a pipe collector it is ***composite***. Layouts are grid (right-angle) or herringbone (sharp-angle).

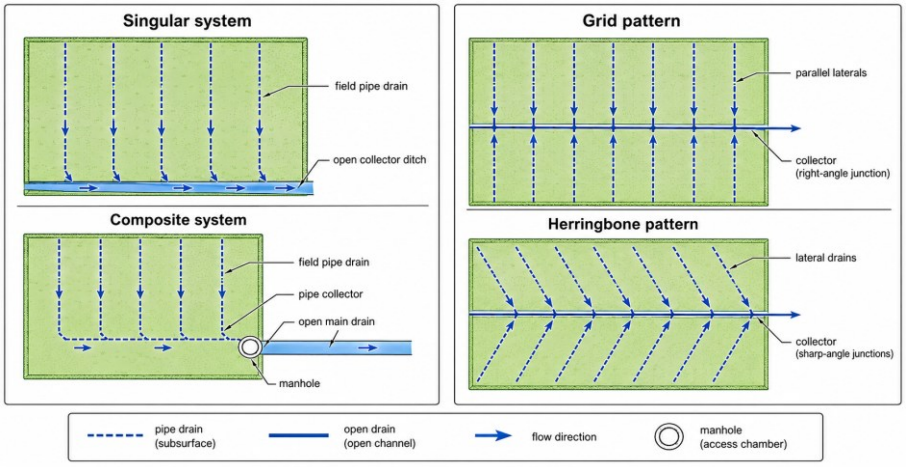
Basis	Open ditch drain	Pipe (tile) drain
Land loss	takes land, splits fields	none — buried, farmed over
Machinery	obstructs	no obstruction
Maintenance	high (weeds, silting)	low

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Cost	low initial, high recurring	high initial, low recurring
Water entry	surface + subsurface	subsurface through perforations

INFORMATION REQUIRED TO DESIGN & INSTALL A SUBSURFACE SYSTEM (IFOS 2025, 2018)

Topographic survey & contour maps; soil profile and texture; ***hydraulic conductivity*** **K** (auger-hole method); ***drainable porosity*** **μ**; depth to the impervious/barrier layer; depth and seasonal fluctuation of the water table; the ***drainage coefficient / recharge rate q***; the level of the outlet (drainage base); soil salinity and irrigation-water quality; the cropping pattern and permissible water-table depth; and existing roads/canals/infrastructure.



6.5 Singular vs composite systems and grid vs herringbone layouts.

DESIGN PARAMETERS & PIPE MATERIALSs

The key design outputs are ***drain depth and spacing*** (from the drainage equations, Section 6) and ***pipe size and gradient*** (Section 7). Pipes are clay/concrete tiles or perforated PVC/HDPE corrugated pipe, wrapped in a ***gravel or synthetic envelope*** that admits water while keeping fines out.

ENVIRONMENTAL ASPECTS (APPSC 2018)

Positive : reclaims waterlogged/saline land, controls the water table, cuts salinity and mosquito breeding. **Negative :** drainage effluent is saline/nutrient- and pesticide-laden, so disposal can pollute downstream water bodies and (near coasts) needs careful management.

PREVIOUS YEAR QUESTIONS

- Discuss the advantages and limitations of surface drain and subsurface drain. Explain and discuss the information required to design and for the installation of subsurface drainage systems.
  [IFOS 2025 | P1/7(a) | 15M]
- Discuss the purpose, benefits and types of subsurface drainage systems. Explain the design of pipe drainage systems used for large irrigation projects. [IFOS 2017 | P1/8(c) | 10M]
- Explain, in detail, the various factors considered in designing a sub-surface drainage system.
  [OPSC·CSE (Main) 2017-18 | P1/4(b) | 15M]
- Explain the surface and subsurface drainage methods with suitable sketch
  [OPSC·CSE (Main) 2022-23 | P1/10(b) | 10M]
- Give two reasons for installing subsurface drainage in a field and discuss its importance. Discuss the positive and negative environmental aspects of subsurface drainage.
  [AP·PSC RFO (Mains) 2018 | 9(a),(b) | 4M + 6M]
- Write the names of different types of surface and sub-surface drainage methods adopted in India. Differentiate between mole drain and bedding system. [mole vs bedding in §8]
  [OPSC·CSE (Main) 2015-16 | P1/6(c) | 10M]

6 TILE-DRAIN SPACING — HOOGHOUDT'S EQUATION

Drain depth is usually fixed by machinery and the barrier layer; the design problem is then the ***spacing*** that holds the water table at the permissible depth midway between drains under the design recharge.

ASSUMPTIONS (HOOGHOUDT / DONNAN)

Soil homogeneous and isotropic (single K); Dupuit-Forchheimer (essentially horizontal flow); steady, uniform recharge q; equally-spaced parallel drains of equal size; an impervious (barrier) layer at a known depth; and radial convergence of flow near the drains handled through an ***equivalent depth d***.

Steady state: $S^2 = (8 \cdot K \cdot d \cdot h + 4 \cdot K \cdot h^2) / q$ Drains on the barrier (d = 0): $S^2 = 4 \cdot K \cdot h^2 / q$

S drain spacing (m); K hydraulic conductivity (m/day); d equivalent depth of barrier below drain level (m); h height of water table above drain level, midway between drains (m); q drainage coefficient / recharge (m/day).

The ***equivalent depth d*** (< actual depth D of the barrier below the drains) is Hooghoudt's correction for the extra head loss as flow converges radially to the small drains; it is read from Hooghoudt's tables (function of D, S and drain radius). Unsteady (falling water-table) design uses the ***Glover–Dumm*** equation, h t/h_0 = $1.16 \cdot e^{(-\alpha t)}$ with $\alpha = \pi^2 Kd/(\mu S^2)$.

◆ **WORKED NUMERICAL — *Tile-drain spacing — drains resting on the barrier*** [IFoS 2022 · P1/5(c) · 8M]

Problem. *In a tile drainage system, drains are to be installed at the impervious layer at a depth of 2.0 m below the ground surface. Hydraulic conductivity is 1.8 m/day and the average rate of recharge is 0.2 cm/day. Calculate the required spacing of the drains if the water table is to be kept at 1.0 m from the ground surface.*

Given. Drains on the impervious layer (so d = 0);

K = 1.8 m/day; q = 0.2 cm/day = 0.002 m/day;

drain depth 2.0 m, WT at 1.0 m ⇒ h = 2.0 − 1.0 = 1.0 m.

Formula. Barrier at drain level (d = 0): $S^2 = 4 \cdot K \cdot h^2 / q$

Substitution. $S^2 = 4 \times 1.8 \times 1.0^2 / 0.002 = 7.2 / 0.002 = 3600 \Rightarrow S = 60$ m

Result. Required drain spacing S = 60 m. (No below-drain term because the drains rest on the impervious layer.)

◆ **WORKED NUMERICAL — *Tile-drain spacing using the equivalent depth*** [OPSC·Forest (Main) 2019-20 · Paper-I Q.6(b) · 20M]

Problem. *Tile drains of 0.2 m diameter are placed 2 m below the surface; an impermeable layer is at 6 m; K = 1 m/day (uniform); average drainage discharge q = 2 mm/day; keep the water table at 1.5 m. Given: for D = 4 m and L = 80 m the equivalent depth d = 3.55 m. Determine the spacing.*

Given. K = 1 m/day; q = 2 mm/day = 0.002 m/day; drain depth 2 m, WT at 1.5 m ⇒ h = 0.5 m;

barrier below drains D = 6 − 2 = 4 m; equivalent depth d = 3.55 m.

Formula. $S^2 = (8 \cdot K \cdot d \cdot h + 4 \cdot K \cdot h^2) / q$

Substitution. $S^2 = (8 \times 1 \times 3.55 \times 0.5 + 4 \times 1 \times 0.5^2)/0.002$

$= (14.2 + 1.0)/0.002$

$= 7600 \Rightarrow S = 87.2$ m

Result. Spacing S ≈ 87 m (first trial L = 80 m → d = 3.55 m → S = 87 m; a further iteration refines it slightly).

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PREVIOUS YEAR QUESTIONS

What are the assumptions of Hooghoudt's equation for drain spacing? Subsurface drains lower the water table from 0.6 m to 1.2 m in 10 days; drains at 2.0 m, impervious layer at 4.8 m, drainable porosity 8%, K = 0.8 m/day. Determine the spacing using Hooghoudt's equation.

[OPSC·CSE (Main) 2024-25 | P1/6 | 15M]

MODEL Q Hooghoudt: h = drain depth − permissible WT depth. If drains sit on the barrier, d = 0 → S = 2hv(K/q). Otherwise use the equivalent depth d (table) in $S^2 = (8Kdh + 4Kh^2)/q$, iterating trial spacing until d and S agree.***

Hooghoudt Drain-Spacing Geometry

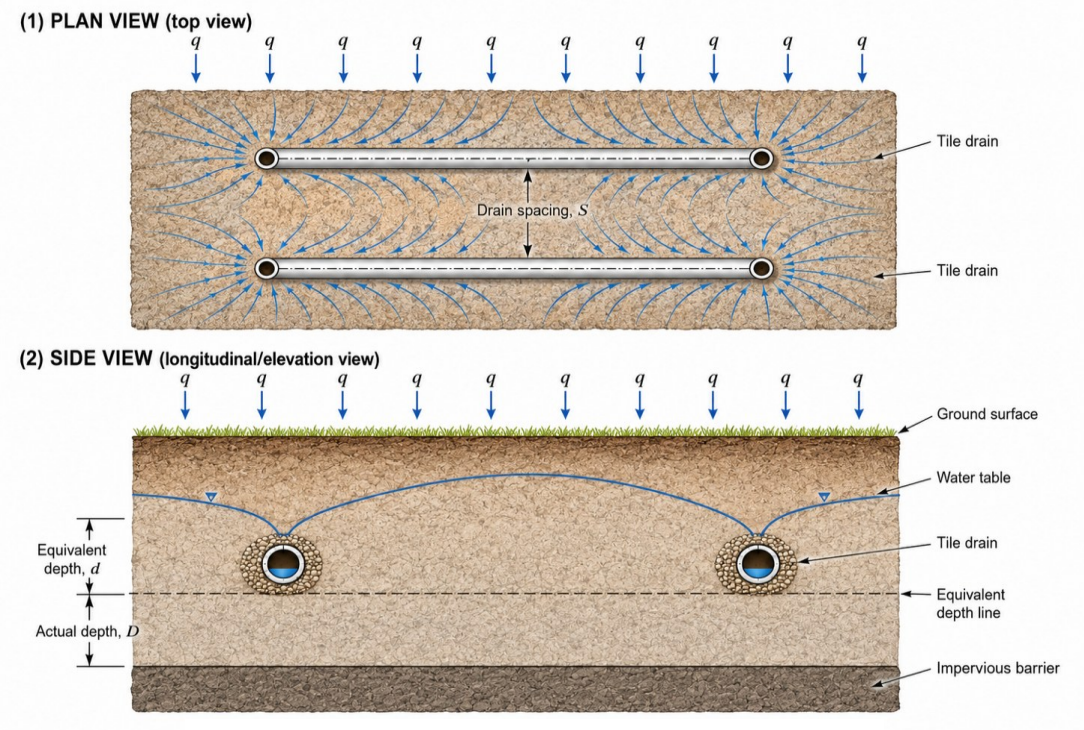


Fig. 6.6 Hooghoudt geometry — S, h, barrier depth D and equivalent depth

7 TILE HYDRAULIC DESIGN & SUPPLEMENTAL STRUCTURES

Once spacing is set, the drain ***pipe is sized*** to carry its share of the drainage coefficient at a self-cleaning velocity, and the system is protected by supplemental structures that give it a long working life.

PIPE SIZE & GRADIENT (MANNING, FLOWING FULL)

$$Q = DC \cdot A \qquad Q = (1/n)\cdot(\pi D^2/4)\cdot(D/4)^{(2/3)}\cdot S^{(1/2)} \qquad V = (1/n)\cdot(D/4)^{(2/3)}\cdot S^{(1/2)}$$

Q design discharge (m^3/s); DC drainage coefficient (m/day → m^3/s); A area served; D pipe diameter (m); n Manning roughness; S pipe grade. Full-pipe R = D/4.

◆ **WORKED NUMERICAL — Velocity & discharge of a tile/pipe drain flowing full** [IFoS 2023 · P1/7(c)(i) · part of 10M]

Problem. *Compute the velocity of flow and the discharge capacity of a 150 mm diameter corrugated plastic pipe flowing full if the slope is 0.4 percent. Manning's roughness coefficient is 0.016.*

Given. D = 150 mm = 0.15 m; flowing full ⇒ R = D/4 = 0.0375 m; S = 0.4% = 0.004; n = 0.016.

Formula. $V = (1/n)\cdot R^{(2/3)}\cdot S^{(1/2)}$; $Q = A\cdot V$, $A = \pi D^2/4$

Substitution. $V = (1/0.016) \times 0.0375^{(2/3)} \times 0.004^{(1/2)} = 62.5 \times 0.112 \times 0.0632 = 0.443$ m/s

$A = \pi/4 \times 0.15^2 = 0.01767$ m²; $Q = 0.01767 \times 0.443 = 0.00783$ m³/s

Result. Velocity = 0.443 m/s; discharge capacity = 7.83 L/s (0.00783 m³/s).

◆ **WORKED NUMERICAL — *Size of a tile drain from the drainage coefficient*** [OPSC·CSE (Main) 2022-23 · Paper-I Q.12(a) · 5M]

Problem. *Determine the size of a tile at the outlet of a 6-hectare drainage system if the drainage coefficient is 1 cm and the tile grade is 0.3%. Take rugosity coefficient 0.011.*

Given. A = 6 ha = 6×10^4 m²; DC = 1 cm/day = 0.01 m/day; S = 0.3% = 0.003; n = 0.011.

Design Q. $Q = DC \cdot A/86\,400 = 0.01 \times 6\times10^4 / 86\,400 = 0.00694$ m³/s

Formula. $Q = (1/n)\cdot(\pi D^2/4)\cdot(D/4)^{(2/3)}\cdot S^{(1/2)} \Rightarrow$ solve for D

Substitution. $0.00694 = (1/0.011)(\pi/4)(1/4)^{(2/3)}(0.003)^{(1/2)}\cdot D^{(8/3)} = 1.552\cdot D^{(8/3)} \Rightarrow D^{(8/3)} = 0.00447$

$D = 0.132$ m = 13.2 cm

Result. Required D ≈ 13.2 cm → provide the next standard size, a 15 cm tile.

SUPPLEMENTAL STRUCTURES FOR LONG-LIFE TILE DRAINAGE (IFOS 2024)

These protect the buried system and keep it working for decades: ***drain outlet*** with headwall, flap/tide gate and animal guard (free outflow ≥ 0.3 m above ditch water); ***manholes / inspection chambers*** with a silt trap for inspection, flushing and junctions; ***junction & connection boxes*** (blind T/cross joints, ~0.10 m drop-in); ***surface-water inlets*** with silt trap and grating; ***breathers / vents / relief wells*** to release trapped air and relieve pressure; ***drain bridges*** across unstable strips; and the ***gravel envelope*** that stops sediment entry — together preventing sedimentation, clogging, erosion and animal/flood entry.

PREVIOUS YEAR QUESTIONS

- What are the supplemental structures used in a tile drainage system for their successful functioning and long life? [IFoS 2024| P1/6(c) | 15M]
- List the various structures used in a subsurface drainage system and state their uses. [OPSC·CSE (Main) 2020-21 | P1/6(b)(i) | 15M]
- Determine the size of the tile required at the end of a 500 m long tile line if the drainage coefficient is 1 cm, grade is 0.3% and the tile spacing is 50 m.[OPSC·CSE (Main) 2016-17 | P1/4(a) | 15M]
- Explain the types of tile drainage system with the help of a neat sketch [UK· PSC·RFO (Main) 2015 | Q. 4(iii) | 10M]

8 MOLE DRAINAGE & PIPELESS DRAINS

In heavy clay soils a cheap, temporary subsurface drain can be formed without any pipe at all — the ***mole drain***.

Mole drain — an unlined cylindrical channel formed in the subsoil by pulling a ***mole plough*** (a bullet-shaped cylinder with an expander) through plastic clay; the channel stays open in the cohesive clay and drains excess subsurface water. It is a ***pipeless drain***.

FORMATION, SUITABLE SOILS & LIFE

Formed by a torpedo/bullet (75-100 mm) with a trailing expander at 0.4-0.6 m depth and 2-5 m spacing, on a slight grade, when the clay is moist and plastic (plasticity index high; moisture between the liquid and plastic

limits so the channel is moulded, not smeared). **Suitable soils** — stable, high-clay soils free of sand/stones. **Life** — temporary, ~2-5 years (longer if it feeds a gravel-filled mole or a collector).

Basis	Mole drain	Bedding
Type	subsurface (unlined clay channel)	surface land form (beds + dead furrows)
Removes	subsurface water — lowers water table	surface (ponded) water
Soil	heavy, plastic clay	flat, slowly-permeable soils
Permanence	temporary (2-5 yr)	semi-permanent land shaping
Made by	mole plough (bullet + expander)	grading / ridging

PREVIOUS YEAR QUESTIONS

- Discuss mole drainage. [IFoS 2022| P1/6(c) | 10M]
- Discuss about the pipe drain and pipeless drains (mole) used in subsurface drainage systems. [IFoS 2020| P1/6(b) | 10M]
- Discuss the concept of a mole drainage system and the suitable soil conditions for making mole drains. [OPSC·CSE (Main) 2020-21 | P1/4(c)(ii) | 12M]
- Explain bio-drainage and mole-drainage with examples. [bio-drainage in §9] [OPSC·CSE (Main) 2017-18 | P1/2(c) | 15M]

Mole Drainagea

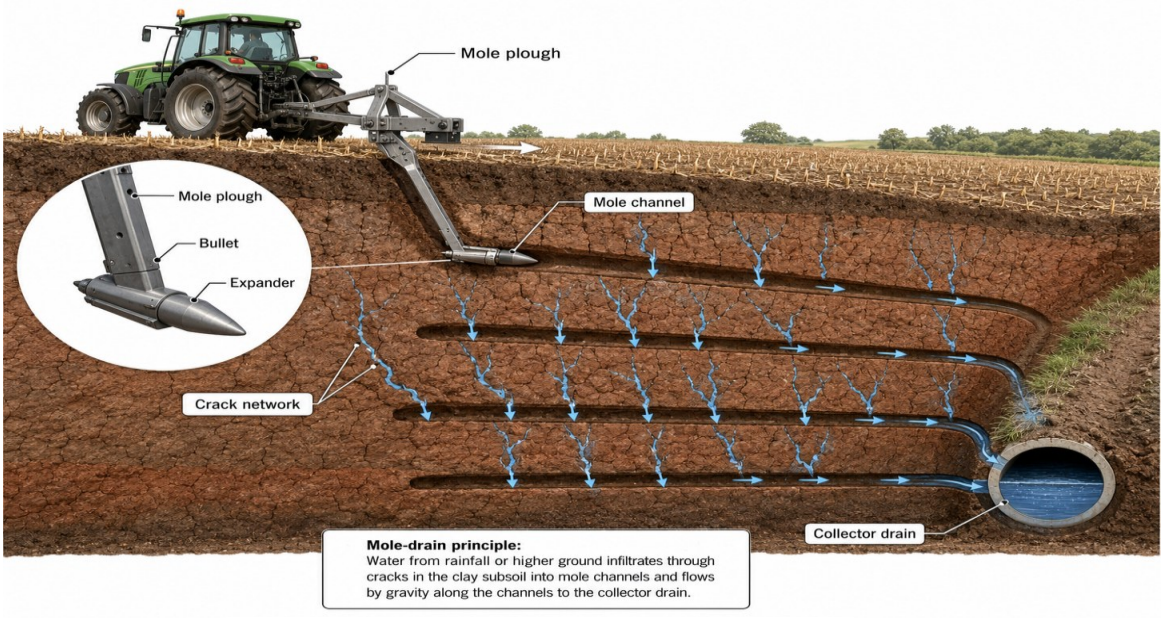


Fig. 6.8 Mole-drain formation by a mole plough in plastic clay.

◆*Source: Jha & Yellareddy, Drainage Engineering, L2, L8; Garg, Ch.6.*

9 SPECIALISED DRAINS: INTERCEPTOR, RELIEF, VERTICAL & BIO-DRAINAGE

Beyond ordinary field drains, specific situations call for specialised drains — to intercept seepage, relieve a flat-land water table, pump from below, or let plants do the draining.

Interceptor drain — a drain laid ***across the direction of flow*** (along the contour) on sloping land or beside a canal to intercept lateral seepage / through-flow before it reaches lower land.

Relief drain — a (usually parallel-grid) drain on ***flat land*** that relieves an already-high water table caused by vertical recharge, lowering it in situ.

Basis	Interceptor drain	Relief drain
Purpose	intercept incoming seepage/through-flow	relieve a high water table in place
Site	sloping land, foot of slopes, along canals	flat land with vertical recharge
Orientation	across the flow (along contour)	parallel grid over the whole area
Action	cuts off inflow from upslope	drains water recharged from above

VERTICAL DRAINAGE

Controlling a high or artesian water table by pumping from ***tube wells*** whose overlapping cones of depression lower the water table; the pumped water can be reused (conjunctive use) if of good quality.

BIO-DRAINAGE

Bio-drainage — lowering the water table by the ***transpiration of deep-rooted, fast-growing, water-loving trees*** (e.g. Eucalyptus, Prosopis, Acacia, poplar) planted in strips/blocks — a living pump.

Why it can be better than conventional drainage : no pipes, outlet or effluent-disposal problem; low cost and maintenance; uses saline shallow groundwater; and yields wood/biomass and carbon benefits. **Limits —** risk of salt build-up in the root zone over time, and species/water-availability dependence.

CHANNEL LINING (AS A DRAINAGE/ANTI-WATERLOGGING MEASURE)

Lining canals and field channels (concrete, brick, LDPE film) cuts seepage — the chief cause of canal-command waterlogging — thereby acting as a preventive drainage measure.

PREVIOUS YEAR QUESTIONS

- Differentiate between Interceptor drainage and Relief drainage. [IFoS 2021| P1/7(a)(iii) | 5M]
- Discuss the following in brief: (i) Mole drain (ii) Interceptor drain (iii) Bio-drainage (iv) Channel lining. [mole drain in §8] [IFoS 2016| P1/7(c) | 10M]
- What is bio-drainage? How is it better than conventional drainage methods? [OPSC·CSE (Main) 2023-24 | P1/12(a) | 20M]
- Explain the concept of Bio-drainage. [OPSC·CSE (Main) 2018-19 | P1/1(c) | 8M]
- Define vertical drainage, mole drain, bio-drainage and interceptor drain. [OPSC·CSE (Main) 2016-17 | P1/4(d) | 15M]

Specialised Drains

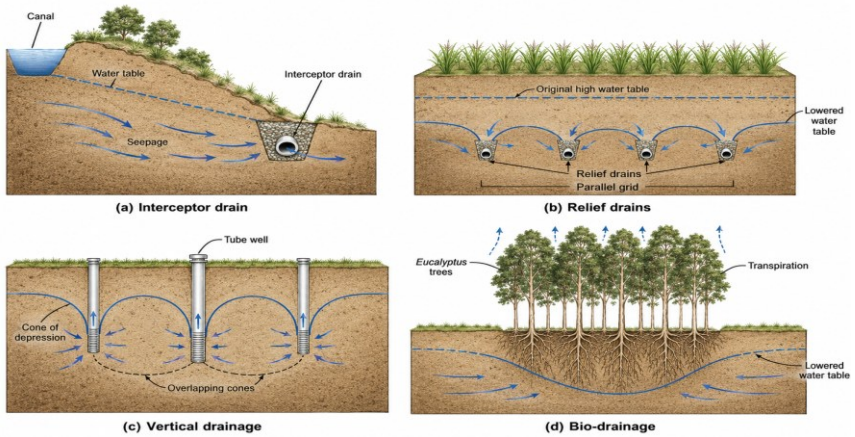


Fig. 6.9Interceptor, relief, vertical and bio-

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10 SANITARY DRAINAGE & SEWAGE HANDLING

On agricultural and homestead premises, foul (waste) water must be handled separately from land/storm drainage to protect health and water quality.

Sanitary drainage : the system that collects and safely disposes of ***foul / waste water*** (from dwellings, cattle sheds, dairies) — as distinct from land drainage, which removes excess rain and groundwater.

TYPES OF DRAINAGE (COLLECTION) SYSTEMS

Separate system — sewage and storm/land water in separate pipes. **Combined system —** both carried in one conduit. **Partially-separate —** some storm water admitted to the sewers, the rest kept separate.

Basis	Sewage	Drainage (land / storm)
Content	foul domestic/animal waste water	excess rain, irrigation & groundwater
Quality	polluted, pathogen-laden	relatively clean
Treatment	must be treated before disposal	usually disposed untreated
Conduit	sanitary sewers (closed)	open/field/storm drains

IMPROVING DRAINAGE SYSTEMS

Provide adequate slope and self-cleansing velocity; keep sewage and storm water separate; add silt traps, manholes and screens; treat sewage (septic tank / soak pit / stabilisation pond on farms) before reuse or disposal; and maintain regularly to prevent clogging and overflow.

