Briefing on Stormwater Hydrology: Principles and Analysis

Executive Summary

This document provides a comprehensive overview of the principles of stormwater hydrology, focusing on the impacts of urbanization and the methods used to analyze and manage stormwater runoff. Green Infrastructure is presented as a multi-benefit approach that uses natural systems to manage rainwater, contrasting with traditional single-purpose gray infrastructure. The foundational concepts of the hydrologic cycle and watersheds are detailed, highlighting how urbanization fundamentally alters natural water balance by dramatically increasing surface runoff and decreasing infiltration.

The analysis delves into the technical methodologies for quantifying stormwater. It covers the types and sources of rainfall data, including 24-hour rainfall depths from NOAA Atlas 14 and NRCS rainfall distributions. Two primary methods for calculating effective precipitation (runoff) are presented: the Runoff Coefficient Method and the more detailed NRCS (SCS) Curve Number (CN) Method, complete with associated tables for land use and soil types.

Furthermore, the document outlines methods for calculating peak discharge, a critical factor in infrastructure design. The Rational Method and the NRCS Graphical Method (TR-55) are explained with step-by-step examples. Finally, it introduces the concepts of hydrographs, which chart flow rates over time, and hydrologic routing, the process of modeling the movement of a flood wave through a reservoir or river channel, with a focus on the Modified Puls method for storage routing. The overarching theme is the systematic, data-driven approach required to understand and mitigate the hydrologic consequences of land development.

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1. Foundational Concepts in Stormwater Management

1.1. Green Infrastructure

Green Infrastructure is defined by the U.S. Environmental Protection Agency (USEPA) as a strategic approach for managing stormwater by integrating natural processes into the built environment. It offers a sustainable alternative to conventional "gray" infrastructure.

- **Definition:** "Green infrastructure is an approach that communities can choose to maintain healthy waters, provide multiple environmental benefits and support sustainable communities."

- **Mechanism:** Unlike gray infrastructure that uses pipes to convey rainwater away, green infrastructure utilizes vegetation and soil to manage rainwater at its source.
- **Multi-faceted Benefits:** Beyond stormwater management, green infrastructure provides a range of co-benefits, including:
    - Flood mitigation
    - Air quality management
    - Habitat creation
    - Energy savings
    - Enhanced community spaces

1.2. Watersheds and the Hydrologic Cycle

A watershed is a land area that channels all precipitation, such as rainfall and snowmelt, to a common outlet like a stream, lake, or ocean. The boundary of a watershed is known as a divide. Key components illustrated in diagrams include hill slopes, valleys, tributaries, sub-basins, and the movement of both surface runoff and groundwater. The Mississippi River Basin serves as a large-scale example, encompassing major sub-basins like the Missouri, Ohio, and Arkansas-Red-White rivers.

The hydrologic cycle describes the continuous movement of water on, above, and below the surface of the Earth. Key processes include:

- **Precipitation:** Water released from clouds as rain, snow, etc.
- **Infiltration:** Water seeping into the ground, contributing to soil moisture and groundwater.
- **Runoff:** Water flowing over the land surface into streams and rivers.
- **Evaporation:** Water turning from liquid to vapor from surfaces like oceans, lakes, and soil.
- **Transpiration/Evapotranspiration:** Water vapor released from plants.
- **Groundwater Flow:** Movement of water underground.

The 2022 USGS Water Cycle diagram explicitly incorporates human impacts, such as urban runoff, agricultural and industrial water use, and the construction of reservoirs, which significantly alter natural water pathways.

2. The Hydrologic Impact of Urbanization

Urbanization, characterized by the increase in impervious surfaces like pavement and roofs, profoundly alters the natural hydrologic cycle. This alteration leads to increased runoff volumes and higher peak flow rates, which are primary concerns in developed areas.

2.1. Changes in Water Distribution

As natural ground cover is replaced with impervious surfaces, the destination of precipitation shifts significantly.

Land Cover	Evaporation / Evapotranspiration	Surface Runoff	Shallow Infiltration	Deep Infiltration
Natural Ground Cover	40%	10%	25%	25%
10-20% Impervious Surface	38%	20%	21%	21%
35-50% Impervious Surface	35%	30%	20%	15%
75-100% Impervious Surface	30%	55%	10%	5%

Source: PlaNYC diagram and "NATURAL ENVIRONMENT vs. URBAN ENVIRONMENT" diagram.

New York City is cited as being over 66% impervious overall, highlighting the scale of this issue in major urban centers.

2.2. Effects on Surface Water Runoff

The increase in imperviousness directly impacts the hydrograph, which plots the rate of water flow over time. Urbanization causes:

- **Increased Peak Flow:** The maximum rate of discharge is significantly higher in urban areas compared to pre-urban conditions.
- **Increased Runoff Volume:** The total volume of water running off the surface (the area under the hydrograph curve) is larger.
- **Reduced Time to Peak:** The peak flow occurs more quickly after a rainfall event.

Stormwater Best Management Practices (BMPs), such as the rain garden installed in Linden, NJ, are designed to mitigate these effects by capturing and infiltrating runoff, thereby helping to restore a more natural hydrology.

3. Rainfall Data and Analysis for Hydrologic Design

Accurate hydrologic analysis relies on standardized rainfall data, which is characterized by depth, duration, frequency, and distribution.

3.1. Rainfall Frequency and Depth

Rainfall frequency data, such as that provided by NOAA Atlas 14, gives the expected rainfall depth for a specific duration (e.g., 24 hours) and recurrence interval (e.g., 25-year, 100-year storm).

