Urban Hydrology
Learning objectives

After completing this section, you will know

• Hydrological processes relevant to urban storm drainage

• Impacts of urbanization on hydrological processes and on surface runoff

• Various methods to mitigate adverse hydrological impacts of urbanizations

• Basic concepts in catchment modelling
Urbanization

• Characterized by development of habitats and associated infrastructure facilities required for economic and social activities necessary for livelihood of growing population in the area

• Brings changes in land use
  – with construction of buildings, roads, parks and other facilities, and increases supply/release of water

Natural hydrological processes are affected
Hydrologic cycle

• Water falls to the ground as rain, snow, hail, sleet etc. from clouds

• Water infiltrates or seeps into the ground, a process called percolation

• Subsurface water
  I. taken up by the vegetation and returns to the atmosphere through transpiration, or evaporation of water from all surfaces
  II. Enter to water bodies as spring water/groundwater.

• Excess water runs over the ground surface as runoff
Atmospheric circulation

Much of the water precipitated on the land surface is derived from moisture evaporated from the oceans and transported by atmospheric circulation.
Precipitation

Cooling of air masses and condensation of water vapour happens when they are lifted to a higher altitudes in the atmosphere.

Main forms

• a) Frontal precipitation
• b) Cyclonic precipitation
• c) Convective precipitation
• d) Orographic precipitation
Frontal Precipitation

warm air mass, moved by wind currents and atmospheric pressure gradients, overtakes and rises above a cooler air mass.

(Source: rst.gsfc.nasa.gov)
Cyclonic Precipitation

Air masses converge on the low pressure area, the incoming mass of air must be balanced by an outgoing one. Because air is entering from all directions horizontally, the outgoing air moves vertically upward.
Convective precipitation is caused by different heating of an air mass. Heated air masses rise with respect to the cooler surrounding air.

(Source - www.metoffice.gov.uk)
Orographic Precipitation

Orographic precipitation occurs when an air mass is forced by topographic barriers to higher altitude. Common in mountainous regions.

Source - krygier.owu.edu
Interception

- leaves and stems of vegetation, buildings, etc capture some of the precipitation

- intercepted water is dissipated by evaporation
Evapotranspiration

Evaporation from land surface includes direct evaporative loss from the soil surface, depression storages and intercepted water.

Transpiration from vegetation depends on heat energy, wind, moisture availability.
Infiltration

• The process of penetrating of water from the ground surface into the soil

Infiltration rate depends on
• condition of soil surface,
• existing land cover,
• properties of soil beneath. porosity, hydraulic conductivity and existing moisture content of the soil.

infiltration vary with time and space
Soil suction head

- In unsaturated soil, the water is attracted and kept bonded to particles through surface tension.
- Soil suction head - energy possessed by unit weight of water due to suction force.
- The suction head diminishes as the soil gets saturated.
- The hydraulic conductivity increases with the increase of moisture content.
Soil suction head and hydraulic conductivity
Infiltration & percolation

Diagram showing the process of infiltration and percolation in the soil. The diagram includes:
- Precipitation
- Soil zone
- Recharge to water table
- Water table
- Capillary fringe
- Saturated zone below the water table
- Unsaturated zone

Ground water is indicated at the bottom of the diagram.
Hortonian overland flow

• rainfall of intensity \( (i) \) occurs on a plain sloping ground
• infiltration rate \( (f) \),
• runoff = the excess precipitation over infiltration \( (i-f) \).
• When the soil profile is saturated, there is no infiltration – Saturation excess overland flow occurs
Surface water flow

- excess over infiltration
- releases from houses, industries and irrigation
- discharge from springs
- secretion (or exfiltration) from saturated and unsaturated soil as base flow
Runoff generation from rainfall

• As the rainfall continues, the rainfall intensity exceeds the infiltration rate

• excess water begins to pond, fill depressions and potholes on the ground surface

• After that overland flow starts

• overland flow concentrates into rill flow, then into gully flow and continues in the catchment slope to discharge into a stream
Stream flow hydrograph