PREVIOUS YEAR QUESTIONS

What is a sanitary drainage system? What are the different types of drainage systems? What is the difference between sewage and drainage? How can drainage systems be improved?

[IFOS 2020| P1/8(b) | 10M]

11 SOIL SALINITY & SALT-AFFECTED SOILS

Where drainage fails, salts accumulate and the soil turns ***salt-affected*** — saline, sodic (alkali) or saline-sodic — each with distinct chemistry and cure.

Property	Saline	Sodic (alkali)	Saline-sodic
EC_e (dS/m)	> 4	< 4	> 4
ESP	< 15	> 15	> 15
pH	< 8.5	8.5 - 10	≤ 8.5
Structure	flocculated, good	dispersed, poor (black alkali)	good until leached, then poor
Chief salts	Cl^-, SO_4^{2-} of Na/Ca/Mg	Na_2CO_3, $NaHCO_3$	mixed

SALINITY & SODICITY INDICES — ESP, ESR, SAR

ESP, ESR & SAR — **ESP** = exchangeable-sodium percentage = 100·(exch. Na)/CEC; **ESR** = exchangeable-sodium ratio = (exch. Na)/(CEC − exch. Na); **SAR** = sodium-adsorption ratio of the soil solution.

$$SAR = Na^+ / \sqrt{[(Ca^{2+} + Mg^{2+})/2]} \qquad ESP = 100\cdot(\text{exch. Na})/CEC \qquad ESR = (\text{exch. Na})/(CEC - \text{exch. Na})$$

ionic concentrations in meq/L; CEC = cation-exchange capacity (meq/100 g). ESP > 15 (or SAR > 13) ⇒ sodic soil.

RELATIONSHIP BETWEEN ESP AND SAR (DERIVATION — IFOS 2017)

From the definitions, $ESR = (\text{exch. Na})/(CEC - \text{exch. Na})$, so exch. Na/CEC = ESR/(1+ESR) and hence $ESP = 100\cdot ESR/(1 + ESR)$. The US Salinity Laboratory found ESR linearly related to the soil-solution SAR: $ESR = -0.0126 + 0.01475\cdot SAR$. Substituting gives the working relationship:

$$ESP = 100\,(-0.0126 + 0.01475 \cdot SAR) \,/\, [1 + (-0.0126 + 0.01475 \cdot SAR)]$$

Links the exchange-complex sodicity (ESP) to the easily-measured soil-solution SAR; both flag sodic soils.

SIGNIFICANCE

SAR (of irrigation water or soil solution) predicts the sodium hazard; ESP measures how much of the exchange complex is already sodium-saturated. High ESP disperses clay, destroys structure and permeability — the reason sodic soils need a chemical amendment, not just leaching.

SEAWATER INTRUSION IN COASTAL AQUIFERS (GHYBEN-HERZBERG)

Over-pumping near the coast lets denser seawater advance inland under the fresh groundwater; the fresh-salt interface follows the ***Ghyben–Herzberg*** relation.

$$h_s = \rho_f / (\rho_s - \rho_f) \cdot h_f \approx 40 \cdot h_f$$

h_s = depth of the fresh-salt interface below sea level (m); h_f = height of the fresh water table above sea level (m); ρ_f, ρ_s = fresh & salt water densities. Control: cut coastal draft, recharge/injection barrier, subsurface dyke, seal saline horizons.

PREVIOUS YEAR QUESTIONS

- Discuss the characteristics of saline, sodic and saline-sodic soils. Explain the principles and approaches of saline-soil management. [management in §12] [IFOS 2025| P1/7(b) | 15M]
- Differentiate between ESP and SAR. Derive the relationship between these two indices. What are salt-affected soils? Explain different reclamation measures to manage salt-affected soils. [reclamation in §12] [IFOS 2017| P1/7(a) | 10M]
- Explain the process of sea-water intrusion with a neat sketch and give the equation connected to it. Also discuss the methods for controlling sea-water intrusion. [OPSC·CSE (Main) 2018-19 | P1/8(c) | 10M]
- What is meant by saline and alkaline soils? How to deal with the salinity and alkalinity problem of soil? [reclamation in §12] [OPSC·CSE (Main) 2015-16 | P1/7(b) | 10M]
- Explain the causes and characteristics of formation of alkaline and saline soils. Describe various methods for reclamation of these problem soils. [reclamation in §12]

[UK·PSC RFO (Main) 2012 | P1(iv) | 10M]

SALT-AFFECTED SOILS & SEAWATER INTRUSION

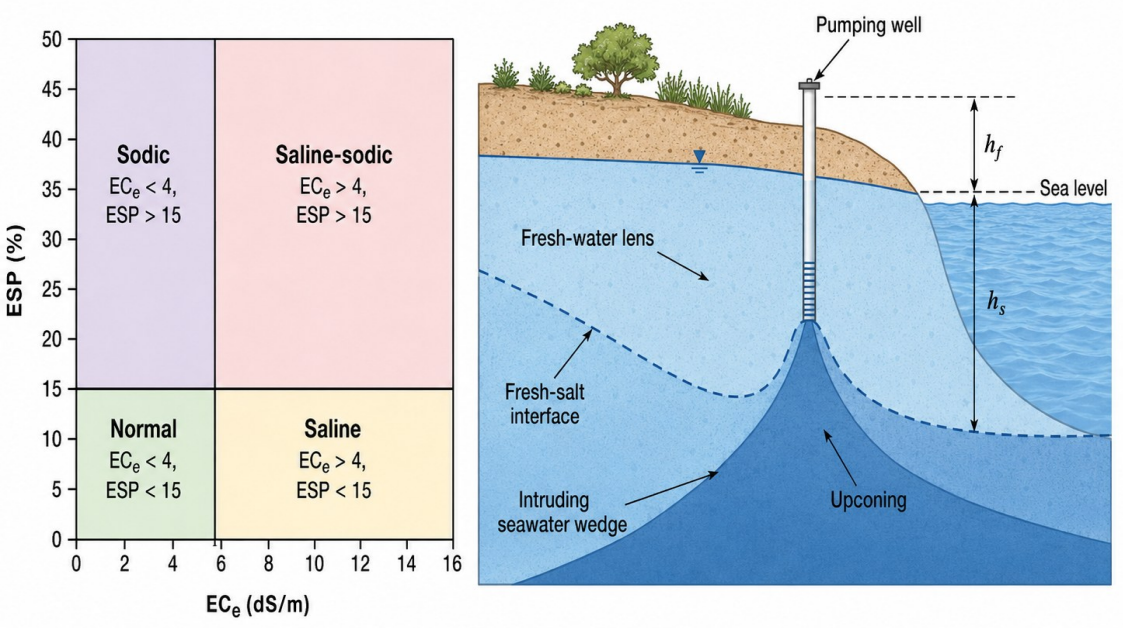


Fig. 6.10 Classification of salt-affected soils (left) and Ghyben-Herzberg seawater intrusion (right).

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12 RECLAMATION OF SALT-AFFECTED SOILS & LEACHING REQUIREMENT

Reclamation removes excess salts (saline soils) or replaces exchangeable sodium and then removes it (sodic soils) — always underpinned by ***drainage*** and quantified by the ***leaching requirement***.

RECLAMATION BY SOIL TYPE

Saline soils : salts are soluble, so provide drainage and ***leach*** them below the root zone with good-quality water; no amendment needed. Surface crusts may be scraped/flushed first.

Sodic (alkali) soils : apply a ***chemical amendment*** (gypsum $CaSO_4 \cdot 2H_2O$ — commonest; also elemental sulphur, pyrite or H_2SO_4) so Ca replaces exchangeable Na, then leach out the displaced sodium through drainage; assist with organic matter and salt-tolerant reclamation crops (e.g. dhaincha).

Saline-sodic soils : apply gypsum first, then leach — ***never leach before amending***, or the clay disperses and permeability collapses.

PRINCIPLES OF SALINE-SOIL MANAGEMENT (IFOS 2025)

Maintain permanent surface & subsurface drainage; irrigate with good-quality water and a leaching fraction; keep the water table deep; grow salt-tolerant crops; add organic matter; avoid over-irrigation; and monitor EC/ESP.

GYPSUM REQUIREMENT

$GR\ (meq/100\ g) = (ESP_i - ESP_f)/100 \times CEC$ $\quad$ $Gypsum\ (t/ha) = exch.\ Na\ to\ replace\ (eq/ha) \times 86 / purity$

ESP_i, ESP_f = initial & target ESP; CEC (meq/100 g); 86 = equivalent weight of gypsum (g/eq); soil mass of 15-cm furrow slice ≈ 2.1×10^6 kg/ha at BD 1.4.

◆ **WORKED NUMERICAL — *Gypsum requirement of a sodic soil (illustrative)*** [reclamation numerical — cf. IFoS 2022/2017]

Problem. *A sodic soil is to be reclaimed by lowering ESP from 30 to 10. CEC = 20 meq/100 g, bulk density 1.4 g/cm³, reclamation depth 15 cm. If gypsum is 80% pure, find the gypsum requirement (t/ha).*

Given. ESP_i = 30, ESP_f = 10; CEC = 20 meq/100 g; BD = 1.4 g/cm³; depth 15 cm; purity 80%.

Na to replace. = (30 − 10)/100 × 20 = 4 meq/100 g

Soil mass (1 ha, 15 cm). = 10^8 cm² × 15 cm × 1.4 = 2.1×10^9 g = 2.1×10^6 kg (2100 t)

Na (eq/ha). = 4 meq/100 g = 0.04×10^{-3} eq/g × 2.1×10^9 g = 8.4×10^4 eq

Gypsum. = $8.4\times10^4 \times 86 = 7.22\times10^6$ g = 7.22 t (pure); at 80% purity = 7.22/0.8

Result. Gypsum requirement ≈ 7.2 t/ha (pure) ≈ 9.0 t/ha at 80% purity.

LEACHING REQUIREMENT (IFOS 2021)

Leaching requirement (LR) **—** the fraction of the irrigation water that must pass through and drain below the root zone to keep root-zone salinity within the crop's tolerance; it fixes the extra ***leaching flux the subsurface drainage must carry***.

$LR = D_{dw} / D_{iw} = EC_{iw} / EC_{dw}$ (with $EC_{dw} \approx 2 \cdot EC_e$ for the tolerable soil) $D_{iw} = CU/(1 - LR)$

D_{dw}, D_{iw} = depth of drainage & irrigation water; EC_{iw}, EC_{dw} = EC of irrigation & drainage water; EC_e = tolerable saturation-extract EC; CU = consumptive use.

◆ **WORKED NUMERICAL — *Leaching requirement for cotton*** [IFoS 2021 · P1/7(c)(ii) · 10M]

Problem. *Estimate the leaching requirement when the EC of the saturation extract of the soil is 11 mmho/cm at 25% reduction in the yield of cotton. The EC of the irrigation water is 1.4 mmho/cm.*

Given. Tolerable EC_e = 11 mmho/cm (cotton, 25% yield reduction); EC_{iw} = 1.4 mmho/cm. Take the drainage-water EC as $EC_{dw} = 2 \cdot EC_e$.

Formula. $LR = EC_{iw} / EC_{dw} = EC_{iw} / (2 \cdot EC_e)$

Substitution. LR = 1.4 /(2 × 11) = 1.4 / 22 = 0.0636

Result. Leaching requirement ≈ 6.4% (0.064). [If EC_dw is taken equal to EC_e, LR = 1.4/11 = 12.7%.]

PREVIOUS YEAR QUESTIONS

- How will you reclaim and manage saline soils? Explain. [IFOS 2023| P1/7(c)(ii) | 10M]
- Describe in brief the reclamation of salt-affected soils. [IFOS 2022| P1/7(b) | 15M]
- Define leaching requirement. How is the leaching requirement estimated for the design of subsurface drainage? [IFOS 2021| P1/7(c)(i) | 5M]
- Explain the technology for reclamation of saline and alkali soils.[OPSC·CSE (Main) 2019-20 | P1/8(a) | 20M]
- Explain the soil-reclamation methods for different types of problem soils.
  [OPSC·CSE (Main) 2022-23 | P1/11(b) | 0M]

Reclamation & Leaching

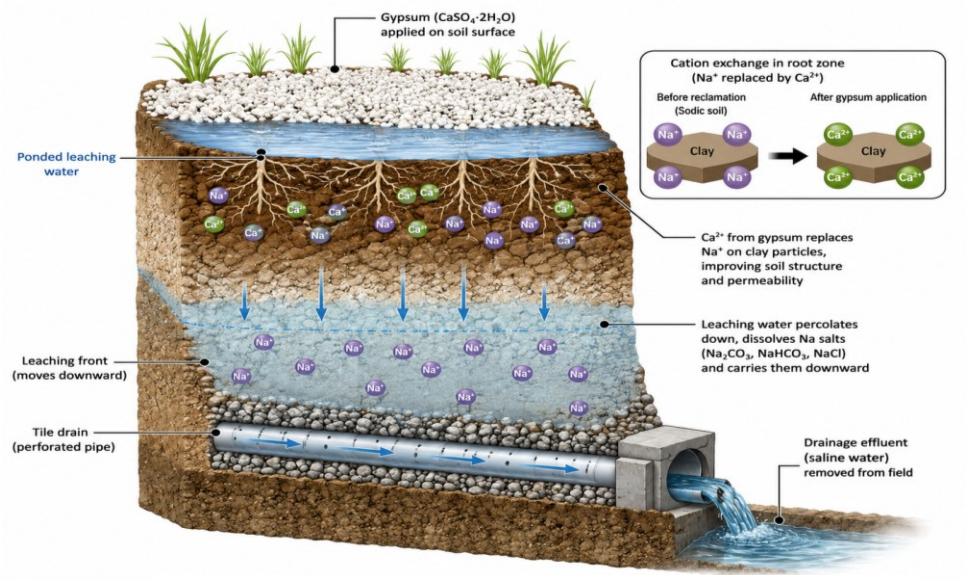


Fig. 6.11Amend (gypsum) → leach → drain: the reclamation sequence for sodic soil.

Formula Sheet — Chapter 6

Quantity	Formula
Void ratio & porosity	$e = n/(1-n)$; $n = e/(1+e)$
Drainable porosity	$\mu = n - \theta r$; $V_{drain} = \mu \cdot A \cdot D$
Drainage coefficient	$DC = Q \cdot 86400/A$; 1 mm/day = 0.116 L/s/ha
DC (water balance)	remove = inflow + $(P-f) \cdot A$ − pond·A
Manning flow	$V = (1/n) \cdot R^{(2/3)} \cdot S^{(1/2)}$; $Q = A \cdot V$
Trapezoidal section	$A = (b+z \cdot y) \cdot y$; $P = b + 2y\sqrt{(1+z^2)}$
Hooghoudt (steady)	$S^2 = (8Kdh + 4Kh^2)/q$
Drains on barrier	$S^2 = 4Kh^2/q$ ($S = 2h\sqrt{(K/q)}$)
Glover-Dumm (unsteady)	$h_t/h_o = 1.16\, e^{(-\alpha t)}$, $\alpha = \pi^2 Kd/(\mu S^2)$
Pipe size (full)	$Q = (1/n)(\pi D^2/4)(D/4)^{(2/3)} S^{(1/2)}$
Sodium-adsorption ratio	$SAR = Na/\sqrt{[(Ca+Mg)/2]}$
ESP / ESR	$ESP = 100 \cdot ExNa/CEC$; $ESR = ExNa/(CEC - ExNa)$
ESP-SAR	$ESP = 100 \cdot ESR/(1+ESR)$; $ESR = -0.0126 + 0.01475 \cdot SAR$

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Gypsum requirement	GR (meq/100g) = (ESP_i−ESP_f)/100·CEC
Leaching requirement	LR = EC_iw/EC_dw = EC_iw/(2·EC_e)
Ghyben-Herzberg	hs = ρf/(ρs−ρf)·hf ≈ 40·hf

SUMMARY

- Drainage = removal of excess surface & subsurface water including salts (ICID); the reverse of irrigation, preventive and curative.
- Waterlogging (WT within ~2 m) plus capillary salt build-up is the twin evil drainage fights; canal-command seepage is the chief cause.
- Drainage coefficient = depth removed in 24 h (1 mm/day = 0.116 L/s/ha); water-balance form nets inflow + rain excess − ponding.
- Drainable porosity μ = n − θr (2-10%); void ratio e = n/(1−n); drainable volume = μ·A·D.
- Surface drainage: land grading + open drains (random, bedding, parallel, cross-slope); size by Manning, keep V below permissible.
- Subsurface drainage: tile/pipe/mole; singular vs composite; open vs pipe; needs K, μ, barrier depth, WT, recharge, outlet data.
- Tile spacing by Hooghoudt $S^2 = (8Kdh + 4Kh^2)/q$ (equivalent depth d); drains on barrier ⇒ $S^2 = 4Kh^2/q$; unsteady by Glover-Dumm.
- Pipe sized by Manning full-flow for its share of DC; supplemental structures (outlets, manholes/silt traps, breathers) give long life.
- Mole drains: unlined channels in plastic clay (2-5 yr). Specialised: interceptor (cut seepage), relief (flat-land WT), vertical, bio-drainage.
- Salt-affected soils: saline (EC>4, ESP<15, pH<8.5), sodic (EC<4, ESP>15, pH>8.5), saline-sodic; SAR & ESP flag sodicity (ESP = 100 ESR/(1+ Biogas holder → moisture trap → H_2S filter → flame arrestor → gas valve → venturi mixer at air intake → diesel engine. Separately show pilot-diesel tank/pump/injector. Link governor to gas valve and pilot rack; engine drives alternator.
- ESR)).
- Reclaim saline by leaching + drainage; sodic by gypsum then leaching (never leach first); leaching requirement LR = EC_iw/EC_dw.
- Seawater intrusion follows Ghyben-Herzberg (hs ≈ 40 hf); control by cutting coastal draft, recharge/injection barriers and dykes.

LAST-NIGHT REVISION

Must-remember	Value / formula
Drainage (ICID)	remove excess surface + subsurface water incl. salts
Waterlogged land	WT < 2 m (2-3 potential · > 3 safe)
Drainage coefficient	depth removed/day; 1 mm/day = 0.116 L/s/ha
Drainable porosity	μ = n − θr (2-10%)
Void ratio	e = n/(1−n)
Hooghoudt	$S^2 = (8Kdh+4Kh^2)/q$; on barrier $S^2 = 4Kh^2/q$
Manning	$V = (1/n)R^{(2/3)}\sqrt{S}$
Mole drain	plastic clay · 2-5 yr · mole plough
Interceptor vs relief	across-slope seepage cut vs flat-land WT relief
Bio-drainage	Eucalyptus transpiration; no effluent
Saline / sodic	EC>4,ESP<15,pH<8.5 / EC<4,ESP>15,pH>8.5
SAR	Na/√[(Ca+Mg)/2]; sodic if ESP>15
Sodic reclamation	gypsum THEN leach (never leach first)
Leaching requirement	LR = EC_iw/EC_dw
Ghyben-Herzberg	hs ≈ 40 hf

CHAPTER

7

FARMSTEAD, STORAGE STRUCTURES & BUILDING MATERIALS

Farmstead planning · Water supply, sewage & farm roads · Dairy & poultry housing · Fencing · Stone, brick, lime, cement, concrete & timber · Soil mechanics & foundations · Grain storage · Silos & grain pressure

SYLLABUS (Paper I | Soil & Water Conservation): Farmstead planning — site selection, layout, factors influencing arrangement, facilities for a good farm house; rural water-supply distribution; sewage and on-farm waste handling; septic-tank function; farm roadway design. Animal shelters — dairy barns (stanchion/stall/loose-housing), cattle sheds, manger and stanchion details; brooder houses; deep-litter and other poultry housing systems; environmental control of animal shelters. Storage structures for grains and feeds — traditional vs improved bins, PUSA storage bin, deep vs shallow bins, bag vs bulk storage, hermetic storage, CAP storage; design considerations and control of storage losses and humidity. Silos and silage storage — classification, pit silos, metallic vs concrete silos, components; silo design (load on bottom, economical diameter/depth). Farm fencing — methods of construction and materials; barbed-wire/electric/woven-mesh fencing; fence-cost estimation. Building materials — cement, concrete (slump test), bricks, stone, tiles, timber (seasoning), Surkhi, lime, mortar, aggregate, RCC. Soil mechanics & foundations — bearing capacity, foundation types, soil shear strength, angle of internal friction, consolidation; structural design considerations for farm buildings.

Chapter Outline

1. **Farmstead Planning & Site Selection**
2. **Farmstead Services: Water Supply, Sewage & Farm Roadways**
3. **Animal Shelters I — Dairy Barns**
4. **Animal Shelters II — Poultry Housing & Environmental Control**
5. **Farm Fencing**
6. **Building Materials I — Stones, Bricks & Tiles**
7. **Building Materials II — Lime, Cement, Surkhi & Mortars**
8. **Building Materials III — Concrete & RCC**
9. **Building Materials IV — Timber**
10. **Soil Mechanics for Farm Structures**
11. **Foundations**
12. **Grain & Feed Storage Structures**
13. **Silos, Silage & Grain Pressure Theory**

Chapter 8 Concept Map

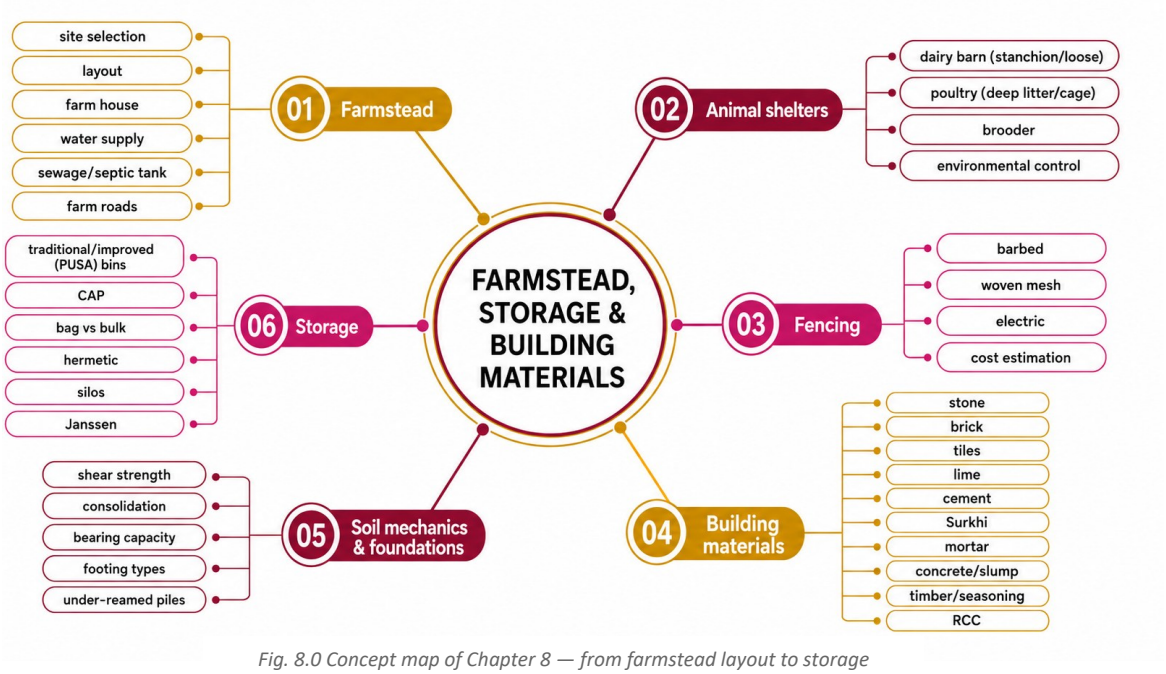


Fig. 8.0 Concept map of Chapter 8 — from farmstead layout to storage

1 FARMSTEAD PLANNING & SITE SELECTION

The farmstead is the ***headquarters of the farm*** — the group of buildings from which the whole enterprise is run. Its siting and arrangement fix labour efficiency, sanitation and cost for the life of the farm.

> ***Farmstead*** **–** the ***building group of a farm*** — farm residence, cattle/dairy barn, poultry and machinery sheds, storage structures, threshing yard and connecting roads — together with the land they occupy, normally ***3–5% of the total farm area***.

FACTORS GOVERNING THE LOCATION OF THE FARMSTEAD (IFOS 2017, 2024)

Centrality : at or near the centre of the farm (or mid-way along a long side) to minimise travel to the fields.

Accessibility : close to a public road/corner for movement of produce and supplies, and for social contact.

Elevation & drainage : on high ground with good natural surface drainage, so surface water flows away from buildings.

Water supply : near a dependable, wholesome source.

Shelter & orientation : protected by trees/windbreaks; buildings oriented for sun and prevailing wind.

Soil & topography : firm bearing soil, gentle slope; and room for future expansion.

FACTORS GOVERNING THE ARRANGEMENT OF BUILDINGS (IFOS 2018)

Place the ***residence up-wind and away from cattle sheds*** (privacy, flies, odour); group buildings by function to shorten daily journeys; put feed and fodder stores, silo pits and manure pits next to the animal sheds; keep the milk house near the barn but separated by a paved passage (~6 m); provide clean, paved approaches and a service road; separate clean and dirty routes; and leave space for extension. Objectives throughout: ***sanitation and well-being, economy of labour, and low initial & maintenance cost***.

