Chapter 29: Modelling Infiltration Capacity

Introduction

Infiltration refers to the process by which water on the ground surface enters the soil. It plays a critical role in the hydrological cycle, affecting runoff, groundwater recharge, and soil moisture dynamics. Accurately modelling infiltration capacity is essential for hydrologic design, flood forecasting, irrigation planning, and watershed management. This chapter focuses on the principles, empirical and conceptual models, and mathematical techniques used to represent infiltration processes.

29.1 Infiltration – Definition and Importance

- **Definition**: Infiltration is the movement of water through the soil surface into the subsurface soil layers.
- **Hydrological Importance**:
  - Determines runoff generation.
  - Influences groundwater recharge rates.
  - Controls soil erosion and water quality.
  - Impacts crop water availability in agricultural planning.

29.2 Factors Affecting Infiltration

- **Soil Properties**: Texture, structure, porosity, and organic matter content.
- **Surface Conditions**: Vegetative cover, compaction, and crusting.
- **Moisture Content**: Initial saturation level plays a major role; dry soils absorb more initially.
- **Rainfall Characteristics**: Intensity, duration, and distribution.
- **Land Use and Land Cover**: Urbanization reduces infiltration due to impervious surfaces.
- **Temperature**: Affects viscosity of water and soil permeability.

29.3 Infiltration Capacity and Rate

- **Infiltration Capacity**: The maximum rate at which soil can absorb rainfall under specific conditions.
- **Infiltration Rate**: The actual rate of infiltration, which may be less than the infiltration capacity if rainfall rate is limiting.

- **Cumulative Infiltration**: The total volume of water infiltrated over a period of time, generally expressed in mm or cm.

29.4 Methods of Measuring Infiltration

- **Field Methods**:
  - *Double Ring Infiltrometer*: Two concentric rings to minimize lateral flow, widely used in field studies.
  - *Tension Infiltrometer*: Measures unsaturated infiltration by applying tension to the water.
- **Laboratory Methods**: Soil column experiments under controlled conditions.
- **Remote Sensing and Modelling Techniques**: Used in large-scale watershed studies.

29.5 Empirical Infiltration Models

These models are based on observed data and curve-fitting techniques. They do not explicitly consider the physical processes of infiltration.

29.5.1 Horton's Infiltration Model

- Proposed by Robert Horton (1933).
- Assumes infiltration capacity decreases exponentially with time.
- **Equation**:

$$f(t) = f_c + (f_0 - f_c)e^{-kt}$$

- where: $f(t)$: infiltration rate at time t f_0: initial infiltration rate f_c: final steady-state infiltration rate k: decay constant
- **Applications**: Widely used in hydrologic simulations, especially for design storms.

29.5.2 Philip's Equation

- Based on soil physics, considers both capillarity and gravity effects.
- **Equation**:

$$f(t) = \frac{1}{2}St^{-1/2} + A$$

- where: S: sorptivity A: transmissivity (constant)
- **Limitation**: Accurate only during early-time infiltration events.

29.5.3 Green-Ampt Model

- Conceptual model based on a sharp wetting front.
- **Assumptions**: Homogeneous soil, uniform initial water content, distinct wetting front.
- **Equation**:

$$f(t) = K\left(1 + \frac{\psi\Delta\theta}{F(t)}\right)$$

- where: K: saturated hydraulic conductivity ψ: wetting front suction head $\Delta\theta$: change in moisture content $F(t)$: cumulative infiltration
- **Advantages**: Physically based; useful in event-based simulations.
- **Limitations**: Not suitable for heterogeneous soils.

29.6 Conceptual and Physically Based Models

Unlike empirical models, these incorporate physical laws like Darcy's Law and conservation of mass.

29.6.1 Richards' Equation

- Governs unsaturated flow in soils.
- Combines Darcy's law with continuity equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} + 1\right)\right]$$

- where:
  - θ: volumetric water content
  - h: pressure head
  - z: vertical coordinate
  - $K(\theta)$: unsaturated hydraulic conductivity
- **Applications**: Used in numerical models like HYDRUS, SWAT.
- **Challenges**: Requires detailed soil properties and initial conditions; computationally intensive.

29.6.2 Numerical Techniques

- *Finite Difference Method (FDM)* and *Finite Element Method (FEM)* are commonly used.
- Models like SWMS, HYDRUS use FEM for solving Richards' equation.

29.7 Model Parameter Estimation

- **Calibration**: Adjusting parameters to match observed infiltration data.
- **Sensitivity Analysis**: Determines influence of parameters like f_0, f_c, k, etc.
- **Inverse Modelling**: Used in physically based models to estimate soil parameters from infiltration data.

29.8 Infiltration Modelling in Watershed Hydrology

- Used to partition rainfall into infiltration and surface runoff.
- Infiltration models are embedded in hydrologic models like:
  - SWAT (Soil and Water Assessment Tool)
  - HEC-HMS (Hydrologic Modeling System)
  - MIKE SHE
- Impacts simulation of flood events, soil erosion, nutrient transport.

29.9 Infiltration in Urban and Agricultural Settings

Urban Areas

- Impervious surfaces reduce infiltration drastically.
- Requires modelling of infiltration in green infrastructure like bioswales and permeable pavements.

Agricultural Areas

- Influenced by tillage, irrigation, and crop rotation.
- Important for irrigation scheduling and drainage design.

29.10 Recent Advances in Infiltration Modelling

- **Machine Learning Approaches**:

  - Use of neural networks, support vector machines, and random forests to model infiltration patterns.

- **Remote Sensing Integration**:
  - Estimation of soil moisture and surface characteristics to improve infiltration estimation.

- **GIS-based Modelling**:
  - Spatially distributed models to simulate infiltration across large catchments.