AB  baseflow recession
Stream flow hydrograph

Segment AB
Prior to the beginning of the rainfall, base flow is diminishing

Segment BC
Direct runoff begins at B, peaks at C

• Segment CD
  Direct runoff reduces from C ends at D

• Segment DE
  base flow recession begins again at D and ends at E
Stream flow hydrograph

- $T_p$ - time of concentration
  - time for the flow from the entire catchment to concentrate at the outlet
- $T_p$ depends on the geometric characteristics including size, shape, hydraulic length, slope and drainage pattern
- Runoff volume for a given r/f depends on the depression storages, imperviousness and infiltration capacity
Impacts of urbanization

• Urban areas
  - high population density, more commercial activities
  - Residents have an advantages over rural settlements
  - Lower specific costs for services
  - larger and concentrated customer base
    - Access to all services
  - More opportunities
Impacts of urbanization on hydrology

In a natural setting,

- vegetation intercepts the precipitation
- the ground’s surface is often pervious, water percolates down into the soil.
Impacts of urbanization on hydrology

In developed areas,

• Removal of vegetation – reduce interception
• Infrastructure (asphalt roads, concrete structures) – increase impervious area and prevent water from infiltrating into the soil.
• Runoff coefficient increases.

More stormwater runoff
Impacts of urbanization on hydrology

In developed areas,

- Efficient and faster hydraulic conveyance systems
- Supply of large volumes of pipe water to generate more drainage water/wastewater
- Increase of discharging pollutants to natural water bodies

Urbanization → More stormwater runoff
               → Poor water quality
Effect of urbanization on runoff

Diagram showing the impact of urbanization on rainfall and runoff:
- **Total Rainfall**
  - Infiltration before urbanization
  - Infiltration after urbanization
  - Additional excess rainfall caused by urbanization

**Runoff Rate**
- Before urbanization
- After urbanization

**Time**
Effect of urbanization on runoff

Urbanization increases peak flows and runoff volumes (the area under the curves).

Impacts of urbanization on hydrology

• Increased peak discharge of runoff
• Increased volume of runoff
• Reduced time of concentration
• Reduced base flow from the catchment
• Increased wastewater flow/drainage flow
Impacts of urbanization on hydrology

- Increased frequency and severity of offsite downstream flooding
- Reduced stream flow and lower water table levels during dry weather
- Loss of wetlands
- Increase in flow velocity
  - increased land erosion
  - increased stream channel erosion
Impacts of urbanization on hydrology

- *Increase in urban drainage flow*
  - Supply more water to urban area
  - Discharge wastewater after consumptive use

- *Has daily, weekly, monthly & seasonally flow variations*
  - Due to time of water use
  - Different usage pattern during weekends and weekdays
  - Climatic variations
  - Other activities in the area
Diurnal variation in an urban drainage flow in a residential area
Impacts of urbanization on hydrology

- Pollution significantly degrade water quality and aquatic habitat.
- Poor water quality during dry weather flow.
- Urbanization increases the amount of pollutants in storm runoff.
- Pollutants and suspended matter in the storm change the nature of the substrate in receiving body.
- Habitats of aquatic life are threatened, biodiversity is affected.
Impacts of urbanization –
Urban heat build-up and rainfall changes

• Buildings, pavements, etc. have high thermal bulk properties and surface radiative properties

• provide multiple surfaces for reflection and absorption of sunlight

• waste heat from automobiles, air conditioning, industry roofs

• surface temperature and overall ambient air temperature in an urban area to rise.
Impacts of urbanization on hydrology

• Heat island changes rainfall around urban areas
Mitigation of adverse impacts of urbanization

• Requires a multi-disciplinary approach through structural and non-structural measures.
• The civil engineering components fall mainly to the structural measures
• Non-structural measures do not involve constructions, policies and legislations
• Preventive actions for hydrological impacts are always simpler and cost effective compared to corrective actions.
Mitigation of adverse impacts of urbanization

*Non structural measures*

- Conducting awareness building on development projects
- Introduction of environmental impact assessment for all development activities
- Introduction of legislations
- Preparedness for facing floods
Non structural measures

• provisions for floodplain zoning and regulation
  – to regulate land use changes
  – some areas are left out for flood control