FACILITIES OF A GOOD FARM HOUSE (IFOS 2024)

Bedrooms (3.6 × 3.0 m), drawing/living room (4.5 × 3.6 m), a well-ventilated kitchen (9-14 m^2) with chimney and store, verandah, bath and latrine, grain and fuel store, space for a biogas plant and slurry pit, cattle shelter with fodder store, and a kitchen garden. Orient for sunlight and cross-ventilation; use cheap local materials; keep the plan simple and extendable.

◆ **WORKED NUMERICAL — *Farm house for a four-member family — floor plan*** [OPSC·Forest 2019-20 · Q.7(a) / OPSC·CSE 2016-17 · Q.8(d) · 20M/10M]

Problem. *What is farmstead? What factors govern the location of the farmstead on the farm? Design a farm house for the owner having a family of 4 members. Draw the floor plan and give reasons for the same.*

Requirement. 4 members ⇒ 2 bedrooms, living room, kitchen + store, bath & WC, verandah, plus farm-related store.

Room sizing. 2 bedrooms @ 3.6×3.0 = 10.8 m² each = 21.6 m²; living 4.5×3.6 = 16.2 m²; kitchen 3.0×3.0 = 9.0 m² + store 2.0×1.5 = 3.0 m²; bath 1.8×1.2 = 2.16 m²; WC 1.2×1.2 = 1.44 m²; verandah 6.0×2.0 = 12.0 m².

Carpet area. 21.6 + 16.2 + 9.0 + 3.0 + 2.16 + 1.44 + 12.0 = 65.4 m²

Plinth area. adding ~30% for walls and circulation ⇒ ≈ 85 m² (say 11.0 m × 8.0 m plot coverage).

Result. A ≈ 85 m² farm house: living room central, bedrooms on the quieter side, kitchen with cross-ventilation and rear access to the store/backyard, verandah on the south/east, bath-WC grouped for common plumbing, cattle shed placed down-wind and away from the house.

PREVIOUS YEAR QUESTIONS

- Discuss the importance of location selection for establishment of a farmstead. What are the facilities to be kept in mind while designing a good farm house? [IFOS 2024 | P1/8(a) | 15M]
- It is very important for a farmstead to be properly arranged. List and explain in brief, the factors to be considered for best arrangement of farmstead. [IFOS 2018 | P1/6(d) | 10M]
- What is a Farmstead? What factors govern the location of the farmstead on the farm? [IFOS 2017 | P1/8(d) | 10M]
- What are the points to be considered in identifying the location of a farmstead? [OPSC·CSE (Main) 2023-24 | P1/17(a) | 20M]
- What is a Farmstead? What factors govern the location of the farmstead on the farm? [UK·PSC RFO (Mains) 2015 | Q.3(iv) | 10M]
- Describe the importance and significance of selection of a suitable site for a nuclear power plant. [Note: as printed; answer on general site-selection principles — see Model Q] [IFOS 2020 | P1/5(c) | 8M]

MODEL Q *Site* : selection answers all share a skeleton: purpose of the facility → centrality/accessibility → topography, elevation & drainage → soil bearing capacity → water & power availability → environmental and safety separation distances → prevailing wind & orientation → room for expansion → cost. Adapt the skeleton to whatever facility the question names.

Model Farmstead Layout



Fig. 8.1 Model farmstead layout — residence up-wind, animal sheds and manure pit down-wind.

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2 FARMSTEAD SERVICES: WATER SUPPLY, SEWAGE & FARM ROADWAYS

RURAL WATER SUPPLY — DEMAND & SOURCES

Design begins with demand: ***domestic*** (India ≈ ***135 L/day/capita*** — drinking 5, cooking 5, bathing 55, clothes 20, utensils 10, house washing 10, latrine flushing 30), commercial/industrial (take 20-25% of total), fire demand (National Board of Fire Underwriters formula, population in thousands), public use, and compensation for losses.

Sources : surface (streams for small villages, ***rivers*** for public schemes, lakes, ponds, impounded reservoirs) and subsurface (wells, tube wells, springs). ***Wholesome water*** = not chemically pure, but containing nothing harmful. Impurities are suspended (turbidity, colour, bacteria), dissolved (Ca/Mg salts → hardness; fluoride → mottled enamel; Fe/Mn → colour & taste; H_2S/CO_2 → odour, acidity, corrosion) and organic.

TREATMENT SUITABLE TO A RURAL COMMUNITY

Of the full train (screening, plain sedimentation, coagulation-sedimentation, filtration, disinfection, aeration, softening), the methods suited to villages are ***screening, plain sedimentation and filtration***. Coarse screens are bars at 30-60° set 2-10 cm apart, fine screens <1 cm openings, velocity ≤0.8-1 m/s. Sedimentation removes ~70% of suspended matter; filtration then removes fine matter, bacteria, colour and odour (sand of effective size D_{10}, uniformity coefficient D_{60}/D_{10}, on a gravel support).

Detention period $t = V/Q$ Surface loading $= Q/A_{plan}$ Displacement efficiency = flowing-through period / detention period

Plain sedimentation 500-750 L/h/m²; coagulation-aided 1000-1250 L/h/m²; depth 1.8-6 m (usually 3-4.5 m); width 10-12 m; L ≤ 4B; horizontal velocity 0.15-0.9 m/min (normally 0.3).

◆ **WORKED NUMERICAL — *Diameter of a circular sedimentation tank*** [design numerical (Ag. Structures L13)]

Problem. *A circular sedimentation tank with mechanical sludge removal is to handle 3.5 million litres per day of raw water. If the detention period is 5 hours and the depth of the tank is 3 m, what should be the diameter?*

Given. $Q = 3.5\times10^6$ L/day; detention t = 5 h; depth H = 3 m.

Capacity needed. $V = Q\cdot t = 3.5\times10^6 \times 5/24 = 728\times10^3$ L = 728 m³

Formula. $V = d^2(0.011\,d + 0.785\,H)$

Substitution. $d^2(0.011d + 0.785\times3) = 728$; by trial: d = 15 → 507; d = 17 → 735; d = 16.9 → 725.7

Result. Diameter d ≈ 16.9 m (adopt 17 m).

SEWAGE & ON-FARM WASTE HANDLING; THE SEPTIC TANK

Farm waste is of three kinds — human sewage, animal dung/urine and domestic sullage. Keep them ***separate from the water supply*** and from the residence. Dung goes to a ***manure/compost pit or biogas plant*** sited down-wind; sullage to a soak pit or kitchen garden; human sewage to a septic tank with soak pit.

Septic tank — function — a watertight, underground settling-cum-digestion chamber through which sewage flows slowly (detention ~24 h). Its functions are: (i) ***sedimentation*** of solids as sludge; (ii) flotation of grease as scum; (iii) ***anaerobic digestion*** of the settled sludge, reducing its volume; and (iv) discharge of the clarified effluent to a soak pit/dispersion trench for final disposal into the soil. Sludge is desludged periodically; the effluent is NOT safe for direct use. ***[Not in the supplied books — standard sanitary-engineering practice; verify against IS 2470.]***

FARM ROADWAY DESIGN

Classes : farmstead roads (heavier, denser traffic → smooth hard surface, cement concrete best) and field roads (need hardness, not smoothness → hard base + gravel/broken stone). By construction: ***flexible*** (gravel, kankar, red earth layers) or ***rigid*** (cement concrete).

Requirements : straightness, levelness, smoothness, hardness, dryness. ***Super-elevation*** counters centrifugal force on curves (WBM 1 in 48, tar macadam 1 in 60, CC 1 in 72). ***Ruling gradient*** 1 in 40 in plains, 1 in 20 in hills. ***Camber*** sheds water — earthen 1 in 20-24, WBM 1 in 30-48, bitumen 1 in 36-48, CC 1 in 60-72.

Layer (Top → Bottom)	Function
Wearing course (surface)	smooth running surface; protects base from abrasion & rain
Base course	main supporting strength; distributes load; bonds to wearing course
Foundation course (soling)	spreads load uniformly over the sub-grade
Sub-grade	compacted granular layer; keeps water out of the foundation
Sub-soil / road bed	natural ground carrying the whole structure

Other design data : formation level ≥ 30 cm above surrounding land; carriageway 2.4-3.0 m in fields (wider at the farmstead); widen on curves (1 m for 30 m radius, 2.5 m for 18 m); berm ≥ 1.2 m so total width 7.2-9.0 m; side ditches ≥1.2 m from the edge and 0.3 m below formation; culvert pipes minimum 22.5 cm diameter. Types by material: earthen, gravel, water-bound macadam (commonest in India), bitumen/tar, cement concrete.

PREVIOUS YEAR QUESTIONS

- What are the requirements of good water supply distribution system for farmstead? Briefly discuss about the different water distribution systems commonly adopted in farmstead. [IFOS 2025 | P1/7(c) | 10M]
- Discuss safe disposal of all human sewage and domestic wastes in farmstead planning, illustrating suitable layout. How is it different from homestead planning? [IFOS 2020 | P1/8(a) | 20M]
- What are the considerations to frame water supply system in rural areas? Illustrate with examples. [IFOS 2020 | P1/8(c) | 10M]
- How can you take care of drainage and sewage management? [IFOS 2022 | P1/5(e) | 8M]
- In your view, how should the design and construction of farm roadways be done? [IFOS 2022 | P1/8(c) | 10M]
- Write a short note on: Functions of Septic Tank. [IFOS 2024 | P1/7(c)(i) | 15M]

Septic Tank & Farm Road Cross-Section

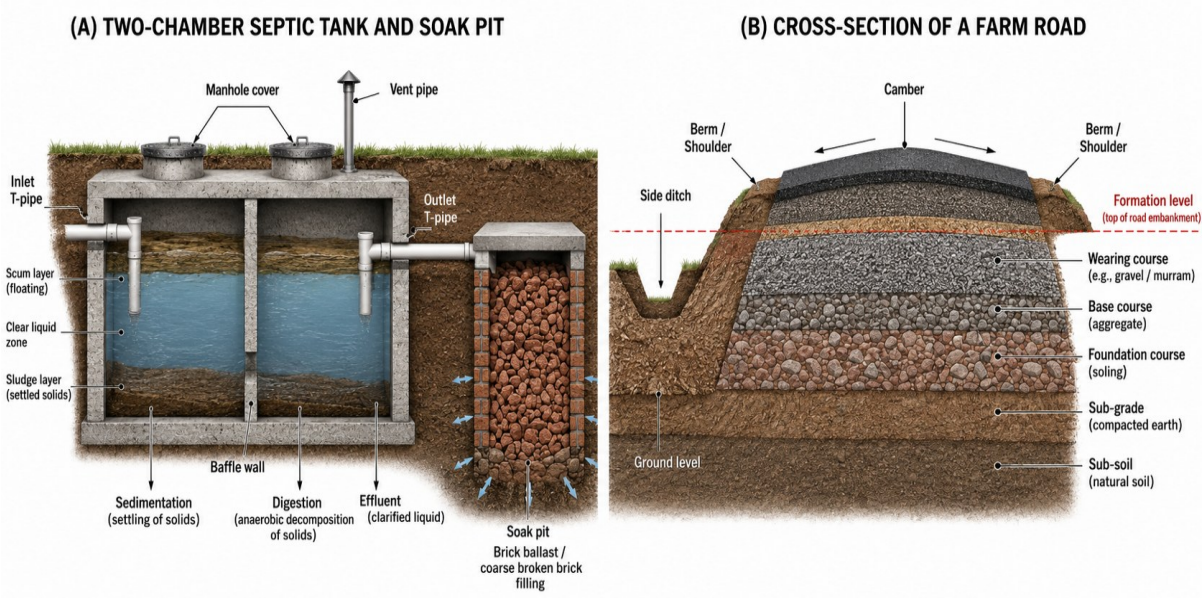


Fig. 8.2 Septic tank with soak pit (left) and farm-road layers with camber and berm (right).

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3 ANIMAL SHELTERS I — DAIRY BARNS

Housing must keep the animal near its ***comfort zone*** (15-27 °C for cattle, buffalo and goats; stress beyond ±5 °C) while making feeding, milking and cleaning efficient.

TYPES OF DAIRY BARN

Stanchion (stall) barn : cows tied in individual stalls and milked in the same building (the general-purpose barn).

Loose housing + milking parlour : cows loose in a covered/partly covered yard, milked in batches in a separate parlour.

Open-air barn : no cover; animals live, are fed and milked in the field (loafing system).

Basis	Stanchion (stall) barn	Loose housing barn
Animal movement	tied in stalls; restricted	free in yard; exercise possible
Milking	in the stall itself	in a separate milking parlour, in batches
Labour	higher (feeding/cleaning each stall)	lower; mechanised parlour
Cost	higher construction cost per animal	cheaper; simple sheds
Manure	removed daily via gutters	accumulates in bedding, cleared 1-2 times/yr
Suitability	cold climates, small herds, individual care	warm climates, larger herds (Indian recommendation)

COMPONENTS OF A STANCHION BARN

Stalls : sized by body weight (363 kg → 1.00 m wide × 1.35 m long; 454 kg → 1.10 × 1.40; 544 kg → 1.20 × 1.50; 723 kg → 1.40 × 1.70); ≤10 cows per row; rows arranged ***face-in*** (head-to-head, central feed alley) or ***face-out*** (tail-to-tail, central litter alley).

Manger : feeding trough, width 60-90 cm; low 'sweep-in' type (cheap, quick feeding) or high-front type (less wastage); a 12.5 cm ***stanchion curb*** stops feed being dragged into the stall. **Stanchion —** pipe/angle-iron frame with an adjustable oval ring (or chain) that secures the cow's neck while letting it rest and reach feed and water.

Alleys : feed alley 1.2 m between mangers; litter alley 1.8-2.4 m behind the stalls. **Gutters —** 40-45 cm wide × 15 cm deep at min ***2% slope*** to carry dung and urine to the manure pit. **Floor —** cement/lime concrete, rough (non-slip) finish, with a toe drain over the front ⅓ of the stall. **Walls & roof —** ≥2.4 m high with ***0.37 m² (4 ft²) of ventilator per cow***; roofing tiled (coolest), AC sheet (moderate) or concrete (best if affordable).

SPACE STANDARDS (BIS) & LOOSE-HOUSING AREAS

Animal	Covered (m²)	Open (m²)	Manger (cm)
Young calf (<8 wk)	1.0	2.0	40-50
Older calf (>8 wk)	2.0	4.0	40-50
Heifer	2.0	4.0-5.0	45-60
Adult cow	3.5	7.0	60-75
Adult buffalo	4.0	8.0	60-75
Bull	12.0	120.0	60-75

Loose housing : feeding shed 3.7 m²/cow; bedding area 6.4 m²/cow; exercising yard 9.2 m²/cow; calf 2.8 m²; one 300 L water tub per 15 cows. Ancillary buildings: chaff-cutter shed, feed & straw store, milking parlour, milk room, silo pits, manure pits.

◆ **WORKED NUMERICAL — *Design of a stanchion barn for 50 cows*** [OPSC·Forest 2019-20 Q.7(b) / OPSC·CSE 2016-17 Q.8(c) · 20M/10M]

Problem. *Design a stanchion barn for 50 cows. Draw the floor plan indicating various portions clearly. Make the list of building materials to be arranged for the construction.*

Arrangement. 50 cows in 2 rows of 25, face-in (head-to-head) with a central feed alley — saves floor area and eases feeding.

Stall size. for ~450 kg cows: width 1.10 m, length 1.40 m.

Length of barn. L = 25 × 1.10 = 27.5 m (plus end walls/passages)

Width of barn. central feed alley 1.2 + 2 × (manger 0.75 + stall 1.40 + gutter 0.45 + litter alley 1.80)

= 1.2 + 2 × 4.40 = 10.0 m

Result. Barn ≈ 27.5 m × 10.0 m (275 m²); wall height 2.4 m; ventilators 0.37 m²/cow; gutters at 2% slope; floor sloped 1 in 40 to the gutter.

Materials. bricks/stone for walls, cement, sand, coarse aggregate, steel for RCC, GI pipe/angle iron for stanchions and posts, AC/tiled roofing sheets with trusses, PVC pipes, whitewash/paint, and doors/windows.

PREVIOUS YEAR QUESTIONS

- With a neat drawing, explain the stanchion barn for housing of dairy animals. Mention its specific advantages. [IFOS 2025 | P1/5(e) | 8M]
- Discuss how you plan to construct a new dairy barn. Discuss various dairy barn equipments. Compare between stall barn and loose housing barn. [IFOS 2023 | P1/8(c) | 20M]
- Give a comparative analysis between Loose housing barn and Stall barn. [IFOS 2021 | P1/8(c) | 10M]
- Discuss dairy barns, their types and their components. Draw a model layout of a dairy farm for a 20 cow/buffalo unit. [IFOS 2017 | P1/8(b) | 10M]
- Name various types of dairy barns. Describe the general purpose of dairy barn. [OPSC·CSE (Main) 2015-16 | P1/7(a)(ii) | 10M]

Stanchion Barn Floor Plan (Two Rows, Face-In)

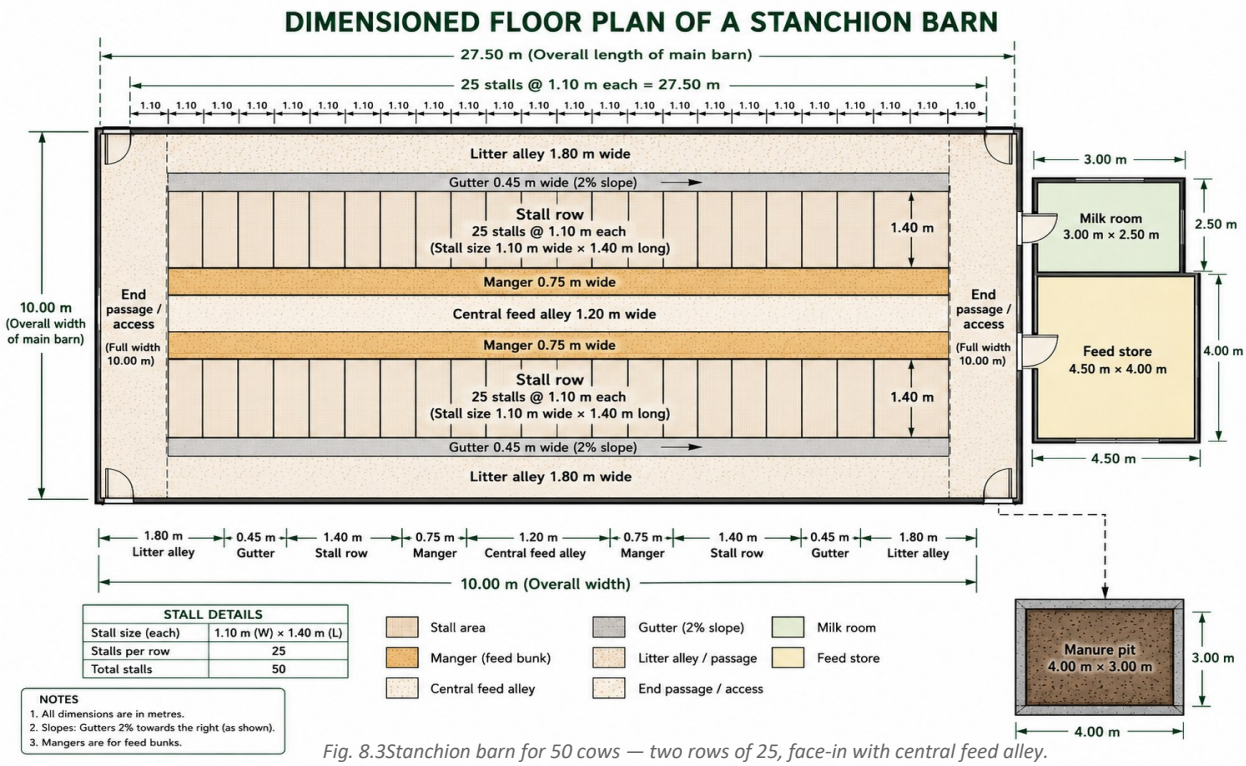


Fig. 8.3Stanchion barn for 50 cows — two rows of 25, face-in with central feed alley.

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4 ANIMAL SHELTERS II — POULTRY HOUSING & ENVIRONMENTAL CONTROL

POULTRY HOUSING SYSTEMS

System	Description	Remarks
Free range / extensive	birds range over fenced land with night shelter	large land need; low output
Semi-intensive	part housing + outdoor run	intermediate
Deep litter	birds on a 15-30 cm litter bed (paddy husk/saw dust) inside a house	commonest; litter becomes manure
Slatted / wire floor	birds on raised slatted or wire floor; droppings fall through	cleaner, higher density
Cage (battery)	birds in tiers of wire cages	highest density, best egg hygiene & feed control

Deep-litter advantages (IFOS 2025) : low initial cost; litter absorbs droppings and stays dry; built-up litter generates heat and yields vitamin B_{12} and antibiotic factors; birds exercise and behave naturally (less vice than in cages when managed); litter is a valuable manure; simple equipment. Limitations — risk of coccidiosis and worms if the litter gets damp, and lower stocking density than cages.

Brooder house (IFoS 2024) : a small, draught-proof, well-insulated house for day-old chicks with a heat source (hover/electric brooder/gas). Chicks start at ***95 °F and the temperature is dropped 5 °F per week to 70 °F***; floor space ~0.05 m²/chick initially; provide chick guard, feeders, waterers and 24-h light in week one.

FUNDAMENTAL REQUIREMENTS OF A POULTRY HOUSE

Temperature : optimum for egg production 50-55 °F (production not affected between 45-65 °F).

Humidity — keep below 85% at 32-45 °F and below 75% at higher temperature.

Ventilation : ***≈ 2/3 ft³/min per ft² of floor***; a laying hen gives 40-50 BTU/h(British Thermal Unit per hr) (25-30 sensible) and ~⅓ lb of water vapour per day, all of which must be removed without draughts.

Light : window area 6-25% of floor area with 75% along the front; artificial light to give a ***12–14 h day*** in winter (≈40 W lamp per 200 ft²).

Sanitation : smooth cleanable surfaces; cleanable feeders, waterers and nests; control condensation (occurs when the inner surface falls below the dew point).

ENVIRONMENTAL CONTROL OF ANIMAL SHELTERS

Animals are ***homeotherms*** maintaining a constant body temperature by ***homeostasis***; design aims to hold them in the thermoneutral (comfort) zone, where heat loss = heat production with least regulation. Below it: shivering, higher feed intake. Above it: vasodilation, panting, falling appetite and yield. The ***temperature–humidity index (THI)*** combines the two — THI 72-75 marks the comfort limit, 75 is critical. Control by orientation, roof insulation and reflective/tiled roofing, adequate eave height and ridge/ventilator openings, cross-ventilation and fans (air movement raises evaporative loss), shade trees, foggers/sprinklers, and adequate floor space.

◆ **WORKED NUMERICAL — *Deep-litter poultry house for 1000 birds*** [IFOS 2025 · P1/8(c) · 10M]

Problem. *What are the advantages of deep litter poultry housing? Draw a neat sketch to accommodate 1000 birds. Take floor area of 0.36 sq. m per bird.*

Given. N = 1000 birds; floor allowance a = 0.36 m²/bird.

Formula. Floor area $A = N \times a$

Substitution. $A = 1000 \times 0.36 = 360$ m²

Proportioning. for natural cross-ventilation keep the span ≤ ~10 m: width = 10 m ⇒ length = 360/10 = 36 m

Result. Deep-litter house 36 m × 10 m (360 m²); litter 15-30 cm deep; eave height ~2.5-3 m; wire-mesh side walls above a 0.6 m dwarf wall; feeders and waterers along the length.

PREVIOUS YEAR QUESTIONS

- Write in brief about different types of poultry housing systems. List out the important equipment being used in poultry system. [IFOS 2021 | P1/5(d) | 8M]
- Write a short note on: Brooder Houses. [IFOS 2024 | P1/7(c)(ii) | 15M]
- Explain the fundamental requirements of a poultry house. [OPSC·CSE (Main) 2020-21 | P1/8(b) | 12M]
- Explain the advantages of deep litter poultry houses in comparison to cage houses. [UK·PSC RFO (Mains) 2015 | Q.3(iii) | 10M]
- What is litter type poultry house? What advantage it got over cage house? [AP·PSC RFO (Mains) 2012 | Q.4(b) | 10M]
- Deep litter poultry house. [MH·PSC Forest Services (Mains) 2024 | Q.1(g) | 8M]

Deep-Litter Poultry House

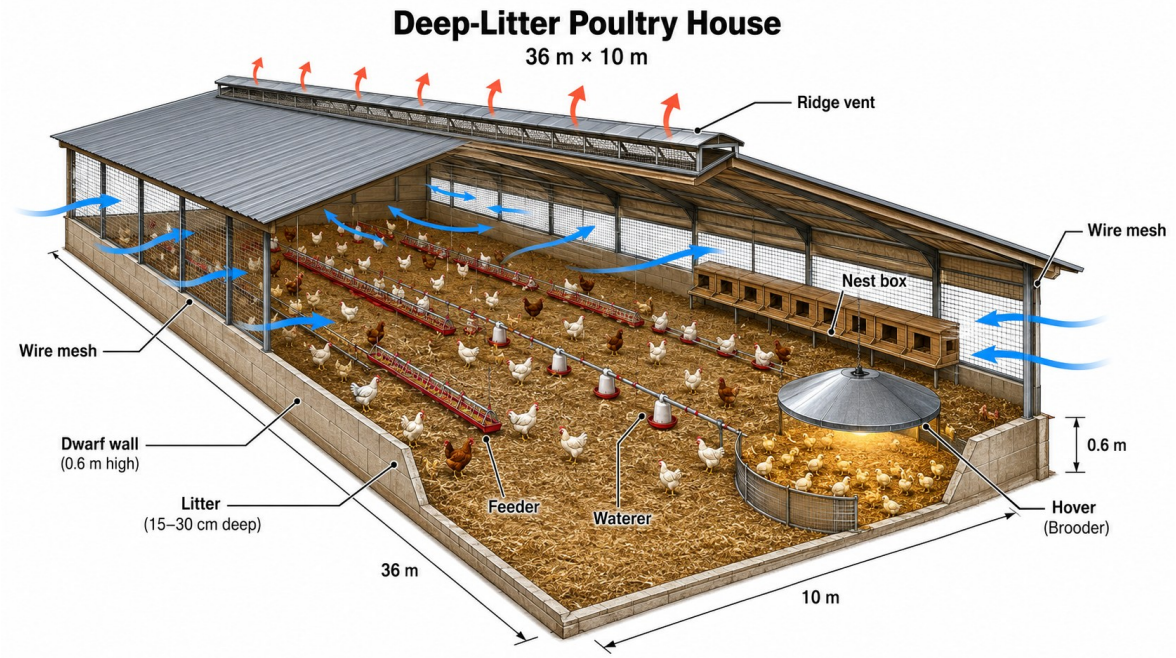


Fig. 8.4 Deep-litter house for 1000 birds (36 m × 10 m at 0.36

5 FARM FENCING

A fence marks the boundary, confines livestock and keeps out trespass and stray animals.