New Jersey 24-Hour Rainfall Frequency Data (Inches)

County	2 year	10 year	25 year	100 year
Atlantic	3.31	5.16	6.46	8.90
Bergen	3.34	5.07	6.28	8.47
Cumberland	3.27	5.09	6.37	8.76
Essex	3.44	5.22	6.44	8.66
Middlesex	3.35	5.12	6.36	8.63
Morris	3.54	5.24	6.37	8.35
Ocean	3.42	5.33	6.68	9.20
Union	3.39	5.17	6.42	8.69

Note: This is a partial representation of the full table provided in the source.

3.2. Rainfall Distribution

The Natural Resources Conservation Service (NRCS), formerly the Soil Conservation Service (SCS), developed synthetic 24-hour rainfall distributions (Types I, IA, II, III) that are used across the United States. These distributions describe how the total rainfall depth is distributed over the 24-hour period, which is crucial for hydrograph development. New Jersey falls within the Type III rainfall distribution region.

3.3. Intensity-Duration-Frequency (IDF) Curves

IDF curves graphically represent the relationship between rainfall intensity, storm duration, and recurrence interval. While older curves (based on 1913-1975 data) are shown for illustration, modern analysis uses data from NOAA Atlas 14 to generate precise Depth-Duration-Frequency (DDF) curves for specific locations, such as the example provided for Piscataway, NJ.

4. Calculation of Effective Precipitation (Runoff)

Effective precipitation (Pe) is the portion of total precipitation (P) that becomes direct surface runoff after accounting for losses like infiltration and depression storage.

4.1. Runoff Coefficient Method

This method estimates effective rainfall intensity (ie) or depth (Pe) using a runoff coefficient (C), which represents the fraction of rainfall that becomes runoff. **Formula:** `Pe = C × P` or `ie = C × i` The coefficient C varies by surface type.

Typical Runoff Coefficients (2-year to 10-year return periods)

Description of Area	Runoff Coefficient
Business: Downtown areas	0.70–0.95
Residential: Single-family areas	0.30–0.50
Pavement: Asphalt or concrete	0.70–0.95
Lawns, sandy soil: Flat, 2%	0.05–0.10
Lawns, heavy soil: Steep, 7% more	0.25–0.35

4.2. NRCS (SCS) Curve Number (CN) Method

This widely used method calculates effective precipitation based on total precipitation and a watershed's potential maximum retention (S), which is determined by a Curve Number (CN). **Formulas:**

- `Pe = (P - 0.2S)² / (P + 0.8S)`
- `S = (1000 / CN) - 10`

The CN is a dimensionless number from 0 to 100 that reflects land use, soil type, and antecedent moisture conditions. NRCS provides extensive tables of CN values for various urban and agricultural land covers and for four hydrologic soil groups (A, B, C, D), which are classified by their minimum infiltration rate.

- **Group A:** High infiltration (e.g., deep sand).
- **Group B:** Moderate infiltration (e.g., sandy loam).
- **Group C:** Slow infiltration (e.g., clay loams).
- **Group D:** Very slow infiltration (e.g., heavy plastic clays).

For a watershed with mixed land uses, a composite (weighted) CN is calculated.

5. Calculation of Peak Discharge

Peak discharge (Qp) is the maximum rate of runoff from a rainfall event and is a key parameter for designing drainage systems.

5.1. Rational Method

The Rational Method is a simple approach used for small drainage areas. **Formula:** $Qp = C \times i \times A$ Where:

- Qp = Peak discharge (cfs)
- C = Runoff coefficient
- i = Rainfall intensity (in/hr) for a duration equal to the Time of Concentration
- A = Drainage area (acres)

Time of Concentration (Tc) is the longest time required for water to travel from the watershed divide to the outlet. It is the sum of travel times for different flow types: overland (sheet) flow, shallow concentrated flow, and channel flow.

5.2. NRCS Graphical Method (TR-55)

This method is used for larger, more complex watersheds and is specifically tied to the NRCS 24-hour storm distributions. **Formula:** $Qp = qu \times A \times Pe$ Where:

- Qp = Peak discharge (cfs)
- qu = Unit peak discharge (cfs/mi²/in), obtained from graphs based on Tc, rainfall distribution type, and the ratio of initial abstraction to precipitation (Ia/P).
- A = Drainage area (mi²)
- Pe = Effective precipitation (in)

An adjustment factor (Fp) can be applied for watersheds with significant pond or swamp areas.

6. Hydrographs and Hydrologic Routing

6.1. Hydrographs

A hydrograph is a graph showing the rate of flow (discharge) versus time at a specific point in a river, channel, or conduit. It provides a complete picture of a watershed's response to a storm event, including the peak discharge, total runoff volume, and timing. The NRCS has developed procedures for creating synthetic hydrographs, such as the dimensionless unit hydrograph, which can be scaled for specific watersheds.

6.2. Hydrologic Routing

Hydrologic routing is the process of determining the flow characteristics (e.g., the outflow hydrograph) at a downstream point, given the flow characteristics at an upstream point (the inflow hydrograph). It is based on the continuity equation: **Mass Balance Equation:** $dS/dt = I - O$ Where:

- dS/dt = Rate of change of storage
- I = Inflow rate
- O = Outflow rate

Routing Methods:

- **Reservoir Routing (Level Pool Routing):** Used to model the effect of storage facilities like detention basins or reservoirs on a flood wave. The **Modified Puls method** is a common technique that solves the continuity equation in finite-difference form. It relates storage and outflow to determine the attenuated outflow hydrograph.
- **Channel Routing:** Used to model flow in rivers and streams. The **Muskingum method** is a widely used approach that accounts for both prism storage (volume of constant cross-section) and wedge storage (additional volume during the rising phase of a flood).