• Introduction of legislations for
  – imposing mandatory storm water retention or detention facility within the premises.
  – Building codes to include stormwater storage facilities

• provisions for flood-proofing of buildings
  – Buildings are required to adopt flood proofing techniques to cope with floods
Non structural measures

• Legislations
  – To control water pollution by imposing quality standards for wastewater and solid waste disposals in urban environments
  – To improve the quality at the premises itself by owners before releasing to public facilities such as stormwater drains
Structural measures

• The traditional “efficient conveyance” approach is shifted gradually towards the “water storing” approach, focusing on detention, retention and recharge

• To increase infiltration for minimizing runoff generation
Structural measures

*Flow detention and retardation structures*

- **storage type**
  - detention ponds
  - retarding basins
  - off-site storage structures

- **infiltration type**
  - pervious pavements
  - infiltration trenches
  - Infiltration ponds and inlets
Detention ponds & Retention ponds
Retention ponds

• Retention pond is a reservoir to provide a residence time
  – to retain water and regulate outflow
  – to settle down pollutants and sediments

• Capacity is based on the runoff generated from the area

• A dead storage is provided to trap heavy metal pollutants and sediments

• Sluices and spillways are provided to discharge the excess water
Detention ponds

• ponds provided in residential and commercial plots
  – to collect excess water during a storm and to release gradually by a controlled outlet
  – stormwater release is regulated to reduce the flood peak downstream.

• open areas such as play grounds and parks are used as on-site detention ponds.
  – Once the water is completely released the facility is cleaned and put into normal use.
**Infiltration trenches**

- A trench is excavated and filled with crushed stone
  - to enhance the infiltration
- top of the trench is covered by a fabric
Grass filter strips

- These are stripes of grassed soil surfaces introduced between the urban impervious surfaces and the storm drains
  - to slow down and partially infiltrate the runoff.
Grass swales

- These are depressions in the grassed terrain designed to function as small unlined channels
Pervious pavements

• Pervious pavements are permeable surfaces where the runoff can pass and infiltrate into the ground.

• Pervious pavements facilitate
  – peak flow reduction
  – ground recharge
  – pollution filtering.

Types:
  i) porous asphalt pavements
  ii) porous concrete pavements
  iii) garden blocks
Pervious pavements

• Porous asphalt pavements are popularly used in urban areas in
  – Roads
  – Parking lots
• Porous concrete pavements are used in
  – open walkways
  – parking areas.
• Garden blocks are used in
  – pavements in gardens that are only used for walking.
Infiltration ponds

• Infiltration ponds are similar to detention ponds but they are specifically provided to infiltrate the routed stormwater
Infiltration inlets

- Infiltration inlets are draining structures that replace the gulley holes, or the uptake points for conventional storm water.
**Wetlands**

- Wetlands are shallow ponds with growing aquatic plants constructed across streams at depressions for removal of pollutants in water.
- They provide a detention time for the water to settle pollutants/sediments and for the aquatic plants to uptake pollutants.

(Source – Ascuntar Rias et al., 2009) (Source – Rich Axler et al., 2008)
Flood proofing

- Flood proofing is the use of permanent, contingent or emergency techniques to prevent flood waters from reaching buildings and infrastructure facilities.
Flood proofing

Relocation:
Moving a building to high ground, above flood level

Elevation:
Raising a building so that flood waters will go under it

Floodwalls:
Building a wall to keep flood water from reaching a building

Dry floodproofing:
Making the walls of the building and the openings watertight

Wet floodproofing:
Altering a building to minimize damage when flood waters enter
Urban catchment modeling concepts

• Simulation of hydrological processes of the urban catchment
  – to derive runoff required for the design of appropriate stormwater drainage system.

• Event-based hydrologic modeling is carried out to estimate flows due to a given storm event
  – useful for deciding design flows of system components

• Continuous hydrologic modeling is carried out to derive long-term continuous flows
  – useful in water quality estimations in the system
Catchment modeling concepts

• Simplified representations of hydrological processes to simulate catchment response to precipitation.