Basis	Types
By material	live hedge · compound wall (costly) · wire fence (economical, commonest)
Wire used	barbed (boundary, anti-trespass) · plain (cattle yards) · woven mesh (poultry & cattle sheds)
Post material	wood (cheap, short life, termite/rot) · angle iron (rusts, needs paint) · cement concrete (best — durable, farm-made)
By principle	physical barrier (barbed/mesh) · psychological barrier (electric fence)

Construction data : concrete posts 1.8-2.1 m long, 12.5 cm square (or tapered to 7.5 cm at top), mix **4:2:1**, cured 2-3 weeks and used after ~3 months; spacing **2.4-3.0 m**; set 0.5-0.6 m deep in 1:2.5:5 concrete; heavier corner/straining posts with struts; bottom wires spaced closer than the top ones.

WOVEN-MESH FENCE (IFOS 2024)

A factory-woven rectangular mesh of galvanised wire stretched between posts, with graduated spacing (closer near the ground). It confines small stock and poultry, resists pressure without injuring animals, and is used for

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poultry runs and cattle sheds; costlier than plain barbed wire but longer-lasting and safer.

ELECTRIC FENCING — PRINCIPLE (IFOS 2021, 2025)

A single (or few) smooth wire(s) on insulated posts is charged by an ***energiser*** that delivers short, high-voltage, very low-energy ***pulses*** (about one per second). When an animal touches the wire it completes the circuit to earth through its body and receives a sharp but harmless shock; after one or two experiences it keeps away. It is therefore a ***psychological, not a physical, barrier*** — cheap, quickly erected and easily moved for rotational grazing, but it needs a good earth, regular vegetation clearance under the wire and a reliable power source.

◆ **WORKED NUMERICAL — *Cost of fencing a square 25-hectare farm*** [IFOS 2019 · P1/6(d) · 10M]

Problem. *Calculate the cost of fencing a square farm of 25 ha fenced by barbed wire using cement concrete posts. Posts ₹335 per post; corner posts ₹500 per post; barbed wire ₹1,000 per 100 m; earthwork ₹50 per pit; cement concrete ₹100 per pit; labour charges for fixing wire ₹3,000; cost of gate ₹15,000. Assume 1.80 m high posts spaced 3 m apart with 6 lines of barbed wire.*

Given. A = 25 ha = 2,50,000 m², square; post spacing 3 m; 6 lines of barbed wire.

Geometry. side $= \sqrt{2{,}50{,}000} = 500$ m; perimeter $= 4 \times 500 = 2000$ m

Posts. number = 2000/3 = 666.7 ⇒ 667 posts, of which 4 are corner posts ⇒ 663 ordinary

Wire. length = 6 × 2000 = 12,000 m

Costing. posts 663 × 335 = ₹2,22,105 ; corner 4 × 500 = ₹2,000 ; wire (12,000/100) × 1000 = ₹1,20,000
earthwork 667 × 50 = ₹33,350 ; concrete 667 × 100 = ₹66,700 ; labour ₹3,000 ; gate ₹15,000

Result. Total cost = 2,22,105 + 2,000 + 1,20,000 + 33,350 + 66,700 + 3,000 + 15,000 = ₹4,62,155 (≈ ₹4.62 lakh).

PREVIOUS YEAR QUESTIONS

- A rectangular farm of 10 ha (500 m × 200 m) is to be fenced by barbed wires with concrete poles. Estimate the cost of fencing with six rows of barbed wires. Assume suitable values for spacing of posts and appropriate prices for posts and wires. [IFOS 2016 | P1/8(c) | 16M]
- What are different types of farm fencing based on method of construction and material used? Briefly describe the principle used for electric fencing of farm. [IFOS 2021 | P1/5(e) | 8M]
- Write a short note on: Electric farm fencing. [IFOS 2025 | P1/8(a)(i) | 15M]
- Write in brief about: Woven Mesh type of farm fence. [IFOS 2024 | P1/5(e)(i) | 8M]
- Calculate the cost of fencing a square farm of 25 hectares fenced by barbed wire using cement concrete posts. Make necessary assumptions. [OPSC·Forest (Main) 2023-24 | P1/8(b) | 20M]

MODEL Q Fence-cost problems: perimeter from the area/shape → number of posts = perimeter ÷ spacing (separate the 4 corner posts) → wire length = perimeter × number of rows → build the cost table (posts, corner posts, wire, earthwork per pit, concrete per pit, labour, gate) → total. State every assumed rate.***

Farm Fencing Types

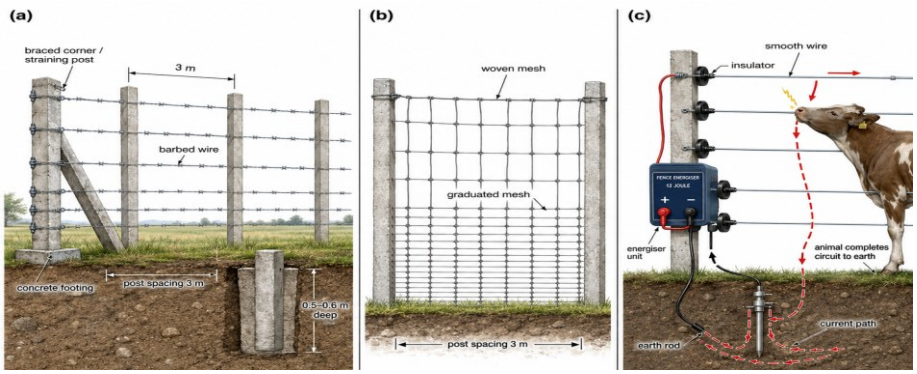


Fig. 8.5Barbed-wire, woven-mesh and electric farm fencing.

6 BUILDING MATERIALS I — STONES, BRICKS & TILES

STONES

Classification : ***geological***: igneous (granite, basalt, trap), sedimentary (sandstone, limestone, laterite), metamorphic (marble, slate, quartzite); ***physical***: stratified, unstratified, foliated; ***chemical***: siliceous, argillaceous, calcareous.

Requirements of a good building stone : high crushing strength (>100 N/mm² for heavy work), low water absorption (<5%), hardness and toughness, durability and weather resistance, fine compact grain, good appearance, and freedom from cracks/cavities. **Tests (IS) —** crushing strength (IS 1121), water absorption & porosity (IS 1124), attrition (Deval) for road stone, impact/toughness (IS 5218), hardness (Dorry), acid test for weathering, crystallisation and smith's test.

Quarrying & dressing : quarrying by digging, wedging, heating or blasting; dressing to hammer-dressed, rough-tooled, punched, chisel-drafted or polished finish depending on the work.

BRICKS — MANUFACTURE IN INDIA (IFOS 2023)

1. **Preparation of clay :** ***unsoiling*** (remove 20-30 cm topsoil), digging, ***weathering*** (expose to atmosphere to disintegrate), blending (add sand/ash and mix), and ***tempering*** (knead with water to a plastic, homogeneous mass — by pug mill for large works).
2. **Moulding :** hand moulding (ground-moulded or table-moulded, with a frog to key the mortar) or machine moulding (plastic — extrusion & wire cut; or dry-press).
3. **Drying :** green bricks are dried in shade on raised hacks for 7-14 days to about 2% moisture, to avoid cracking during burning.
4. **Burning :** the vital stage; vitrification gives strength. In ***clamps*** (temporary, cheap, uneven quality, ~20-25% good bricks) or in ***kilns*** — intermittent (up/down draught) and continuous (Bull's trench, Hoffman's, tunnel), which give uniform, better-quality bricks with fuel economy. Burning temperature ~900-1100 °C: under-burnt bricks are weak and porous, over-burnt (jhama) are distorted.

CLASSIFICATION OF BRICKS (IFOS 2023)

Class	Characteristics	Use
First class	table-moulded, kiln-burnt; sharp edges, uniform deep red; no cracks; absorption <20%; strength ≥10.5 N/mm²; rings when struck	face work, load-bearing walls, permanent work
Second class	ground-moulded, kiln-burnt; slight irregularity; absorption <22%; strength ≥7 N/mm²	walls with plaster, ordinary work
Third class	ground-moulded, clamp-burnt; soft, under-burnt, light coloured; absorption >25%; strength ≥3.5 N/mm²	temporary work in dry areas
Over-burnt (jhama)	over-fired, distorted, brittle, very hard	broken as aggregate / lime concrete, road metal

Tests (IS 3495) : compressive strength, water absorption (24-h immersion; ≤20% for first class), efflorescence (nil to slight), dimensional tolerance, hardness (no scratch by fingernail) and soundness (metallic ring when two bricks are struck). **Standard modular brick :** 190 × 90 × 90 mm (nominal 200 × 100 × 100 mm with mortar).

TILES

Made from brick earth but thinner and better finished. ***Roofing tiles*** — Mangalore, Allahabad, country/pan, corrugated; ***flooring & wall tiles*** — ceramic, terrazzo, mosaic, vitrified. Requirements: uniform size and shape, low absorption, hardness, strength and weather resistance; roofing tiles must be light, impermeable and easy to lay with adequate overlap.

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PREVIOUS YEAR QUESTIONS

- How are bricks (the common building material) prepared in India? Classify bricks and briefly discuss about each type of brick. [IFOS 2023 | P1/8(B) | 10M]
- Write short notes on the properties of the common building materials used in construction: (i) Timber (ii) Brick (iii) Stone (iv) Tiles (v) Concrete. [timber §9, concrete §8] [IFOS 2022 | P1/8(B) | 15M]

Brick Manufacture & Kilns

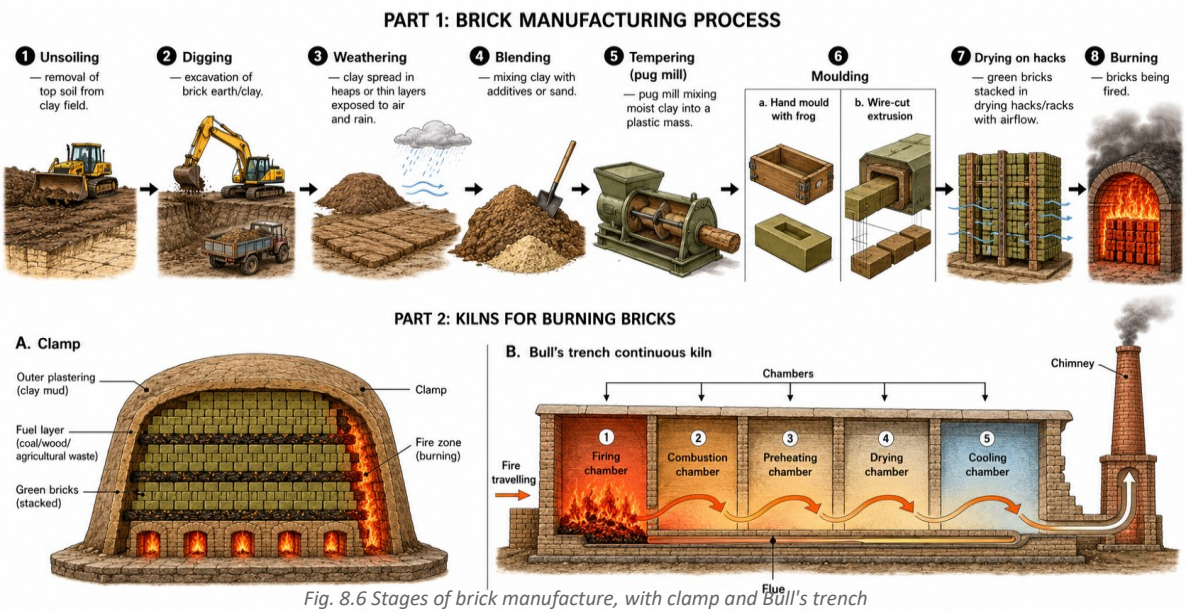


Fig. 8.6 Stages of brick manufacture, with clamp and Bull's trench

7 BUILDING MATERIALS II — LIME, CEMENT, SURKHI & MORTARS

LIME — CLASSIFICATION (IS 712) (IFOS 2025)

Made by calcining limestone: $CaCO_3 \rightarrow CaO + CO_2$ at ~900 °C. ***Quicklime (CaO)*** is slaked with water to ***hydrated lime*** $Ca(OH)_2$. ***Fat (white) lime*** is nearly pure, slakes vigorously, sets slowly by carbonation and is used for plaster and whitewash; ***hydraulic lime*** contains clay, sets under water, and is used for masonry mortar. Hydraulic lime is graded feebly (5-10% clay), moderately (11-20%) and eminently (21-30%) hydraulic.

IS 712 Class	Type	Chief use
Class A	eminently hydraulic lime	structural work, arches
Class B	semi-hydraulic lime	masonry mortar, concrete
Class C	fat (white) lime	finishing coat, plaster, whitewash
Class D	magnesium/dolomitic lime	finishing coat, plaster
Class E	kankar lime	masonry mortar
Class F	siliceous dolomitic lime	undercoat & finishing plaster

CEMENT

Manufacture : raw materials (limestone + clay/shale + correcting materials) are crushed and ground, then burnt in a rotary kiln at ~1400-1500 °C to form ***clinker***, which is ground with 3-5% gypsum (to retard setting). Two processes: the ***wet process*** — raw materials ground with water to a slurry (35-40% water) in wash mills, corrected in slurry tanks, fed to the kiln; better mixing and uniformity but high fuel cost; and the ***dry process*** — raw materials dried and ground to a raw meal, blended in silos, then burnt; much lower fuel consumption, now standard.

Bogue compounds : C_3S (alite — early strength, high heat), C_2S (belite — later strength, low heat), C_3A (flash set, highest heat, sulphate-vulnerable), C_4AF (colour, little strength).

Types : OPC (grades 33/43/53), PPC, rapid-hardening, low-heat, sulphate-resisting, blast-furnace slag, white and coloured.

IS 4031 tests : fineness (sieve/Blaine), consistency and ***setting time by Vicat*** (initial ≥30 min, final ≤600 min for OPC), ***soundness by Le Chatelier*** (≤10 mm) and autoclave, and compressive strength on 1:3 cement-sand cubes at 3, 7 and 28 days.

SURKHI & POZZOLANAS (IFOS 2024)

Surkhi — finely powdered, well-burnt ***brick or clay-ball*** — an artificial pozzolana. Added to fat lime it imparts ***hydraulic properties*** (set under water) and to concrete it improves workability and reduces cost and heat of hydration. Natural pozzolanas include volcanic ash; artificial ones include fly ash, rice-husk ash and Surkhi.

BUILDING MORTARS

Mortar	Typical proportion	Use
Cement mortar	1:3 to 1:6 (cement : sand)	load-bearing masonry, plaster, pointing
Lime mortar	1:2 to 1:3 (lime : sand)	ordinary masonry, plaster
Gauged mortar	1:1:6 to 1:2:9 (cement : lime : sand)	economical; workability of lime + strength of cement
Mud mortar	clay + chopped straw	cheap rural construction

A good mortar must be workable and cohesive, develop adequate strength and bond, be durable and impermeable, and shrink little on setting.

PREVIOUS YEAR QUESTIONS

- Write a short note on: Classification of lime used in farm housing. [IFOS 2025 | P1/8(a)(v) | 15M]
- Write a short note on: Surkhi. [IFOS 2024 | P1/7(c)(iii) | 15M]
- Describe the manufacture of ordinary Portland cement by wet process. Also, draw the flow diagram. [OPSC·CSE (Main) 2018-19 | P1/7(c)(iii) | 15M]

Cement manufacture flow diagram (wet & dry process)

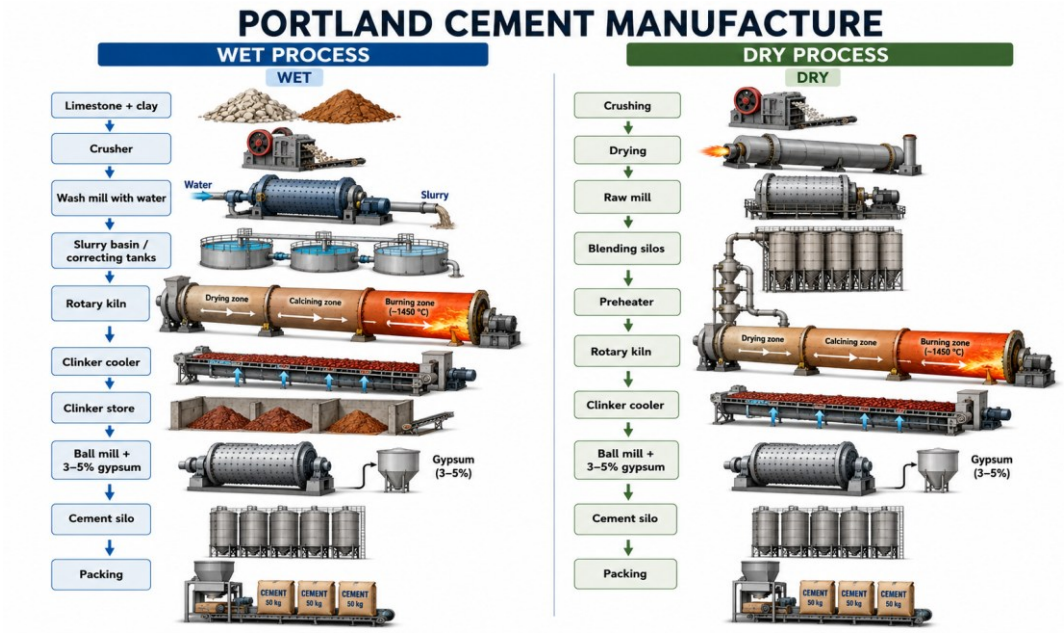


Fig. 8.7 Manufacture of OPC — wet and dry

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8 BUILDING MATERIALS III — CONCRETE & RCC

Concrete is cement + fine aggregate + coarse aggregate + water (± admixtures). It is strong in compression, weak in tension — hence steel reinforcement in RCC.

GRADES, MIXES & WATER-CEMENT RATIO

Graded by characteristic compressive strength of 150 mm cubes at 28 days: **M15, M20, M25 … M40** (M20 = 20 N/mm²). ***Characteristic strength*** = the value below which not more than 5% of test results are expected to fall. Nominal mixes: M15 = 1:2:4, M20 = 1:1½:3, M25 = 1:1:2. The ***water-cement ratio*** governs strength — strength falls as w/c rises (Abrams' law); practical range 0.4-0.6, minimum ~0.35 for hydration.

WORKABILITY & THE SLUMP TEST (IFOS 2024)

Slump test (IS 1199) **—** the standard field measure of ***workability***. A frustum-shaped mould, ***bottom 200 mm, top 100 mm, height 300 mm,*** is placed on a smooth surface and filled in ***four layers, each tamped 25 times*** with a 16 mm rod; the top is levelled, the mould lifted vertically, and the ***slump = the drop in height of the concrete*** in mm.

Types of slump : ***true*** (uniform subsidence — a valid mix), ***shear*** (one half slides — lean/harsh mix, retest), and ***collapse*** (mix too wet). Typical values: mass concrete 25-50 mm; beams/slabs (lightly reinforced) 50-100 mm; heavily reinforced sections 100-150 mm; pumped concrete 100-150 mm. Other workability tests: compaction-factor and Vee-Bee consistometer (for very dry mixes).

PROPERTIES, CURING & GOOD PRACTICE

Properties : high compressive strength, durability, fire resistance, mouldability into any shape, low maintenance and economy; weak in tension, low tensile/shrinkage cracking, heavy. **For best results —** use correct grade and clean, well-graded aggregate; batch by weight; keep w/c low; mix thoroughly; place within the initial setting time without segregation; compact fully (vibrator); and ***cure*** continuously for at least 7 days (14 for PPC/blended) by ponding, wet covering, sprinkling or membrane — curing lets hydration continue and is what actually delivers the design strength.

Nominal mixes: M15 = 1:2:4 · M20 = 1:1½:3 · M25 = 1:1:2 Slump mould 200/100/300 mm, 4 layers × 25 strokes

Characteristic strength f_ck = 28-day cube strength below which ≤5% results fall. Modular ratio m = 280/(3σ_cbc) in working stress design.

RCC : steel is placed where tension occurs; the two act together because their coefficients of thermal expansion are nearly equal and concrete protects steel from corrosion and fire by adequate ***cover*** (25-50 mm depending on exposure). Admixtures — accelerators, retarders, plasticisers/superplasticisers, air-entraining agents and waterproofers — modify setting, workability and durability.

PREVIOUS YEAR QUESTIONS

- Write a short note on: Slump Test on Concrete. [IFOS 2024 | P1/7(c)(iv) | 15M]
- What are the important properties of concrete and why it has attained the status of major building material? What procedure should be followed for obtaining the best results from concrete work? [UK·PSC RFO (Mains) 2021 | Q.4(iv) | 10M]
- What is slump test? Explain it with suitable figures. [OPSC·CSE (Main) 2020-21 | P1/8(e)| 12M]
- What is slump test? Explain it with suitable figures. [AP·PSC RFO (Mains) 2012 | Q.2(d)| 5M]
- Discuss the properties of concrete and curing process. [AP·PSC RFO (Mains) 2012 | Q.4(a)| 10M]

Slump Test

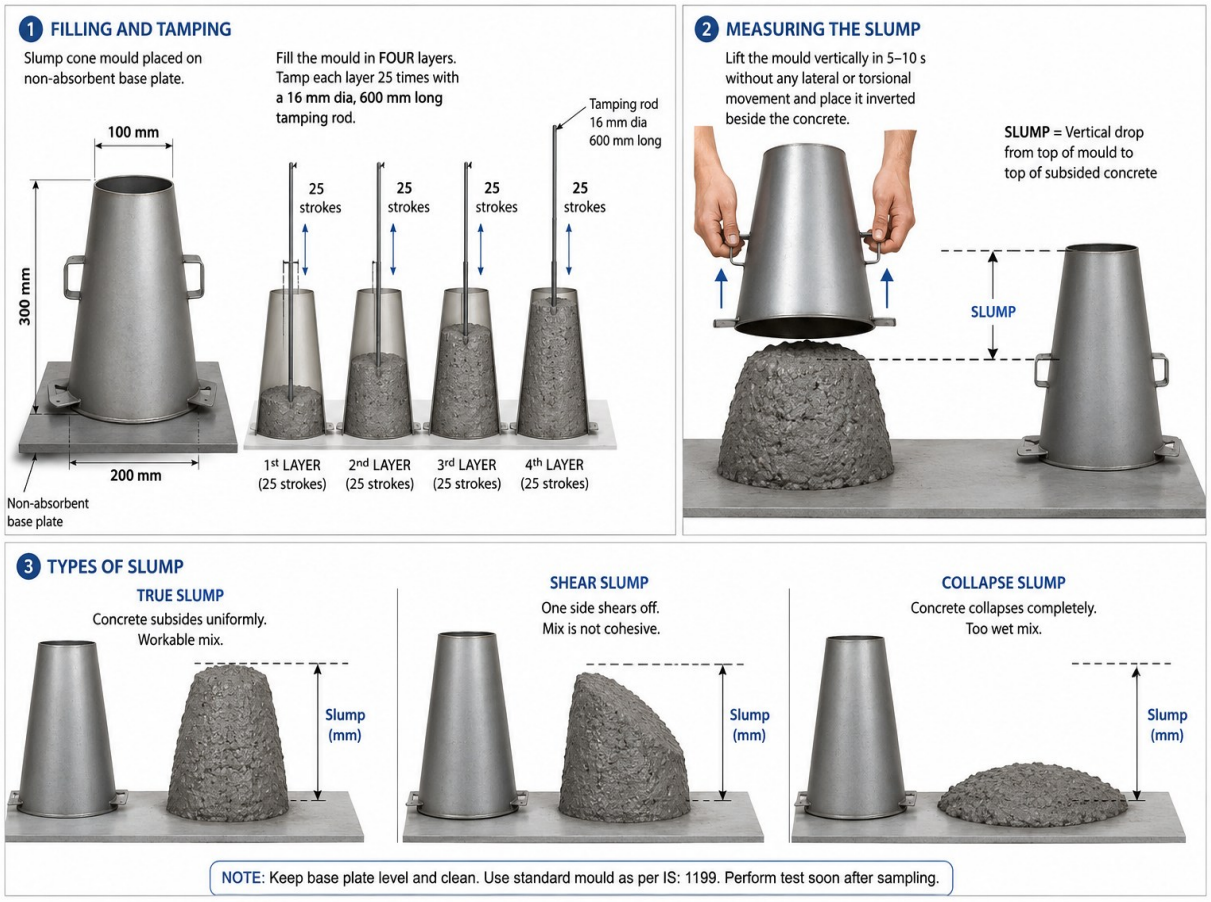


Fig. 8.8 Slump test apparatus, procedure and the three types of slumps.

9 BUILDING MATERIALS IV — TIMBER

Timber is wood converted for construction — light, strong in both tension and compression, easily worked and repaired, and still the common choice for farm-building roofs, doors and shuttering.

STRUCTURE, CLASSIFICATION & DEFECTS

Trees : ***exogenous*** (outward growing, annual rings; used as timber — teak, sal, deodar, shisham) and ***endogenous*** (inward growing — bamboo, palm). A cross-section shows pith, heartwood (dark, strong, durable — the useful part), sapwood (light, containing sap, perishable), cambium, bast and bark.

Defects : ***natural/growth***: knots, shakes (heart, cup, star, ring), twisted fibres, rind galls, upsets, foxiness; ***seasoning defects***: bow, cup, split, warp, honeycombing, case-hardening, collapse; plus defects from fungi (dry & wet rot) and insects (termites, beetles).

SEASONING OF TIMBER (IFOS 2024; UKPSC 2025)

> ***Seasoning*** **—** the controlled removal of ***sap and moisture*** from felled timber to bring it near the moisture content it will have in service (about 10-12% indoors, 15-18% outdoors).

Necessity : green timber holds 50%+ moisture; unless it is removed the timber will shrink, warp, split and lose shape after fixing; seasoning also ***increases strength, hardness and durability***, reduces weight (cheaper transport), makes the timber take paint, polish and preservative properly, improves workability and glue adhesion, and greatly reduces the risk of ***fungal decay and insect attack*** (fungi need >20% moisture).

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Method	How it works	Remarks
Natural / air seasoning	logs stacked on a raised platform in a shed with free air circulation and spacers	cheap, simple; slow (6-24 months); no control
Kiln seasoning	timber in an airtight chamber with regulated hot air, humidity and circulation	fast, fully controlled, any moisture content; costly plant
Water seasoning	logs immersed in running water 2-4 weeks to leach sap, then air-dried	quick sap removal; reduces elasticity
Boiling	timber boiled/steamed 3-4 hours then dried	very quick, good strength; costly for large sections
Electrical seasoning	high-frequency current heats the moisture out	very rapid, uniform; expensive
Chemical (desiccation)	timber steeped in a salt solution that draws out moisture, then dried	uniform; may affect finishing

Preservation (APPSC 2018) : seasoned timber for roofing is treated to resist ***termites, borers and fungal rot and to reduce moisture movement***, so extending life. Preservatives: creosote oil, coal tar, ASCU, copper-chrome-arsenate, zinc chloride, and oil paints/varnish for exposed surfaces; applied by brushing, spraying, dipping, hot-and-cold or pressure (Bethel) treatment.

PREVIOUS YEAR QUESTIONS

- Write in brief about: Seasoning of Timber. [IFOS 2024 | P1/5(e)(ii) | 8M]
- What is seasoning of timber? Explain the necessity of seasoning and describe the various methods used for seasoning of timber. [UK·PSC ACF/RFO (Mains) 2025 | Q.3(ii) | 8M]
- Mention the reasons of treating timber before roofing farm building. [AP·PSC RFO (Mains) 2018 | Q.10(d) | 3M]

Timber: Cross-Section & Seasoning

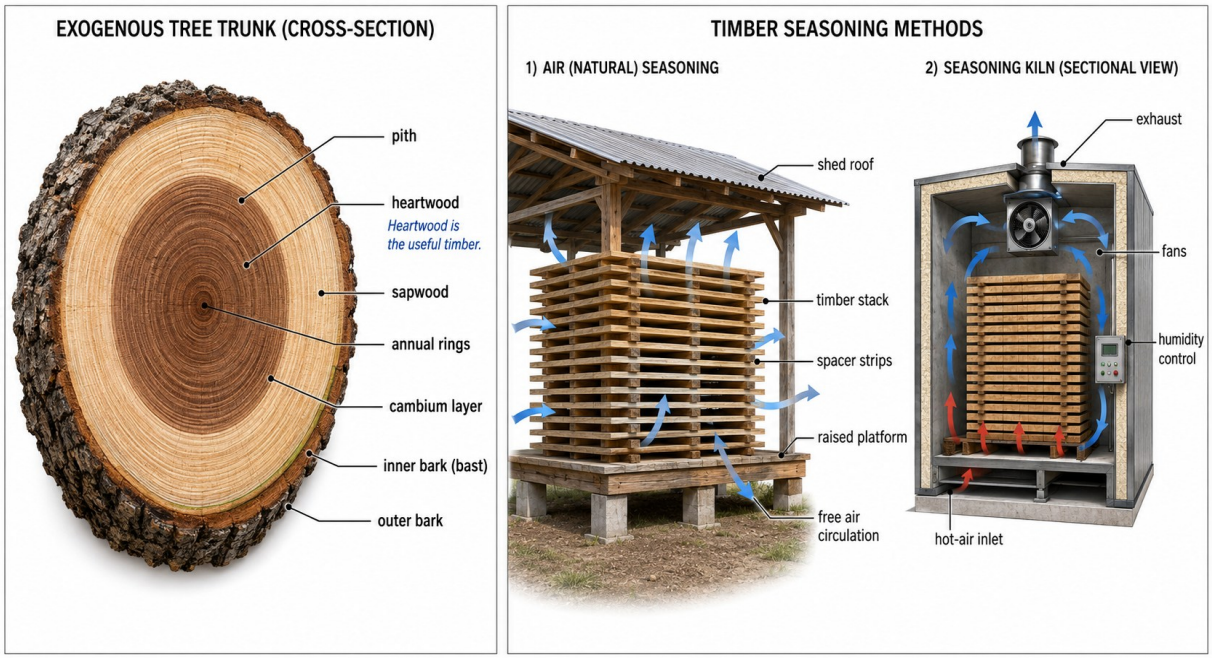


Fig. 8.9 Timber structure (left) and air seasoning with a kiln (right).

10 SOIL MECHANICS FOR FARM STRUCTURES

Every farm building ultimately rests on soil, so its ***shear strength*** (which fixes bearing capacity) and its ***compressibility*** (which fixes settlement) decide the foundation.

BASICS & INDIAN SOILS

Soil is a three-phase system (solid, water, air): void ratio e = V_v/V_s, porosity n = V_v/V, water content, degree of saturation. Index properties and Atterberg limits give the classification. **Indian soils of note — *black cotton soil*** (expansive — swells when wet, shrinks and cracks when dry; Maharashtra, Gujarat, MP, Karnataka, TN, AP), laterite, alluvial, marine deposits (very soft, low bearing, high settlement) and desert soils.

SHEAR STRENGTH & ANGLE OF INTERNAL FRICTION

Mohr-Coulomb: $\tau_f = c + \sigma \cdot \tan\varphi$ (effective stress) $\tau_f = c' + \sigma' \cdot \tan\varphi', \sigma' = \sigma - u$

τ_f = shear strength (kN/m²); c = cohesion (kN/m²); φ = angle of internal friction (°); σ = normal stress; u = pore-water pressure. Failure occurs when the Mohr circle touches this envelope.

Test	Principle	Best suited to
Direct shear	square split box; shear at 4-5 normal stresses; plot τ_f vs σ	sands
Unconfined compression	$\sigma_3 = 0$; q_u at failure; $c_u = q_u/2$	saturated clay ($\phi_u = 0$)
Triaxial — UU	no drainage; total-stress c_u; quick	short-term stability
Triaxial — CU	consolidate, shear undrained, measure pore pressure → c′, ϕ′	preferred for effective parameters
Triaxial — CD	fully drained, very slow → c′, ϕ′	long-term stability

CONSOLIDATION & SETTLEMENT

Consolidation is the time-dependent expulsion of pore water from a saturated soil under load, causing settlement — important in clays because of their low permeability. It differs from ***compaction*** (instantaneous, unsaturated soil, removes air voids by mechanical effort). Total settlement S_t = immediate + primary consolidation + secondary (creep).

$\Delta H = H_0 \cdot \Delta e/(1+e_0)$ $\partial u/\partial t = c_v \partial^2 u/\partial z^2$ $T_v = c_v t/H^2$ $S = (C_c/(1+e_0)) \cdot H \cdot \log_{10}[(\sigma'_0+\Delta\sigma')/\sigma'_0]$

c_v = coefficient of consolidation (m²/yr); T_v = time factor (U = 50% at T_v = 0.197; U = 90% at 0.848); C_c = compression index ≈ 0.009(w_L − 10) (Skempton); OCR = σ'_c/σ'_{v0}.

SOIL EXPLORATION

Methods: ***direct*** (test pits/trenches, ≤3 m), ***semi-direct*** (boring — auger, wash, rotary, percussion) and ***indirect*** (penetration and geophysical tests). ***Disturbed*** samples serve for grain size, Atterberg limits and classification; ***undisturbed*** samples (area ratio <10%; Shelby tubes) are essential for consolidation and shear tests.

SPT: hammer 63.5 kg, free fall 760 mm, driven 450 mm; N = blows for the LAST 300 mm $N'_{70} = C_N \cdot N \cdot \eta_1\eta_2\eta_3\eta_4$, $C_N = (95.76/p'_0)^{1/2}$

The first 150 mm is the seating drive and is ignored. η = corrections for hammer energy, rod length, sampler and borehole diameter.

11 FOUNDATIONS

DEFINITIONS

Ultimate bearing capacity (q_u) : the intensity at which the soil shears and fails. ***Net ultimate (q_{nu})*** = q_u − γD_f. ***Safe bearing capacity*** = q_{nu}/F + γD_f (F = 2-3). ***Allowable bearing pressure*** — the lesser of the safe

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bearing capacity and the pressure that keeps settlement within permissible limits. Failure modes: ***general shear*** (dense/stiff soil, clear failure surface), ***local shear*** and ***punching shear*** (loose/soft soil).

Terzaghi (strip): $q_u = c \cdot N_c + \gamma \cdot D_f \cdot N_q + 0.5 \cdot \gamma \cdot B \cdot N_\gamma$

Square: $1.3cN_c + \gamma D_f N_q + 0.4\gamma B N_\gamma$

Circular: $1.3cN_c + \gamma D_f N_q + 0.3\gamma B N_\gamma$

c cohesion (kN/m²); γ unit weight (kN/m³); D_f depth of foundation (m); B width (m); N_c, N_q, N_γ = bearing-capacity factors, functions of φ. Local shear: use c′ = ⅔c and tan φ′ = ⅔ tan φ. Submergence halves the γ term (water table at/above base).

Rankine's minimum depth of foundation: $D_f = (p/\gamma) \cdot [(1 - \sin\varphi)/(1 + \sin\varphi)]^2$

p = safe bearing capacity / intensity of loading (kN/m²); γ = unit weight of soil (kN/m³); φ = angle of repose / internal friction.

FIELD DETERMINATION & SETTLEMENT LIMITS

Plate load test (IS 1888) : a rigid steel plate (300-750 mm) is loaded in increments in a test pit and the load-settlement curve gives q_u and settlement; results must be corrected for size (sand settles in proportion to width). ***Penetration tests*** (SPT/SCPT) give N and q_c, from which safe bearing pressure is read. ***Permissible settlement*** (IS 1904): isolated footings on sand 40 mm, on clay 65 mm; rafts 40-65 mm on sand and 65-100 mm on clay; differential settlement and angular distortion (≈1/500) usually govern.

TYPES OF FOUNDATION

Group	Type	When used
Shallow (D_f ≤ B)	spread / isolated footing	individual columns, good soil near surface
	combined & strap footing	columns close together or near a property line
	wall (strip) footing	load-bearing walls
	mat / raft	weak soil, heavy or closely-spaced columns; >50% of area covered
Deep (D_f > B)	pile foundation	weak upper strata; load taken by end bearing and skin friction
	under-reamed pile	expansive black cotton soils (IS 2911 Pt.III)
	well / caisson	bridge piers, deep scour

Factors fixing depth & size (APPSC 2018) : the load and its nature; safe bearing capacity of the soil; depth of good bearing strata and of the water table; zone of seasonal moisture change/shrinkage-swelling (black cotton soil) and frost depth; scour and adjoining foundations; and permissible settlement. Size follows from area = load/allowable bearing pressure; depth from Rankine and the above.

FOUNDATIONS IN BLACK COTTON SOIL (OPSC 2020)

The problem is ***alternate swelling and shrinkage*** with moisture change, which lifts and cracks ordinary footings. Remedies: take the foundation below the zone of moisture variation (1.5-3.5 m); provide a ***sand/moorum cushion*** under the footing; use ***under-reamed piles*** with a bulb anchoring the pile below the active zone, tied by a grade beam kept clear of the ground by an air gap; or replace/stabilise the soil (lime stabilisation) and keep water away by aprons and good drainage. A ***polythene sheet*** under the foundation/floor acts as a damp-proof and moisture barrier — it stops capillary rise into the masonry and keeps moisture changes (and hence swelling) out of the soil directly beneath (APPSC 2018).

◆ **WORKED NUMERICAL — *Design of a foundation for a brick pier*** [OPSC·CSE (Main) 2020-21 · Paper-I Q.8(c) · 12M]

Problem. *A brick pier 600 mm × 600 mm is 4 m high. It has to carry an axial load of 520 kN. The allowable bearing capacity of the soil is 250 kN/m². The weight of brick masonry is 18.84 kN/m³. The angle of repose is 30° and the weight of earth is 16 kN/m³. Design the suitable foundation for the pier.*

Given. pier 0.6 × 0.6 m, H = 4 m; P = 520 kN; SBC = 250 kN/m²; γ_masonry = 18.84 kN/m³; ϕ = 30°; γ_soil = 16

kN/m³.

Self weight of pier. W = 0.6 × 0.6 × 4 × 18.84 = 27.13 kN

Total load. = 520 + 27.13 = 547.13 kN; adding 10% for the footing's own weight ⇒ 601.8 kN

Area of footing. A = load/SBC = 601.8/250 = 2.407 m²

⇒ side = √2.407 = 1.55 m, adopt 1.6 m × 1.6 m

Check. pressure = 601.8/(1.6²) = 235 kN/m² < 250 kN/m² ✓ ;

offset = (1.6 − 0.6)/2 = 0.50 m each side

Depth (Rankine). $D_f = (p/\gamma)\,[(1-\sin\phi)/(1+\sin\phi)]^2 = (250/16)\,(0.5/1.5)^2$

= 15.625 × 0.1111 = 1.74 m

Result. Provide a 1.6 m × 1.6 m square footing at 1.74 m (say 1.75 m) below ground level, with a 0.50 m offset all round.

◆ **WORKED NUMERICAL — *Ultimate & safe bearing capacity by Terzaghi's equation*** [illustrative — cf. OPSC 2022-23 Q.18(a)]

Problem. A strip footing 1.5 m wide is laid at a depth of 1.5 m in a soil having c = 15 kN/m², ϕ = 25° and γ = 18 kN/m³. Taking Terzaghi's factors N_c = 25.1, N_q = 12.7, N_γ = 9.7, find the ultimate and safe bearing capacity (factor of safety 3).

Formula. $q_u = c\cdot N_c + \gamma\cdot D_f\cdot N_q + 0.5\cdot\gamma\cdot B\cdot N_\gamma$

Substitution. q_u = 15×25.1 + 18×1.5×12.7 + 0.5×18×1.5×9.7 = 376.5 + 342.9 + 131.0

q_u = 850.4 kN/m² ; net q_{nu} = 850.4 − (18×1.5) = 823.4 kN/m²

Safe value. q_{ns} = 823.4/3 = 274.5 ; safe bearing capacity = 274.5 + 27 = 301.4 kN/m²

Result. q_u ≈ 850 kN/m²; safe bearing capacity ≈ 301 kN/m².

PREVIOUS YEAR QUESTIONS

- Explain about the analysis of bearing capacity of soil. [OPSC·CSE (Main) 2022-23 | P1/18(a) | 8M]
- Explain, in detail, about foundation in black cotton soil. [OPSC·CSE (Main) 2020-21 | P1/8(a) | 12M]
- What are the building materials used on farm for various uses? Elaborate the bearing capacity of soil, factor of safety etc. [OPSC·CSE (Main) 2017-18 | P1/8(c) | 15M]
- Name the different types of masonry foundations and explain. [OPSC·CSE (Main) 2015-16 | P1/6(c)(ii) | 10M]
- State the factors that determine the depth and size of foundation in a farm building. [AP·PSC RFO(Main) 2018 | Q.10(c) | 4M]
- Give the reasons for placing a polythene sheet on a foundation of farm buildings. [AP·PSC RFO(Main) 2018 | Q.10(e) | 3M]
- A straight gravity masonry dam of trapezoidal section has top width 1.6 m, base width 3.2 m and height 6.2 m; water impounding height 5.6 m; coefficient of friction 0.5; bearing capacity of soil 25,000 kg/m². Test the structural stability of the dam. [stability: check overturning, sliding and base pressure ≤ SBC] [OPSC·CSE (Main) 2016-17 | P1/7(c) | 30M]

Foundation Types & Under-Reamed Pile

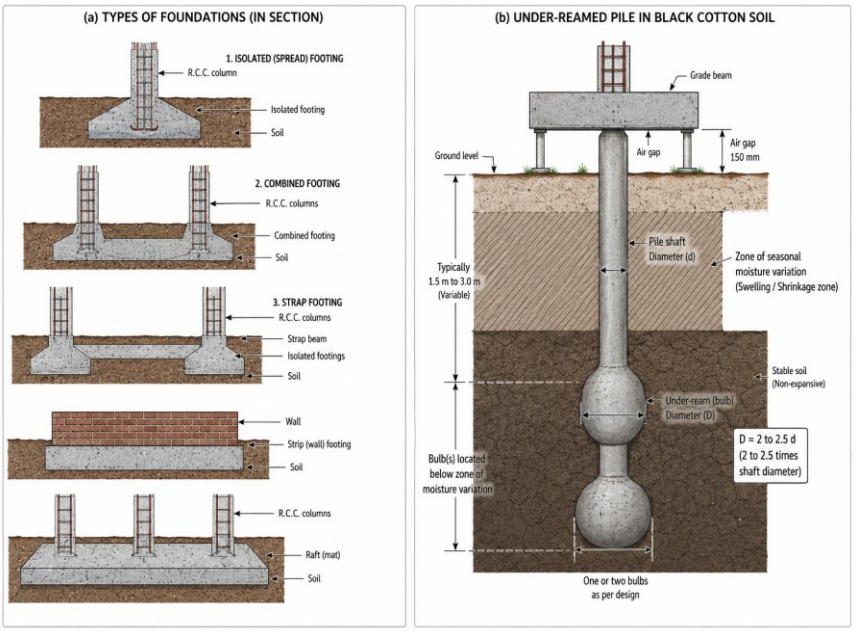


Fig. 8.10 Shallow foundation types (left) and an under-reamed pile for black cotton soil (right).

12 GRAIN & FEED STORAGE STRUCTURES

Roughly 60-70% of India's food grain is stored at farm level, and the bulk of post-harvest loss happens in storage — so the storage structure is as much a part of production as the field.

PRINCIPLES & CAUSES OF LOSS

Grain is a living, respiring body; safe storage means keeping it ***dry, cool, clean and sealed from pests***. Losses are ***direct*** (grain actually eaten/removed by insects, rodents, birds) and ***indirect*** (loss of quality, germination, weight, and contamination by webbing, excreta and mould).

Factor group	Agents
Abiotic (physical)	moisture content & humidity, temperature, moisture migration, oxygen, time
Biotic — insects	primary (rice weevil, lesser grain borer, khapra) attack sound grain; secondary (red flour beetle) attack broken grain
Biotic — micro-organisms	fungi/moulds (aflatoxin), bacteria — active above ~13% m.c. and 70-75% RH
Biotic — vertebrates	rodents (rats, mice) and birds

Safe storage: moisture ≤ 13-14% (in equilibrium with 70-75% RH) · <12% for long-term · <13% checks micro-organisms · <10% checks insects

EMC = moisture at which the grain neither gains nor loses moisture from air of a given RH & temperature. Moisture migration: in a bulk, warm moist air rises and condenses at the cold top surface, wetting the top layer and causing mould.

Control of losses : dry the grain to safe moisture before storage; clean and disinfest the structure; use rodent-proof and moisture-proof construction; stack on dunnage away from walls; aerate to keep the bulk cool and uniform; fumigate when infested (aluminium phosphide, EDB); inspect regularly; and practise first-in-first-out.

REQUIREMENTS OF A GOOD STORAGE STRUCTURE (IFOS 2025)

Moisture-proof (damp-proof course, plinth above ground, leak-free roof); ***air-tight where hermetic storage is intended***; rodent- and bird-proof; insect-proof and easy to fumigate; strong enough for the grain pressure; easy to fill, empty, clean and inspect; protection from direct sun and rain; and economical in local materials.

TRADITIONAL (RURAL) STORAGE STRUCTURES

Structure	Description
Morai (Mudki)	conical/cylindrical bamboo-framed structure plastered with mud, on a raised platform; 3-18 t
Bukhari	cylindrical mud/mud-brick bin on a raised platform, roofed; 3-9 t
Kothar	large wooden box-type store raised on pillars, with roof; common in eastern India
Kanaja / mud kothi	bamboo or mud bins inside the house; small capacity
Bags in the dwelling	gunny bags stacked in the house — highest losses

These are cheap and made of local materials, but are neither moisture-proof nor rodent-proof and cannot be fumigated — hence the improved designs.

IMPROVED & MODERN STRUCTURES

PUSA bin (IFoS 2025) : an improved mud/brick bin developed at IARI in which a ***polyethylene (LDPE) film, 700–1000 gauge, is embedded within the walls and floor*** as a continuous moisture barrier. It keeps the grain dry even in humid weather, is nearly air-tight (so it can be fumigated and kills insects by oxygen depletion), is rodent-proof, and is built of cheap local materials. Capacities ~1-3 t (commonly 2 t and 4 t designs); an inlet at the top and an outlet near the bottom.

Other improved bins : Hapur bin, Nanda bin, domestic metal bins, and ***modern structures***: RCC and aluminium/GI ***silos*** for bulk, and ***godowns/warehouses*** (CWC/FCI) for bag storage — plinth ≥0.6 m, damp-proof course, rat-proof, ventilators with wire mesh, stacks on wooden dunnage 15 cm clear of walls, aisles for inspection.

CAP *storage* (IFoS 2024) : Cover And Plinth — open-air bulk-bag storage on a raised, damp-proof ***plinth*** with the bag stack covered by a ***1000-gauge low-density polyethylene cover*** lashed down with ropes, over polythene-lined dunnage. A typical unit of 9.11 m × 6.10 m × 18 bags high holds about 150 t. It is a cheap, quickly-erected scientific alternative when godown space is short — but it is only an interim measure (2-6 months).

Hermetic (air-tight) storage* (IFoS 2024) –** sealed storage in which respiration of the grain and insects consumes the oxygen and raises CO_2. Insects die when O_2 falls to about **2%** (fungi persist to ~0.2%). Advantages: ***no chemical fumigant needed, insects and moulds controlled, quality and germination preserved, moisture kept constant, and it suits organic produce. It demands a genuinely gas-tight structure (underground pits, sealed metal/plastic bins, GrainPro-type liners) and grain dried to safe moisture first. Related: ***controlled-atmosphere (CA)*** and ***modified-atmosphere (MA)*** storage, where CO_2/N_2 is deliberately introduced.

BAG VS BULK STORAGE (IFOS 2021)

Basis	Bag storage	Bulk storage
Space use	poor — a 15×60×6 m shed holds ~1,440 t	excellent — same shed holds ~2,840 t
Handling	manual, labour-intensive	mechanised (conveyors, elevators) — fast
Cost	low initial; recurring cost of bags & labour	high initial; low running cost
Losses	higher — bag damage, spillage, rodents	lower; easy aeration & fumigation
Inspection	easy — individual stacks; partial despatch simple	sampling harder; whole bin affected if spoilage starts
Suitability	small quantities, mixed varieties, frequent despatch	large uniform quantities, long storage

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◆ **WORKED NUMERICAL — *Design of a bag-storage structure for 300 t of wheat*** [IFoS 2023 · P1/5(d) · 8M]

Problem. *Design a bag storage structure for storing 300 tonnes of wheat with a stack of 10 bags in length, 10 bags in width and 10 bags in height. Each bag is of 100 cm × 60 cm × 30 cm dimension having capacity of 100 kg. Take clear distance between the walls and the end of the stack as 0.8 m and between the stacks as 2.0 m. Give the complete floor plan of the structure with dimensions and draw layout.*

Capacity of one stack. 10 × 10 × 10 = 1000 bags × 100 kg = 1,00,000 kg = 100 t

Number of stacks. 300/100 = 3 stacks

Stack dimensions. length = 10 × 1.00 = 10.0 m; width = 10 × 0.60 = 6.0 m; height = 10 × 0.30 = 3.0 m

Layout — 3 stacks side by side across the width:

Total width. = 3 × 6.0 + 2 × 2.0 (between stacks) + 2 × 0.8 (wall clearance) = 18.0 + 4.0 + 1.6 = 23.6 m

Total length. = 10.0 + 2 × 0.8 = 11.6 m

Result. Godown floor plan 23.6 m × 11.6 m = 273.8 m²; stack height 3.0 m, so keep eaves ≥ 4.5 m for handling and ventilation; plinth 0.6 m above ground with damp-proof course and wooden dunnage.