• Catchment models provide changes in catchment water storages, outflows due to a given precipitation.
Types of catchment models

- Hydrologic Models
  - Stochastic
  - Deterministic

Spatial description
- Lumped
- Distributed

Process description
- Conceptual
- Physically based
Types of catchment models

**Stochastic models**

Statistical concepts are used to link input to the model output

**Deterministic models**

Determines an output for a given input based on certain formulation
Lumped vs. Distributed Models

**Lumped Models**
- Use average values of catchment characteristics
- Ignore spatial variation of catchment characteristics
- Applicable for small areas where physical characteristics of the catchment are homogeneous

**Distributed Models**
- Catchment heterogeneity is considered
- Catchment is divided into small elements (grid) and all characteristics are computed at element level
- Usually physically based
- Enable researchers to take advantage of currently available satellite information
**Conceptual vs. physically based models**

**Conceptual Models**
- Catchment is conceptualized as having homogeneous characteristics
- Not physically based
- Do not have physically measurable identity

**Physically based models**
- Incorporates physical formulations of hydrologic processes observed in the real world
- Usually distributed type, considering catchment heterogeneity
- Have the advantage of using complex hydrologic systems and utilizing distributed hydrologic data
- Spatial and temporal distribution of responses is available
Hydrologic processes modeling

Include,

• Catchment and sub catchment delineation
• Rainfall Analysis
• Infiltration Analysis
• Surface flow analysis
Catchment and sub catchment delineation

- The catchment area to be drained is required to be defined based on the topography of the area.
Rainfall Analysis

• Important parameters for design of stormwater drainage in a catchment area
  – Rainfall intensity
  – rainfall duration
  – rainfall depth
  – spatial variation
  – recurrence interval of rainfall.

• *Intensity-Duration-Frequency* (IDF) curves
  – IDF curves presents rainfall characteristics at location by statistical analysis.
  – IDF curves provide average rainfall intensities corresponding to a particular return period for different durations.
Infiltration Analysis

Estimation of Infiltration rate: Horton method

• For a continuous precipitation where the rainfall intensity is greater than the potential infiltration rate, infiltration rate \( f(t) \), after time \( t \) is given by,

\[
f(t) = f_c + (f_o - f_c) e^{-k(t-t_0)}
\]

where, \( f_c \) = steady state infiltration rate (mm/hr)

\( f_o \) = initial infiltration rate at the time that infiltration begins (mm/hr)

\( k \) = decay coefficient (1/hr)

\( t_o \) = time at which infiltration begins (hr)
Infiltration Analysis

Estimation of infiltration rate: Green – Ampt method

- The infiltration rate \( f \) is related to the total accumulated infiltration \( F \) as

\[
f = K_s \left[ \frac{\psi (\theta_s - \theta_i)}{F} + 1 \right]
\]

where, 
- \( f = \frac{dF}{dt} = \) infiltration rate (cm/hr)
- \( K_s = \) saturated hydraulic conductivity (cm/hr)
- \( \psi = \) capillary suction (cm)
- \( \theta_s = \) volumetric moisture content under saturated condition, (= \( \eta \), Porosity)
- \( \theta_i = \) volumetric moisture content under initial conditions
- \( F = \) total accumulated infiltration (cm)
Infiltration Analysis

Estimation of infiltration rate: Green – Ampt method

• The total infiltration up to time $t$ (hr) can be determined by integrating the above equation,

$$F = K_s t + \psi (\theta_s - \theta_i) \cdot \ln \left[ \frac{F}{\psi (\theta_s - \theta_i)} + 1 \right]$$
Surface flow analysis

- Surface water flow is driven by gravity as a free surface flow

- Flow analysis is carried out under varying assumptions in catchment modelling
Surface flow analysis

Assumptions

1). Outflow from the catchment is directly related to excess rainfall by statistical/empirical means

2). Hydraulic analysis of surface flow is by the application of conservation laws
   — Laws of conservation of mass and momentum are applied to route flow through the catchment
     (Physically based approaches) under various assumptions, e.g. overland flow as sheet flow, uniform flow, etc.
References

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• Haestad Methods (2003), Wastewater Collection System Modelling and Design, Bentley Institute Press, USA