PREVIOUS YEAR QUESTIONS

- Discuss various factors to be taken care in designing a storage structure for grains. What measures can be adopted to improve the performance of traditional storage structure?
  [IFOS 2023 | P1/8(a) | 10M]
- Explain the causes by which losses of grain occur during storage. Discuss about humidity to be maintained in the storage system. How can you control the losses?
  [IFOS 2022 | P1/8(a) | 15M]
- What would be the storage structure for grains? [IFOS 2022 | P1/5(d) | 8M]
- What is hermetic storage? List the advantages of using hermetic storage structures.
  [IFOS 2024 | P1/5(d) | 8M]
- Differentiate between Deep and Shallow bins. Give the merits and demerits of Bag and Bulk storage system. [deep vs shallow bins in §13]
  [IFOS 2021 | P1/8(a) | 15M]
- Write short notes on: (ii) PUSA storage bin; (iv) Requirements of good storage structures.
  [IFOS 2025 | P1/8(a)(ii), (iv) | 15M]
- Write a short note on: CAP Storage System. [IFOS 2024 | P1/7(c)(v) | 15M]
- Enumerate the advantages of bulk storage of grain compared to bag storage. What is meant by CAP storage? State its importance in grain handling in India. List the biotic and abiotic factors affecting stored grain in warehouses.
  [OPSC·CSE (Main) 2024-25 | P2/9) | 15M]
- Explain the major effects of biotic and abiotic factors on stored grain in a silo.
  [OPSC·CSE (Main) 2022-23 | P2/6(a) | 10M]
- List types of grain storage structures used in different states of India and briefly describe Murai type grain storage structure.
  [UK·PSC RFO (Mains) 2021 | Q.4(ii) | 10M]
- What are various types of food grain storage structures? Explain aluminium bin and R.C.C. bin with schematic diagram. List out the factors affecting the design of silo.
  [OPSC·CSE (Main) 2020-21 | P2/6(a) | 20M]
- How do you design grain storage structure and storage structures for semi perishables?
  [OPSC·CSE (Main) 2016-17 | P1/5(d) | 20M]

***Storage Structures*: *Traditional*, PUSA Bin & CAP**

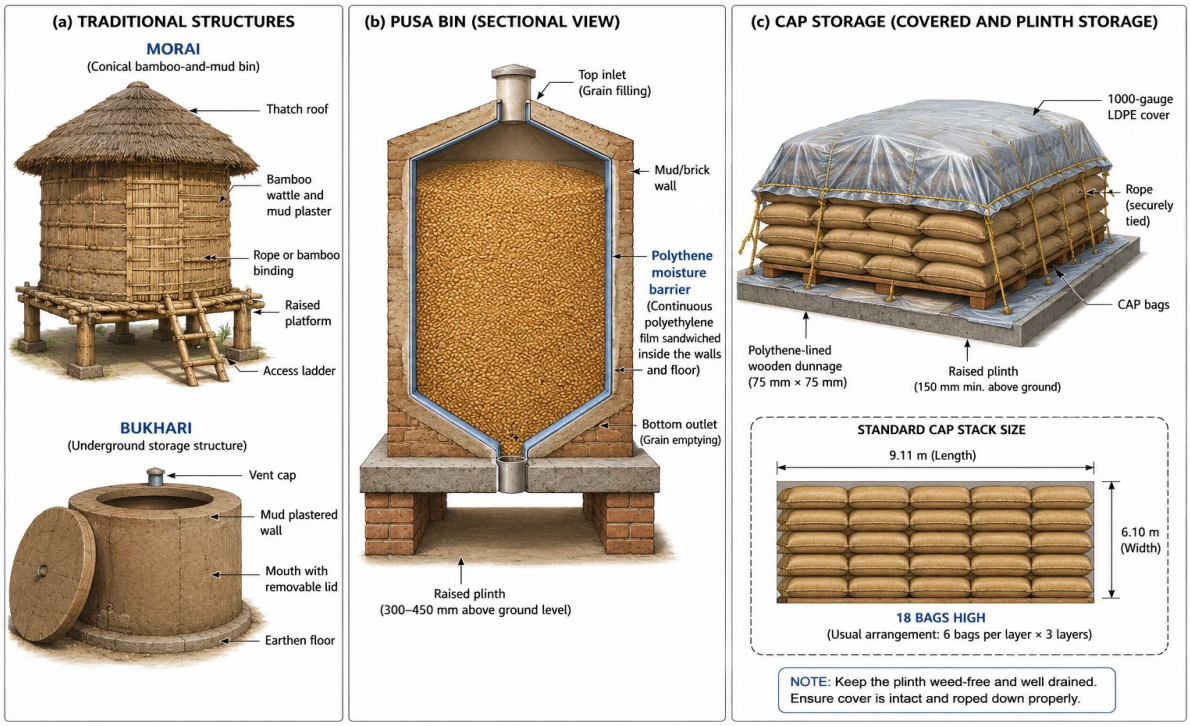


Fig. 8.11 Morai/Bukhari (traditional), the PUSA bin, and CAP storage.

13 SILOS, SILAGE & GRAIN PRESSURE THEORY

SILAGE & SILOS

Silage **—** green succulent fodder preserved by ***partial anaerobic fermentation*** in an air-tight structure — sugars are converted to lactic acid, which drops the pH and checks further decay. The structure is the ***silo***; density of silage 480-800 (≈650-675) kg/m³; dry-matter loss 20-30%. Suitable crops: maize, sorghum, bajra, oats and grasses (high sugar, 30-35% DM).

Type of silo	Description / suitability
Tower silo	vertical cylinder above ground; needs heavy reinforcement; costly; used where water table is high
Pit silo	vertical pit dug in the ground; cheap; needs deep water table and stable soil
Trench silo	trench excavated with sloping sides; cheapest for large herds; needs drainage
Horizontal / bunker	on the ground with side walls, sealed with polythene; easy mechanised filling
Metallic vs concrete	metallic: lighter, quicker to erect, air-tight, corrosion-resistant coatings, re-locatable, lower dead load & foundation cost; concrete: heavier, durable, better insulation, higher initial cost

Components of a silo storage system : foundation and floor; wall/steining (RCC, brick or steel plate); roof with filling hatch; ***filling and levelling equipment*** (blower/elevator, distributor); ***unloading equipment*** (bottom or top unloader, auger conveyor); ladder and doors/chutes; aeration and ventilation system; and the drainage of silage effluent.

DESIGN OF SILO CAPACITY — ECONOMICAL DIAMETER & DEPTH

$$\text{Daily silage} = (\text{kg per 100 kg BW}/100) \times \text{BW} \times \text{No. of animals}$$

$$\text{Daily volume} = \text{daily mass} \times (1 + \text{loss})/\text{density}$$

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$$\text{Depth} = \text{removal rate} \times \text{feeding days}$$

$$\text{Area} = \text{daily volume} / \text{removal rate}$$

$$D = \sqrt{(4A/\pi)} \le D_{max}$$

Removal rate ~10 cm/day (prevents spoilage of the exposed face); feeding rate 3-4 kg per 100 kg body weight per day; density ≈650-675 kg/m³; maximum practical diameter 6 m — if the required area needs a bigger diameter, provide several silos.

◆ **WORKED NUMERICAL — *Economical diameter and depth of silos for 650 cows*** **[IFoS 2021 · P1/5(c) · 8M]**

Problem. *Work out the economical diameter and depth of silo/silos to store sufficient silage for a herd of 650 dairy cows of average weight 400 kg each. Feeding days = 240; weight of 1 m³ of silage = 675 kg; thickness of silage fed each day = 10 cm; quantity fed per 100 kg body mass = 4 kg; maximum diameter permitted = 6 m; allowable handling loss = 10%.*

Daily requirement. per cow = 4 × 400/100 = 16 kg/day ; herd = 16 × 650 = 10,400 kg/day

Allow 10% handling loss. = 10,400 × 1.10 = 11,440 kg/day

Daily volume. $= 11{,}440/675 = 16.95\ m^3/day$

Depth. = removal rate × days = 0.10 × 240 = 24 m

Cross-sectional area. $A = \text{daily volume} / \text{daily removal} = 16.95/0.10 = 169.5\ m^2$

Diameter check. single silo D = √(4×169.5/π) = 14.69 m > 6 m permitted

Number of silos. area of one 6 m silo = π/4 × 6² = 28.27 m² ⇒ 169.5/28.27 = 5.99 ⇒ 6 silos

Result. Provide 6 silos, each 6 m diameter × 24 m deep (total silage ≈ 2746 t over 240 days).

DEEP VS SHALLOW BINS (IFOS 2021)

Basis	Shallow bin	Deep bin
Plane of rupture	emerges from the TOP of the fill (does not meet the far wall)	meets the OPPOSITE WALL before reaching the top
Wall friction	negligible — ignored	significant — carries much of the load
Pressure law	increases ~linearly with depth (Rankine/Airy)	approaches a limiting value (Janssen)
Rule of thumb	height ≲ 1.5 × width/diameter	height ≳ 2-3 × width/diameter
Design theory	Rankine's earth-pressure theory	Janssen's / Airy's deep-bin theory

GRAIN PRESSURE THEORIES

Janssen: $p_v = (w \cdot R)/(\mu' \cdot K) \cdot [1 - e^{(-K \cdot \mu' \cdot h/R)}]$ $\quad p_{lat} = K \cdot p_v$ $\quad R = A/\text{perimeter} = D/4$ (circular)

p_v = vertical pressure on the bottom (kg/m²); w = bulk density (kg/m³); R = hydraulic radius (m); μ′ = coefficient of wall friction = tan(angle of wall friction); K = (1 − sin φ)/(1 + sin φ); h = depth of grain (m); φ = angle of internal friction. Airy's and Rankine's theories give the shallow-bin/lateral-pressure forms.

◆**WORKED NUMERICAL — *Load on the bottom of a cylindrical silo (Janssen)*** **[IFoS 2019 · P1/5(e) · 8M]**

Problem. *A cylindrical silo of 2.5 m diameter and 20 m height is filled with wheat. Calculate the load on the bottom only. The silo is made of steel with smooth walls. Minimum bulk density 720 kg/m³; maximum 830 kg/m³; minimum angle of internal friction 25°; maximum 30°; minimum angle of friction on smooth sheeting 18°.*

Why this combination. The bottom must be designed for the MAXIMUM vertical pressure. p_v rises as K falls, and K = (1−sinϕ)/(1+sinϕ) falls as ϕ rises ⇒ use ϕ = 30° with the maximum density 830 kg/m³ and the given wall-friction angle 18°.

Given. D = 2.5 m ⇒ R = D/4 = 0.625 m; h = 20 m; w = 830 kg/m³; ϕ = 30°; wall friction δ = 18°.

Parameters. K = (1 − sin30°)/(1 + sin30°) = 0.5/1.5 = 0.3333 ; μ′ = tan 18° = 0.3249 ; K·μ′ = 0.1083

Formula. $p_v = (w \cdot R)/(\mu' K) \cdot [1 - e^{(-K\mu' h/R)}]$

Substitution. exponent = 0.1083 × 20/0.625 = 3.466 ; $e^{(-3.466)}$ = 0.0313 ⇒ bracket = 0.9687

$(w \cdot R)/(\mu' K)$ = (830 × 0.625)/0.1083 = 4789.5 kg/m² ; p_v = 4789.5 × 0.9687 = 4640 kg/m²

Total load on bottom. = $p_v \times (\pi/4)D^2$ = 4640 × 4.909 = 22,774 kg ≈ 22.8 t

Result. Vertical pressure on the bottom ≈ 4640 kg/m² (45.5 kN/m²); total load on the bottom ≈ 22.8 tonnes (223 kN).

PREVIOUS YEAR QUESTIONS

- Classify silos. Describe constructional features and use of pit silos. [IFOS 2016 | P1/8(b) | 12M]
- What are the different components of silo storage system? Mention specific advantages of metallic silos over concrete silos. [IFOS 2024 | P1/8(b) | 15M]
- What is silage? Which crops are considered suitable for making silage? Differentiate between pit and trench silos. [UK·PSC RFO (Mains) 2021 | Q.5(iv) | 10M]
- Explain the procedures for designing a silo. [OPSC·CSE (Main) 2018-19 | P1/8(d) | 10M]
- Work out the economical diameter and depth of a silo to store sufficient quantity of silage for a herd of 400 dairy cows having an average body weight of 450 kg each. The cows are fed silage for 200 days a year. [OPSC·Forest (Main) 2015-16 | P1/6(d) | 10M]

MODEL Q Silo sizing: daily silage = feeding rate × body weight × number of animals (+ handling loss) → daily volume = mass/density → DEPTH = daily removal thickness × feeding days → AREA = daily volume ÷ removal thickness → diameter from area; if D exceeds the permitted maximum, divide the area among several silos.***

Silo Types & Janssen Pressure Distribution

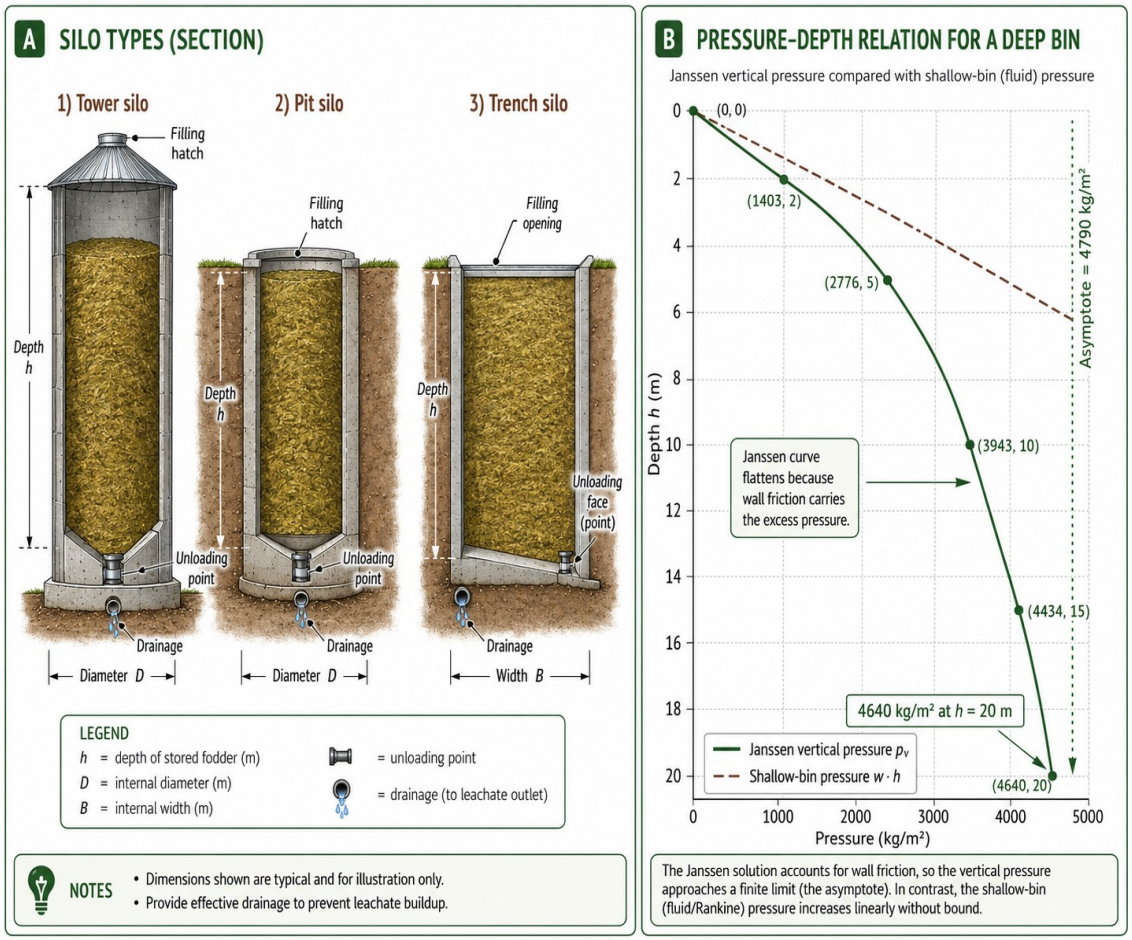


Fig. 8.12 Silo types (left); Janssen pressure flattening with depth vs the shallow-bin straight line (right).

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Quantity	Formula
Farmstead area	3-5% of total farm area
Domestic water demand	≈135 L/day/capita (India)
Sedimentation tank	$V = Q \cdot t$; $V = d^2(0.011d + 0.785H)$
Road super-elevation / camber	WBM 1 in 48 ; camber earthen 1 in 20-24, CC 1 in 60-72
Ruling gradient	1 in 40 (plains) ; 1 in 20 (hills)
Stall size (454 kg cow)	1.10 m wide × 1.40 m long ; gutter 2% slope
Poultry floor / ventilation	0.36 m^2/bird ; ⅔ ft^3/min per ft^2 ; light 12-14 h
Fence posts	no. = perimeter/spacing ; wire = perimeter × rows
Concrete nominal mixes	M15 = 1:2:4 · M20 = 1:1½:3 · M25 = 1:1:2
Slump cone	200 mm bottom /100 top /300 high ; 4 layers × 25 strokes
Mohr-Coulomb	$\tau_f = c + \sigma \tan \phi$
Consolidation	$T_v = c_v t/H^2$; $S = (C_c/(1+e_0))H \log_{10}[(\sigma'_o+\Delta\sigma')/\sigma'_o]$
Terzaghi bearing capacity	$q_u = cN_c + \gamma D_f N_q + 0.5\gamma B N_\gamma$
Rankine minimum depth	$D_f = (p/\gamma)[(1-\sin\phi)/(1+\sin\phi)]^2$
SPT	63.5 kg hammer, 760 mm fall; N = blows for last 300 mm
Safe storage moisture	≤13-14% (70-75% RH) ; <10% checks insects
Silo sizing	depth = removal rate × days ; area = daily volume/removal
Janssen (deep bin)	$p_v = (wR/\mu'K)[1 - e^{(-K\mu' h/R)}]$; $K = (1-\sin\phi)/(1+\sin\phi)$; $R = D/4$

SUMMARY

- The farmstead (3-5% of farm area) is sited for centrality, access, high ground with drainage, water and shelter; residence up-wind, animal sheds and manure pit down-wind.
- Farmstead services: 135 L/day/capita domestic demand; rural treatment = screening + plain sedimentation + filtration; septic tank settles, digests and discharges to a soak pit; farm roads need camber, ruling gradient 1 in 40 and five structural layers.
- Dairy barns are stanchion, loose-housing or open-air; stall 1.10 × 1.40 m, feed alley 1.2 m, litter alley 1.8-2.4 m, gutter at 2% slope; loose housing is recommended for most Indian conditions.
- Poultry: deep litter (commonest), cage, slatted and free range; egg optimum 50-55 °F, ventilation ⅔ ft^3/min/ft^2, 12-14 h light; brooder starts at 95 °F dropping 5 °F/week.
- Fencing may be live hedge, wall or wire (barbed, plain, woven mesh); concrete posts at 2.4-3.0 m; electric fencing is a psychological barrier using pulsed high-voltage low-energy shocks.
- Stones are classified geologically/physically/chemically; bricks are made by unsoiling → weathering → tempering → moulding → drying → burning (clamp or kiln) and graded first/second/third / jhama.
- Lime is fat or hydraulic (IS 712 Classes A-F); cement is burnt to clinker at ~1450 °C by the wet or dry process and ground with 3-5% gypsum; Surkhi is an artificial pozzolana.
- Concrete is graded by 28-day cube strength; workability is measured by the slump test (200/100/300 mm cone, 4 layers × 25 strokes); curing for ≥7 days delivers the design strength.
- Timber seasoning removes sap to ~10-12% moisture, preventing warping and decay and raising strength; methods are air, kiln, water, boiling, electrical and chemical.
- Soil shear strength follows Mohr-Coulomb $\tau_f = c + \sigma \tan \phi$; consolidation is time-dependent settlement of saturated clay (Terzaghi); SPT and plate load tests give field parameters.

- Bearing capacity by Terzaghi; minimum depth by Rankine; foundations are shallow (isolated, combined, strap, raft) or deep (pile, well); black cotton soil needs under-reamed piles below the active zone.
- Grain stores must be dry (≤13-14% m.c.), sealed and rodent-proof; traditional morai / bukhari / kothar are improved by the PUSA bin (polythene moisture barrier), CAP storage and hermetic/CA storage; bulk beats bag on space and handling.
- Silage is preserved by anaerobic fermentation in tower, pit, trench or bunker silos; silo depth = removal rate × feeding days; deep bins follow Janssen (pressure reaches a limit) and shallow bins Rankine.

LAST-NIGHT REVISION

Must-remember	Value / formula
Farmstead area	3-5% of farm area
Domestic demand	135 L/day/capita
Cattle comfort zone	15-27 °C
Cow stall (454 kg)	1.10 m × 1.40 m ; gutter slope 2%
Cow floor space (BIS)	covered 3.5 m² / open 7.0 m²
Poultry	0.36 m²/bird ; light 12-14 h ; brooder 95 °F → 70 °F
Fence post spacing	2.4-3.0 m ; concrete post mix 4:2:1
First-class brick	absorption <20% ; strength ≥10.5 N/mm²
Lime IS 712	Class A eminently hydraulic → Class C fat lime
Slump cone	200/100/300 mm ; 4 layers × 25 strokes
Nominal mixes	M15 1:2:4 · M20 1:1½:3 · M25 1:1:2
Timber seasoning	to 10-12% m.c. ; air, kiln, water, boiling, electrical, chemical
Mohr-Coulomb	$\tau_f = c + \sigma \tan \phi$
Terzaghi	$q_u = cN_c + \gamma D_f N_q + 0.5\gamma B N_\gamma$
Rankine depth	$D_f = (p/\gamma)[(1-\sin\phi)/(1+\sin\phi)]^2$
Safe storage m.c.	13-14% (70-75% RH)
PUSA bin	polyethylene film moisture barrier in walls & floor
Hermetic storage	insects die at ~2% O_2
Silo	depth = 0.1 m/day × feeding days ; D ≤ 6 m
Janssen	$p_v = (wR/\mu'K)[1 - e^{(-K\mu' h/R)}]$; R = D/4

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CHAPTER

8

PLANT ENVIRONMENT, GREENHOUSE & PROTECTED CULTIVATION

Greenhouse effect · Classification · Design & loads · Glazing materials · Fan-and-pad cooling · Polyhouses & net houses · Hydroponics & aeroponics · Solar greenhouse drying

SYLLABUS : (Paper I · Soil & Water Conservation) Greenhouse fundamentals — definition, principle of the greenhouse effect, advantages of greenhouse cultivation; classification of greenhouses (by shape, utility and construction). Greenhouse design and selection — location, orientation, structural-design factors, environmental-control requirements. Greenhouse environmental control — methods of cooling and heating; fan-and-pad evaporative cooling system, ventilation, shade nets. Greenhouse covering/glazing materials — glass, polyethylene, polycarbonate, acrylic, fibreglass; properties and selection. Polyhouses — components, types (low-cost, medium-cost, high-tech), design factors and installation in Indian conditions. Net houses and shade-net structures. Soilless cultivation — hydroponics, aeroponics — concepts and overview. Plant environment / climate control — light, temperature, humidity and CO2 enrichment in protected cultivation systems.

Chapter Outline

1. **Greenhouse Fundamentals & the Greenhouse Effect**
2. **Classification of Greenhouses**
3. **Design, Site Selection & Structural Loads**
4. **Covering / Glazing & Framing Materials**
5. **Greenhouse Environmental Control**
6. **Polyhouses & Net Houses**
7. **Soilless Cultivation & Solar Greenhouse Drying**

▣ MIND-MAP — *Chapter 9 concept map*

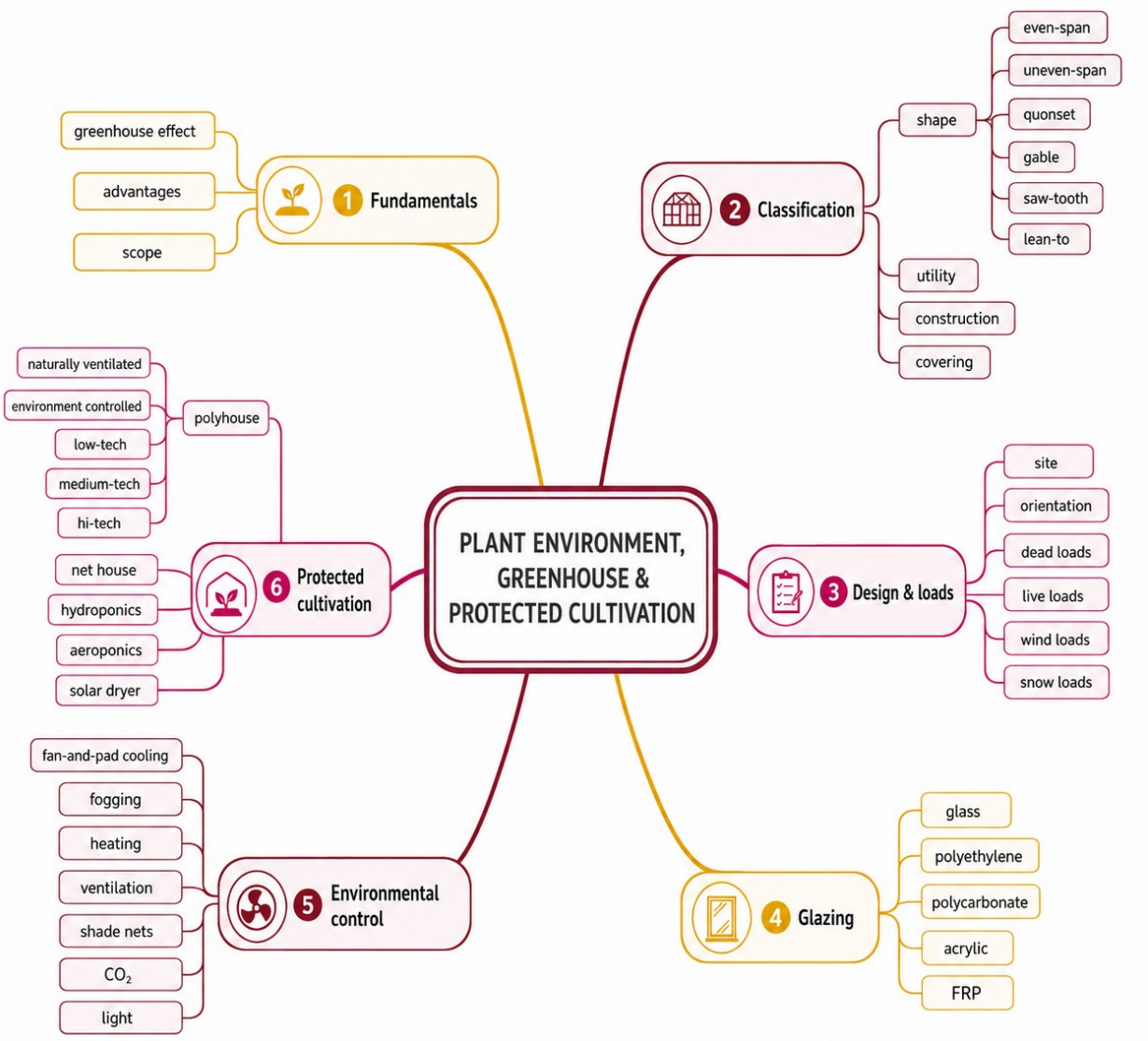


Fig. 9.0 Concept map of Chapter 9 — greenhouse fundamentals to protected cultivation.

1 GREENHOUSE FUNDAMENTALS & THE GREENHOUSE EFFECT

Protected cultivation grows crops inside a structure that ***modifies the plant's environment*** — light, temperature, humidity and CO2 — so that high-value crops can be raised off-season and under adverse weather. The greenhouse is its most complete form.

> ***Greenhouse*** — a framed or inflated structure covered with a ***transparent or translucent material*** (glass or plastic) large enough to grow crops under partial or full control of the interior environment, giving higher yield and quality than the open field.

PRINCIPLE — THE GREENHOUSE EFFECT (IFOS 2020)

Short-wave solar radiation passes freely through the transparent cover and is absorbed by the plants, soil and floor, which warm up and re-radiate energy as ***long-wave (thermal infra-red) radiation***. Glass and most plastics are largely opaque to this long-wave radiation, so it is ***trapped inside***; the interior therefore heats up. Warm air is also prevented from escaping by convection. This natural warming — the same effect that CO2 produces in the atmosphere — is the ***greenhouse effect***, and it is desirable in cold climates and off-season production but must be relieved by cooling in hot Indian summers.

ADVANTAGES OF GREENHOUSE CULTIVATION

Year-round / off-season production of high-value crops; higher yield (2-5×) and better quality; efficient use of water and fertilizer (drip/fertigation); protection from rain, wind, hail, frost and pests, so lower pesticide use; ideal conditions for propagation and quality planting material; and cultivation possible on poor or problem soils (soilless media). Limitations: high initial cost, need for skilled management and reliable power.

SCOPE & STATUS

World protected area was ~6.8 lakh ha by 1999; India's greenhouse area was only ~100 ha in the mid-1990s but has grown rapidly under the National Horticulture Mission / NHB subsidies, especially for flowers and off-season vegetables in Maharashtra, Karnataka, Punjab and the hills. ***[India area figures are time-sensitive — verify latest NHB/NCPAH data.]***

PREVIOUS YEAR QUESTIONS

- What do you mean by Greenhouse Effect? How does it affect the climate? How can you build a low-cost greenhouse? [low-cost greenhouse in §6]

  [IFoS 2020 · P1/5(d) · 8M]

- What are the advantages of greenhouse and polyhouse technologies? Explain the principles of greenhouse. Also describe the procedure for selection of site for the greenhouse. [site selection in §3]

  [UK·PSC RFO (Mains) 2021 · Q.4(iii) · 10M]

FIGURE 9.1 — The greenhouse effect

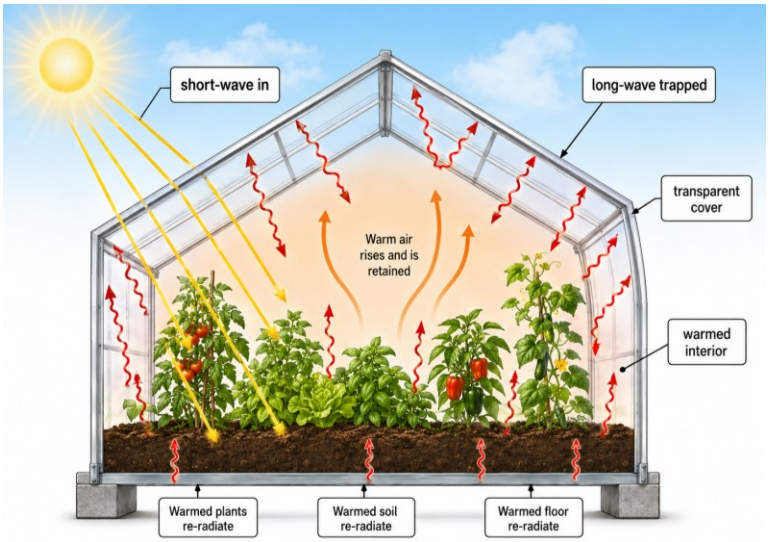


Fig. 9.1 Greenhouse effect — short-wave enters, long-wave is trapped, warming the interior.

2 CLASSIFICATION OF GREENHOUSES

Greenhouses are classified on several bases; a real structure is described by naming its type under each.

BY SHAPE (ROOF FORM)

Shape	Description / suitability
Lean-to	single slope built against a wall; small, cheap; limited light
Even-span	symmetrical twin slopes of equal width; good light & ventilation; the common free-standing type
Uneven-span	two slopes of unequal width, for hilly/sloping ground
Ridge-and-furrow (gutter-connected)	several spans joined at common gutters; economical for large

	areas; snow can load the valley
Saw-tooth	single-slope roofs with a vertical vent face; excellent natural ventilation (hot climates)
Quonset / hoop	semi-circular pipe-framed tunnel, plastic-covered; cheapest; common low-cost polyhouse
Gable / gothic-arch	steep or pointed roof; sheds rain & snow; good headroom

BY UTILITY, CONSTRUCTION & COVERING

By utility : for active heating (cold regions) or for active cooling (warm regions); production vs research/display houses.

By construction : ***free-standing*** (single independent house) or

Gutter : connected (several units sharing gutters — cheaper per unit area, uniform climate).

By framing : wooden, pipe-framed (GI) or trussed (large spans).

By covering : glass houses, plastic-film houses and rigid-panel (FRP/polycarbonate) houses.

BY COST / LEVEL OF TECHNOLOGY

Class	Features	Environment control
Low-cost (naturally ventilated)	bamboo/wood or GI-pipe frame, UV film, gravity ventilation; ₹300-500/m²	none beyond vents & shade net
Medium-cost	GI-pipe frame, better film/net, exhaust fans or foggers, manual control; ₹800-1600/m²	partial — cooling/ventilation only
High-tech (environment-controlled)	galvanised structure, fan-and-pad + heating, automated sensors & controls; ₹2000-4000+/m²	full — temperature, humidity, CO2, light

[The three-tier cost classification follows standard NHB/NCPAH practice; the supplied books give the naturally-ventilated vs environment-controlled poles and the low-cost type — flagged per SOP.]

PREVIOUS YEAR QUESTIONS

- Classify various types of greenhouse and briefly discuss each of them.

  [IFoS 2023 · P1/5(e) · 8M]

- What are the classifications of greenhouses based on shape? List the different covering materials used for greenhouses. [covering materials in §4]

  [IFoS 2021 · P1/8(b) · 15M]

▣ *FIGURE 9.2 — Greenhouse types by shape*

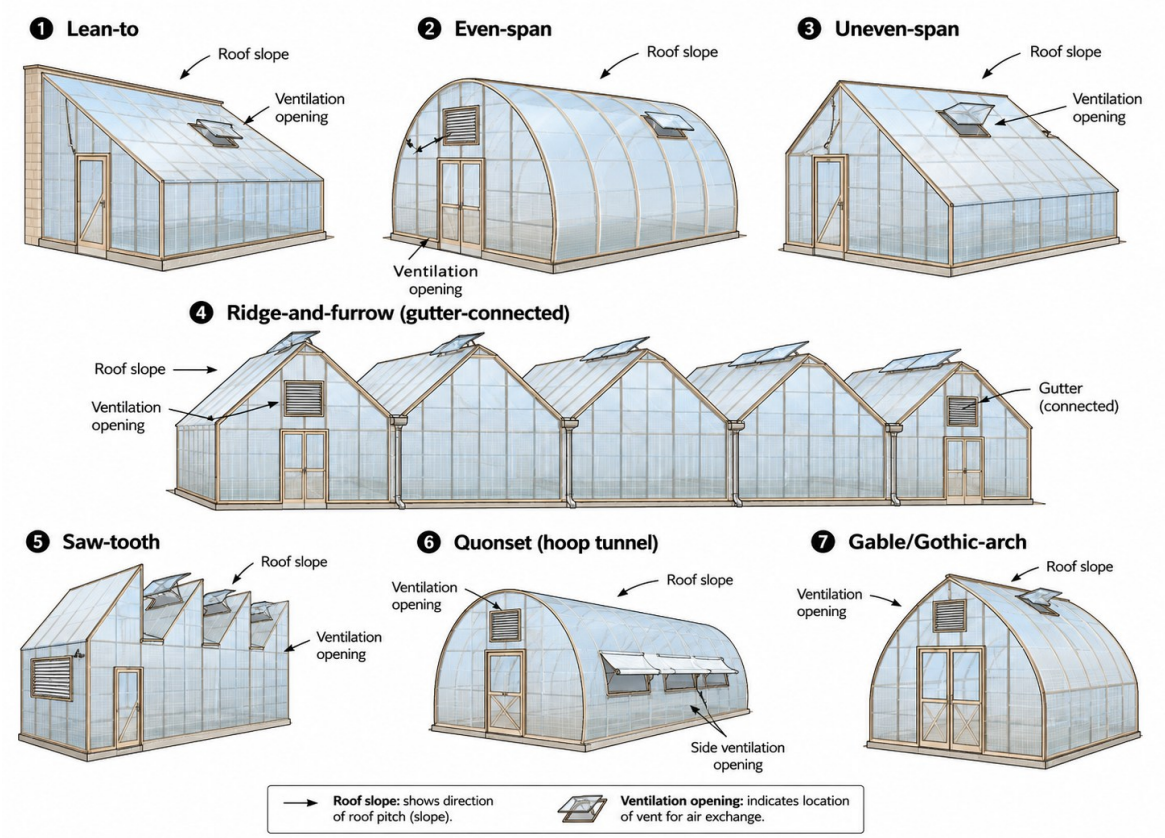


Fig. 9.2 Greenhouse classification by shape.

3 DESIGN, SITE SELECTION & STRUCTURAL LOADS

SITE SELECTION

Choose a site with ***maximum sunshine*** and no shading by buildings/trees; level, well-drained ground with firm bearing soil; a dependable supply of ***good-quality water and power***; shelter from strong winds (or a windbreak); good road access and nearness to the market/labour; and freedom from industrial pollution and frost pockets.

ORIENTATION & DESIGN FACTORS

In India a free-standing house is usually oriented with its ***ridge east–west*** (long axis) so that the low winter sun enters the south face — maximising light in winter and easing summer shading; gutter-connected ranges run north-south. Design must fix the span, gutter height, roof slope (for light and drainage), ventilator area, foundation, and the environmental-control system to suit the crop and climate.

STRUCTURAL DESIGN LOADS (HP·PSC 2021)

The frame is designed (per NGMA/ASAE practice) for the worst combination of:

Dead load — self-weight of frame, glazing and fixed services. **Live load** — temporary loads during erection/maintenance (workers). **Collateral / crop load** — hanging plants, irrigation lines, equipment. **Wind load** — the governing load in India (design wind ~130-150 km/h); acts as pressure on the windward face and suction on the leeward and roof. **Snow load** — on roofs in hilly regions. **Seismic load** — in seismic zones.

Wind: $q = 0.6\,V^2$ (N/m^2; V in m/s) ; wind force $= q \cdot C_p \cdot A$ Snow: $p_f = 0.7 \cdot C_e \cdot C_t \cdot I_s \cdot p_g$

q = velocity pressure; V = design wind speed; C_p = pressure coefficient; A = exposed area; p_f = design roof snow load; C_e exposure, C_t thermal, I_s importance factors; p_g = ground snow load.

◆ **WORKED NUMERICAL — *Design loads on an even-span greenhouse*** [cf. HP·PSC RFO 2021 · Q.4(d) · 10M (illustrative data)]

Problem. *Work out the dead, live, wind and snow loads on an even-span greenhouse of 8 m span and 20 m length, eave height 2.5 m and ridge height 4.0 m, at a design wind speed of 130 km/h. Take dead load 0.15 kN/m² of roof, live load 0.15 kN/m² of plan, snow 0.20 kN/m², and roof pressure coefficient 0.8.*

Geometry. plan area = 8 × 20 = 160 m² ; roof rise = 4.0 − 2.5 = 1.5 m over half-span 4 m ⇒ slope 20.6°, slope length = √(4²+1.5²) = 4.27 m ; roof area = 2 × 4.27 × 20 = 170.9 m²

Dead load. = 0.15 × 170.9 = 25.6 kN

Live load. = 0.15 × 160 = 24.0 kN

Wind load. $V = 130/3.6 = 36.1$ m/s ;

$$q = 0.6 \times 36.1^2 = 782 \text{ N/m}^2 = 0.78 \text{ kN/m}^2 ;$$

$$\text{force} = q \times C_p \times A = 0.78 \times 0.8 \times 170.9 = 107 \text{ kN}$$

Snow load. = 0.20 × 160 = 32.0 kN

Result. Dead ≈ 25.6 kN, Live ≈ 24.0 kN, Wind ≈ 107 kN (governs), Snow ≈ 32.0 kN — design the frame and anchorage for the dead + wind combination.

PREVIOUS YEAR QUESTIONS

- (i) Write briefly about the various aspects of selection and design of greenhouse. [10 M] (ii) Briefly describe the different types of silos which can be used to store animal feed/forage. [5 M] [part (ii) belongs to Ch.8 — silos/silage; answer briefly with cross-reference: tower, pit, trench and horizontal/bunker silos, metallic vs concrete.]

  [IFoS 2025 · P1/8(b) · 15M]

- Briefly describe different types of loads for design and construction of a greenhouse.

  [HP·PSC RFO (Mains) 2021 · Q.4(d) · 10M]

FIGURE 9.3 — Greenhouse orientation & loads

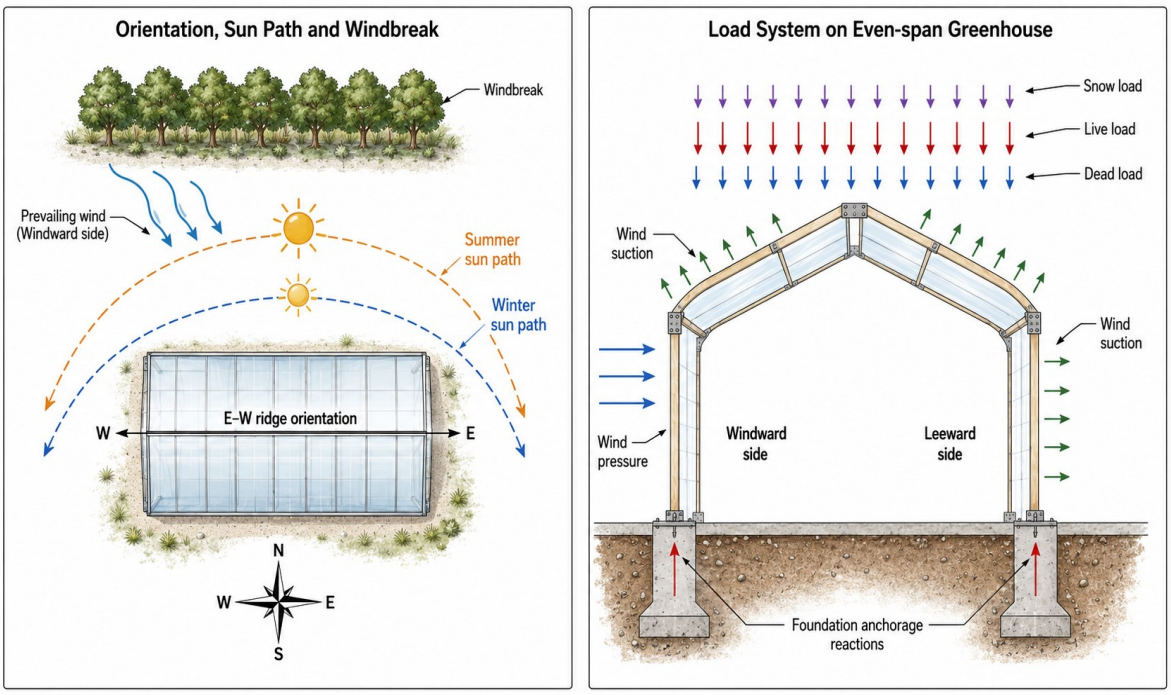


Fig. 9.3 E-W orientation (left) and the load system on a greenhouse frame (right).

4 COVERING / GLAZING & FRAMING MATERIALS

The covering (glazing/cladding) admits light and traps heat; its light transmission, life, cost, weight and insulation decide the greenhouse's performance and running cost.

Covering	Light transmission	Life / remarks
Glass	~90%	20+ yr; best clarity & durability; heavy, fragile, costly frame
Polyethylene (LDPE) film	~85-87%	UV-stabilised film 2-3 yr; cheapest; commonest in India; low insulation
Polycarbonate (twin-wall)	~80%	10+ yr; rigid, light, unbreakable, good insulation; costly; can yellow
Acrylic (PMMA)	~90%	long life, clear, UV-stable; brittle, costly
Fibreglass (FRP)	~85-90%	light, strong; transmission falls as it weathers/yellows

Selection : balance light transmission and diffusion, service life, initial cost, insulation (double layers cut heat loss), weight (affects the frame) and durability. For most Indian low/medium-cost houses ***UV-stabilised polyethylene film*** is used; polycarbonate/acrylic for hi-tech permanent houses; glass mainly for research/display. **Framing materials —** galvanised iron (GI) pipe (commonest, durable), wood (cheap, low-cost houses, but rots), and aluminium (light, corrosion-free, costly).

PREVIOUS YEAR QUESTIONS

- Give the details of different greenhouse construction materials and covering materials.
  [IFoS 2019 · P1/7(b) · 10M]
- List the different covering materials used for greenhouses. [full question in §2]
  [IFoS 2021 · P1/8(b)(part) · 15M]

FIGURE 9.4 — Covering materials comparison

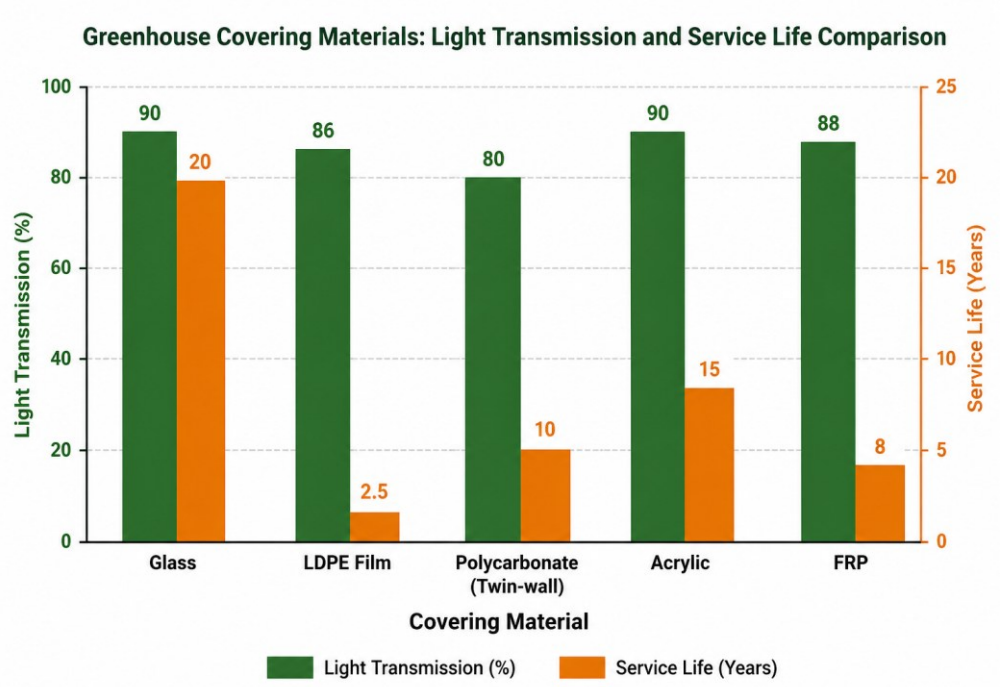


Fig. 9.4 Light transmission and service life of common glazing materials.

5 GREENHOUSE ENVIRONMENTAL CONTROL

Because the greenhouse effect over-heats the interior in Indian summers, ***cooling*** is usually the main problem; heating matters in the hills and winter, and light, humidity and CO2 are managed for the crop.

NECESSITY OF ENVIRONMENTAL CONTROL (IFOS 2024)

Crop growth depends on temperature, humidity, light and CO2 being kept within the optimum band. Uncontrolled, a closed greenhouse can exceed 45-50 °C, wilting the crop; high humidity invites disease; and CO2 is depleted by photosynthesis. Control keeps all four near optimum, giving maximum yield and quality — hence the need for cooling, heating, ventilation, shading and enrichment.

COOLING — FAN-AND-PAD EVAPORATIVE SYSTEM (IFOS 2016, 2017)

The commonest active cooling method in India. A ***wetted cellulose/wood-wool pad*** is fixed on one (upwind) wall and ***exhaust fans*** on the opposite wall. The fans draw outside air in through the pad; water trickling down the pad evaporates, and the ***latent heat of evaporation cools the incoming air*** before it sweeps across the house and out through the fans. It can drop the air temperature close to the ***wet-bulb temperature*** an efficiency of about 80% of the wet-bulb depression.

$$T_{cool} = T_{out} - \eta \cdot (T_{out} - T_{wb})$$

Air change ≈ 1 house-volume per minute

Pad area = airflow / face velocity (≈75 m/min)

T_{cool} cooled air temp; T_{out} ambient; T_{wb} wet-bulb temp; η pad efficiency (≈0.80). Rule of thumb: ~1 gal water per ft of pad; fan-to-pad distance ≤150-200 ft; provide 8 m³/min per m² of floor as a guide.

◆ **WORKED NUMERICAL — *Fan-and-pad sizing & cooled-air temperature*** **[IFoS 2016/2017 · P1/8(a) · 12M/10M (design of the fan-and-pad system)]**

Problem. *Design the fan-and-pad cooling for an 8 m × 20 m polyhouse of average height 3.25 m in a place where the summer air is 40 °C at 24 °C wet-bulb; pad efficiency 80%. Find the exhaust airflow, number of fans, pad area and the cooled-air temperature.*

Air-change airflow. house volume = 160 × 3.25 = 520 m³ ; at 1 air change per minute, airflow = 520 m³/min (≈18,400 cfm)

Fans. with 20,000 m³/h (333 m³/min) fans ⇒ 520/333 = 1.56 ⇒ 2 exhaust fans on the leeward wall

Pad area. = airflow / face velocity = 520 / 75 = 6.9 m² of pad on the upwind wall

Cooled-air temperature. $T_{cool} = 40 - 0.80 \times (40 - 24) = 40 - 12.8 = 27.2$ °C

Result. Provide ~7 m² of wetted pad, 2 exhaust fans of ~20,000 m³/h, giving cooled air at ≈ 27 °C — a 13 °C drop.

OTHER CONTROL METHODS

Fogging/misting : fine water fog evaporates in the air; near-100% efficient, also raises humidity.

Ventilation : natural (ridge + side vents, chimney effect) or forced (exhaust fans); ridge/roof vents of ~15-25% of floor area.

Shading : ***shade nets*** (25-75% shade, black/green/white), whitewash or movable screens cut excess light and heat.

Heating : unit heaters, central hot-water/steam, or solar with rock/water storage, for cold nights/hills; heat loss $Q = A \cdot \Delta T / R$.

CO2 enrichment : raising CO2 to ~1000-1500 ppm boosts photosynthesis in closed winter houses.

Supplemental light : for photoperiod control and dark-season growth.

PREVIOUS YEAR QUESTIONS

- What is the necessity of controlling environment inside the greenhouse? Briefly mention different methods to control greenhouse environment.

  [IFoS 2024 · P1/8(c) · 10M]

- Discuss various types of poly houses (low to high cost) used for cultivation of high value crops. Explain the working principle of fan and pad evaporative cooling systems. [polyhouse types in §6]

  [IFoS 2017 · P1/8(a) · 10M]

- What is polyhouse? Describe the working of fan and pad cooling system with a neat sketch. [polyhouse in §6]

  [IFoS 2016 · P1/8(a) · 12M]

FIGURE 9.5 — Fan-and-pad evaporative cooling system

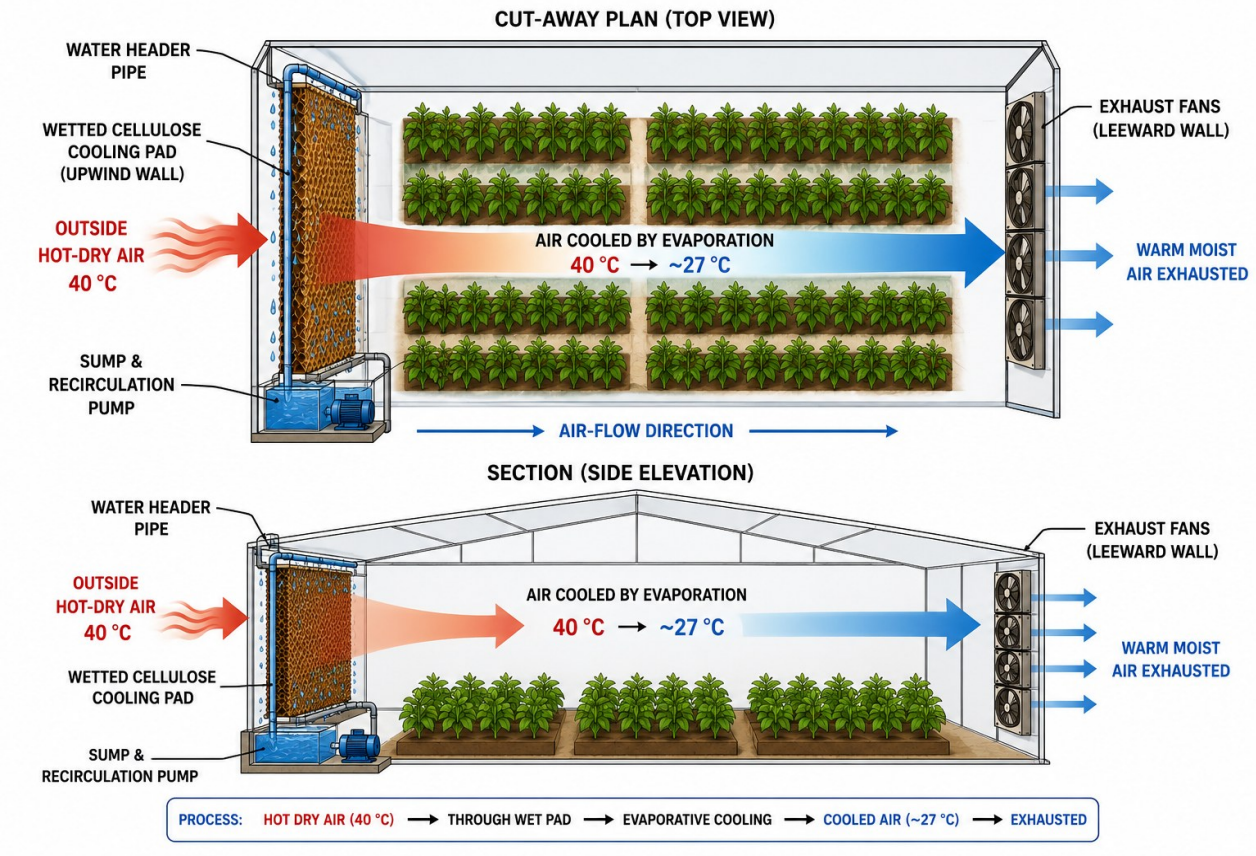


Fig. 9.5 Fan-and-pad evaporative cooling — air cooled through a wet pad and drawn out by exhaust fans.

6 POLYHOUSES & NET HOUSES

Polyhouse : a greenhouse whose covering is a ***polyethylene (plastic) film*** — the low-cost, widely-used form of protected structure in India; a framed (bamboo/wood or GI-pipe) structure clad with UV-stabilised film.

COMPONENTS OF A POLYHOUSE (IFOS 2018)

Foundation and anchoring (concrete footings / grouted GI pipes); the ***GI-pipe frame*** (columns, bottom & top chords, purlins, arches); the ***cladding*** (UV-stabilised LDPE film with aluminium/spring profiles and 'poly-grip' locks); ***gutters*** (for gutter-connected units); ***doors and an entry/air-lock***; ventilation (ridge/side roll-up vents or exhaust fans); the ***cooling/fogging and shade-net system***; drip irrigation and fertigation lines; and instrumentation/controls in hi-tech units.

TYPES OF POLYHOUSE (LOW TO HIGH COST) (IFOS 2017)

Type	Construction & control	Suitability
Low-cost / naturally-ventilated	bamboo/wood or light GI frame, UV film, side/roof gravity ventilation, shade net; no powered control	mild climates; low-value crops; small farmers
Medium-cost / partially-controlled	GI-pipe frame, film + insect net, exhaust fans or foggers, manual/thermostat control	moderate climates; vegetables & cut flowers
High-tech / environment-controlled	galvanised structure, fan-and-pad + heating, automated climate & fertigation control	extreme climates; high-value export flowers/vegetables

FACTORS INFLUENCING POLYHOUSE DESIGN & INSTALLATION IN INDIA (IFOS 2018)

Local climate (temperature, humidity, wind, rainfall) and the crop's requirement; site and orientation; the ***cladding and its life under Indian UV***; ventilation and cooling need (fan-pad vs natural); structural design for wind (130-150 km/h) and the monsoon; water and power reliability; cost and the ***available subsidy (NHB/NHM)***; and the grower's skill and market for the produce.

NET HOUSES & SHADE-NET STRUCTURES

Net house **—** a protected structure clad with ***agro shade-net (polypropylene)*** instead of film — used mainly for propagation, hardening and shade-loving crops in warm regions where heating is not needed and film cooling is expensive; roof may be net, glass or film with net sides.

Shade nets : woven/knitted polypropylene with a rated shade percentage (25, 35, 50, 75%); ***black, green or white*** (black is most used and durable; white/green alter light quality); they cut solar radiation and heat, reduce wind and hail damage and exclude larger pests. Uses: nurseries, hardening of tissue-culture plants, and cultivation of shade-loving flowers (anthurium, orchids) and vegetables.

BUILDING A LOW-COST GREENHOUSE (IFOS 2020)

Select a sunny, sheltered, well-drained site; erect a simple ***bamboo or GI-pipe frame*** on concrete/grouted footings with an east-west ridge; clad with UV-stabilised polyethylene film fixed by battens/poly-grip; provide roll-up side curtains and ridge vents for ***natural ventilation***, a shade net for summer, and a door with an air-lock; add drip irrigation. This naturally-ventilated house needs no powered cooling and costs a fraction of a hi-tech unit.

PREVIOUS YEAR QUESTIONS

- What are the main components of Polyhouse? Discuss various factors influencing the design and installation of Polyhouses in India for surface covered cultivation.
  [IFoS 2018 · P1/8(a) · 10M]
- Discuss various types of poly houses (low to high cost) used for cultivation of high value crops. [fan-and-pad part in §5]
  [IFoS 2017 · P1/8(a)(part) · 10M]
- What is polyhouse? [fan-and-pad part in §5] [IFoS 2016 · P1/8(a)(part) · 12M]

▣ *FIGURE 9.6 — Polyhouse components & net house*

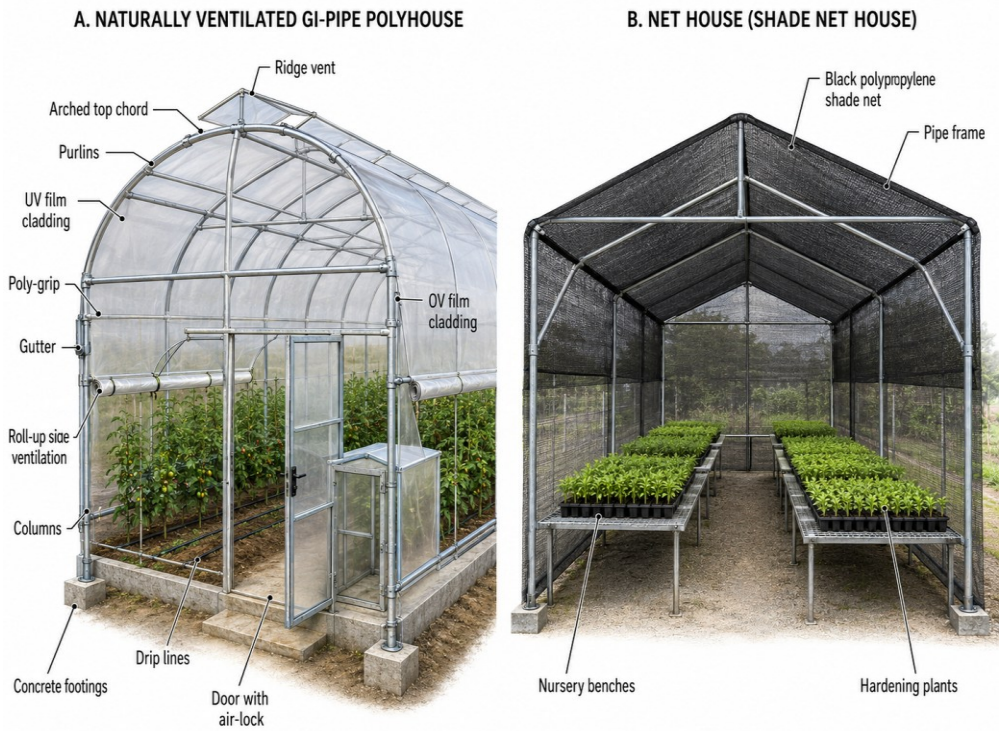


Fig. 9.6 Polyhouse components (left) and a shade-net house (right).

7 SOILLESS CULTIVATION & SOLAR GREENHOUSE DRYING

HYDROPONICS

Hydroponics : growing plants ***without soil***, with the roots supported in an inert medium (or none) and supplied with a balanced ***nutrient solution*** in water.

Systems : NFT (*nutrient film technique*) — a thin film of nutrient solution recirculates along sloping channels past bare roots; ***deep-flow / floating raft*** — plants float on an aerated nutrient pool; ***substrate (aggregate) culture*** — roots grow in cocopeat/perlite/rockwool fed by drip. Advantages: no soil-borne disease, precise nutrition, high water-use efficiency, and cultivation on non-arable land; needs power, skill and careful EC/pH control.

AEROPONICS

Aeroponics : plants grown with their roots suspended in a ***closed chamber and misted*** with nutrient solution at intervals — no medium at all. It gives excellent root aeration and the highest water/nutrient efficiency and is used for seed-potato mini-tuber production and research; but it fails quickly if the misting/power stops.

SOLAR GREENHOUSE DRYING (OPSC 2024)

When not cropping, a greenhouse makes an excellent ***solar dryer***: the transparent cover admits solar radiation that heats the air and the produce, while an air path (natural or fan-forced, often up a ***black-painted chimney***) carries away the evaporated moisture. It dries faster and more hygienically than open-sun drying (no dust, rain, birds or spoilage) and gives a better-coloured product; used for grapes→raisins, chillies, fruits, vegetables, tobacco curing and ***copra***.

DESIGNING A SOLAR TUNNEL DRYER FOR COPRA

1. **Load & moisture :** fix the batch of coconut (kernel ~50% initial moisture, to be brought to ~6-7% for copra) and the drying time.
2. **Collector/tunnel area :** size the semi-cylindrical polyethylene tunnel-cum-collector from the heat needed to evaporate the water (latent heat) and the local solar insolation.
3. **Air flow :** provide a black inlet section to pre-heat air and an exhaust (chimney or small PV-driven fan) to sweep out moist air.
4. **Trays :** spread kernels in a thin layer on raised mesh trays inside the tunnel.
5. **Controls :** shade/vent to avoid case-hardening; protect from rain.

PREVIOUS YEAR QUESTIONS

- Describe briefly the principle of operation and applications of solar greenhouse dryer in agriculture. Enumerate the steps involved in designing a solar tunnel dryer for a coconut farmer producing copra.

[OPSC·CSE (Main) 2024-25 · Paper-II Q.5 · 15M]

FIGURE 9.7 — Soilless culture & solar tunnel dryer

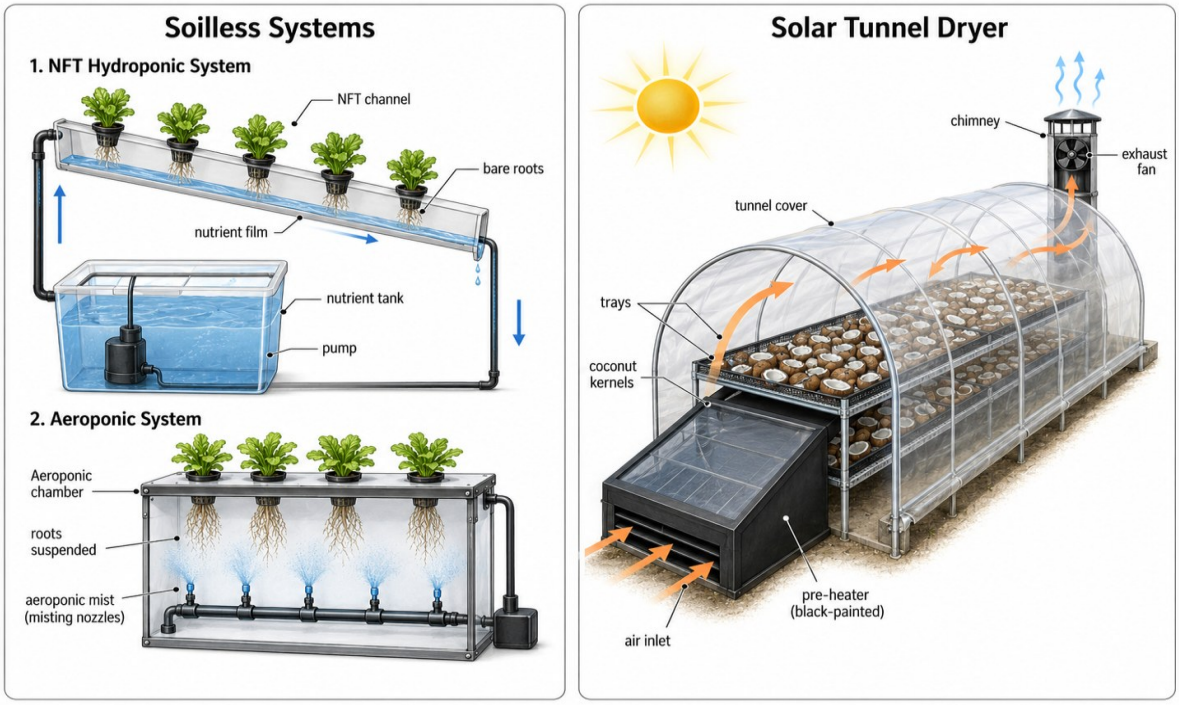


Fig. 9.7 Hydroponics/aeroponics (left) and a solar tunnel dryer for copra (right).

FORMULA SHEET — CHAPTER 9

Quantity	Formula / value
Greenhouse effect	short-wave in → long-wave trapped by glazing
Wind velocity pressure	$q = 0.6\ V^2$ (N/m^2, V in m/s)
Wind force	$F = q \cdot C_p \cdot A$
Snow load	$p_f = 0.7\ C_e\ C_t\ I_s\ p_g$
Heat loss (heating)	$Q = A \cdot \Delta T / R$
Evaporative cooling	$T_{cool} = T_{out} - \eta\ (T_{out} - T_{wb})$; $\eta \approx 0.80$
Cooling air change	≈ 1 house-volume per minute
Pad area	= airflow / face velocity (≈75 m/min)

CO2 enrichment	raise to ~1000-1500 ppm
Shade nets	25-75% shade; black/green/white

SUMMARY

- A greenhouse is a transparent-covered framed structure that controls the plant environment; the greenhouse effect (short-wave in, long-wave trapped) warms the interior.
- Advantages: off-season high-value production, higher yield & quality, water/fertiliser efficiency, protection from weather and pests; limits are high cost and skilled management.
- Classify by shape (lean-to, even/uneven-span, ridge-furrow, saw-tooth, quonset, gable), utility, construction (free-standing/gutter-connected), covering, and cost (low/medium/hi-tech).
- Site for maximum sunshine, level well-drained firm ground, water & power, wind shelter; orient the ridge east-west; design span, slope, vents, foundation and control system.
- Design loads: dead, live, collateral/crop, wind (governs in India, ~130 km/h; $q = 0.6V^2$), snow (hills) and seismic.
- Glazing: glass (90%, 20 yr), UV polyethylene film (86%, 2-3 yr, cheapest, commonest), polycarbonate (rigid, insulating), acrylic and FRP; frames of GI pipe, wood or aluminium.
- Cooling dominates in India: the fan-and-pad system draws air through a wet pad so evaporation cools it toward the wet-bulb ($\eta \approx 80\%$); also fogging, ventilation and shade nets; heating for the hills.
- Polyhouse = plastic-film greenhouse; components are foundation, GI frame, film cladding, vents, cooling, drip; types low-cost (naturally ventilated) → high-tech (environment controlled).
- Net houses clad in polypropylene shade net (25-75%, black/green/white) are used for propagation, hardening and shade-loving crops.
- Soilless culture: hydroponics (NFT, deep-flow, substrate) and aeroponics (misted roots) give soil-free, disease-free, water-efficient production; a greenhouse also serves as a solar dryer (grapes, chillies, copra).

LAST-NIGHT REVISION

Must-remember	Value / point
Greenhouse effect	short-wave enters, long-wave trapped by cover
Shapes	lean-to · even/uneven-span · ridge-furrow · saw-tooth · quonset · gable
Cost tiers	low-cost (natural vent) · medium · hi-tech (env. controlled)
Orientation	ridge E-W (free-standing)
Governing load	wind ~130 km/h ; $q = 0.6V^2$
Glazing (commonest)	UV polyethylene film ~86%, 2-3 yr
Glass / polycarbonate	90% / rigid insulating
Fan-and-pad	wet pad + exhaust fans ; $\eta \approx 80\%$; $T_{cool} = T_{out} - \eta(T_{out} - T_{wb})$
Air change (cooling)	1 house-volume per minute
Shade net	25-75% ; black most used
Polyhouse	plastic-film greenhouse ; GI frame + UV film
Net house	shade-net clad ; propagation & hardening
Hydroponics	NFT · deep-flow · substrate (no soil)
Aeroponics	roots misted in air ; seed-potato minitubers
Solar greenhouse dryer	faster, hygienic; grapes, chillies, copra

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Test Series



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Forestry Comprehensive Course



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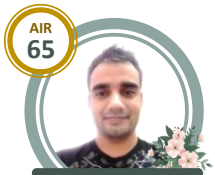
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64 Out of 147 Total Selections in

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Congratulations

To all our successful candidates in

INDIAN FOREST SERVICE (IFOS) 2025



Siddharath

Comprehensive Interview Guidance Program (CIGP)



Karan Kumar Singh



Aanchal Sharma

Comprehensive Interview Guidance Program (CIGP)



Sankalp Dixit

Comprehensive Interview Guidance Program (CIGP)



Ravi Laxmipriya

Comprehensive Interview Guidance Program (CIGP)



Abhimanyu Balyan

Comprehensive Interview Guidance Program (CIGP)



Ravinanadan Gupta

Comprehensive Forestry Course + Test Series + CIGP



Divyanjali Jaiswal

Comprehensive Forestry Course



Abhay Raghav

Comprehensive Interview Guidance Program



Puneet Kumar

Comprehensive Forestry Course + CIGP



Kadam Sumati Yashawant

Comprehensive Forestry Course + CIGP



Aman Ayushkar

Comprehensive Interview Guidance Program (CIGP)



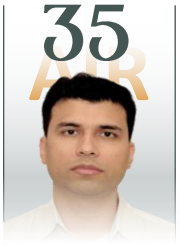
Sushmita Singh

Comprehensive Interview Guidance Program (CIGP)



Athul Ajay

Test Series



Anurag Kumar

Comprehensive Interview Guidance Program (CIGP)



Deepshikha

Comprehensive Forestry Course + CIGP



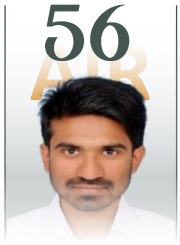
B Jaya Aswantha Reddy

Comprehensive Forestry Course 2022



Sanskar Bharti

Test Series



Sachin Datt

Test Series + CIGP



Anusha Srinivas

Comprehensive Forestry Course + Test Series



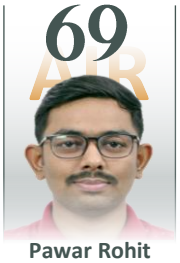
Ashish

Comprehensive Forestry Course + Test Series



Saurabh Singh

Comprehensive Forestry Course



Pawar Rohit Sanjay

Comprehensive Interview Guidance Program (CIGP)



Omkar Kumar

Comprehensive Forestry Course 2024



Manav Gupta

Comprehensive Forestry Course + CIGP



Prityesh Raj

Comprehensive Interview Guidance Program (CIGP)



Reshma Nivetha R

Comprehensive Forestry Course + CIGP



Pawar Akshay Haribhau

Comprehensive Interview Guidance Program (CIGP)



Sambhav Kumar Jain

Test Series



Rajat Kataria

Comprehensive Interview Guidance Program (CIGP)

Congratulations

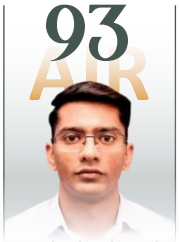
To all our successful candidates in

INDIAN FOREST SERVICE (IFOS) 2025



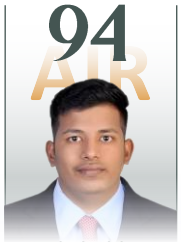
Rajat Kumar

Comprehensive Forestry Course + CIGP



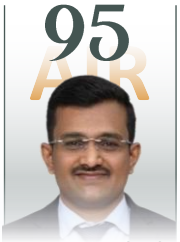
Kailash Chand Yadav

Comprehensive Forestry Course + CIGP



Patil Shubham Jaysing

Comprehensive Forestry Course



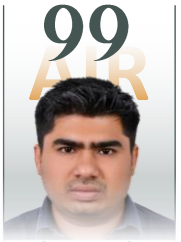
Hinge Harshad Pandurang

Comprehensive Forestry Course (2023) + Test Series + CIGP



Pawar Onkar Mahesh

Comprehensive Interview Guidance Program (CIGP)



Dharmendra Choudhary

Comprehensive Interview Guidance Program (CIGP)



Kushare Pratik Chandrashekhar

Comprehensive Interview Guidance Program (CIGP)



Venkatesh M

Comprehensive Forestry Course + CIGP



K Sai Goutham

Comprehensive Forestry Course



Kritika Negi

Comprehensive Forestry Course 2023 + CIGP 2025



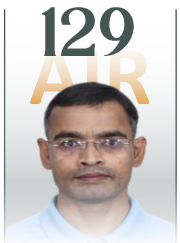
Himanshu Kumar

Comprehensive Forestry Course 2023 + CIGP



Satyam Shivam Sundaram

Comprehensive Interview Guidance Program (CIGP)



Satya Pal Arya

Comprehensive Interview Guidance Program (CIGP)



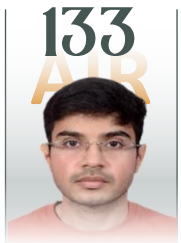
Aakash Verma

Comprehensive Forestry Course



Ajay Kumar Ushara

Comprehensive Forestry Course + CIGP



Vikalp Mandawaria

Comprehensive Forestry Course + Test Series + CIGP



Prateek Kumar Meena

Comprehensive Forestry Course + CIGP



Chinthanai Selvan T

Comprehensive Forestry Course



Naresh Mandhan

Comprehensive Forestry Course



Rajan Sharma

Comprehensive Interview Guidance Program (CIGP)

50 Out of **148** Total Selections in

Indian Forest Service (IFoS) 2025



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