Briefing Document

Topic 14 – Solids Deposition and Flushing in Urban Sewer Systems

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Executive Summary

Urban sewer systems behave as **non-equilibrium sediment transport systems**, characterized by two contrasting phases:

1. **Storage of solids during dry-weather flow (DWF)**
2. **Rapid release of stored material during wet-weather flow (WWF)**

This dynamic produces the **first-flush phenomenon**, in which high concentrations of sediment and associated pollutants are discharged early during storm events, often before peak discharge occurs.

Unlike many river systems, sewer sediments are commonly **mixed sediments**, consisting of:

- Noncohesive particles (sand, grit)
- Cohesive materials (organic matter, biofilms, fine particles)

These mixed sediments exhibit **hysteresis**, meaning that the hydraulic conditions required for resuspension differ substantially from those associated with deposition:

$$\tau_{\text{resuspension}} > \tau_{\text{deposition}}$$

Sediment accumulation affects:

- Hydraulic performance
- Water quality
- Infrastructure durability
- Odor generation
- Combined Sewer Overflow (CSO) frequency

Management requires a combination of:

- Appropriate hydraulic design
- Self-cleansing criteria
- Sediment removal strategies

- Integrated control systems

1. System Context and Infrastructure Impacts

Urban sewer systems differ according to how sanitary wastewater and stormwater are conveyed.

Combined versus Separate Systems

Combined Sewer Systems

Combined sewer systems transport:

$$Q_{\text{total}} = Q_{\text{sanitary}} + Q_{\text{storm}}$$

Characteristics:

- Highly variable discharge
- Strong deposition–resuspension cycles
- Greater risk of Combined Sewer Overflows (CSOs)

Separate Sewer Systems

Sanitary Sewers

Characteristics:

- Relatively steady flow
- Low discharge conditions
- Different sediment accumulation behavior

Storm Sewers

Characteristics:

- Intermittent flow
- Event-driven sediment transport

Geographic and Environmental Relevance

Combined Sewer Overflow outfalls are concentrated primarily in:

- Northeastern United States
- Great Lakes region

Examples:

New York City

- 70% combined sewer
- 30% separate sewer
- Approximately 700 CSO outfalls

Philadelphia

- 60% combined sewer
- 40% separate sewer
- Approximately 164 CSO outfalls

Consequences of Sediment Accumulation

Water Quality Degradation

Stored pollutants released during storm events adversely affect receiving waters.

Infrastructure Corrosion

Corrosion results from coupled biological and chemical processes:

Sulfate-reducing bacteria (SRB) produce:

$$H_2S$$

Hydrogen sulfide subsequently undergoes oxidation:

$$H_2S \rightarrow H_2SO_4$$

Sulfuric acid causes severe corrosion, especially near the upper pipe crown.

Flooding and Odor Problems

Excessive deposition:

- Reduces hydraulic capacity
- Produces foul gases
- Increases flooding risk

2. Sediment Classification and Characteristics

Sewer sediment is rarely homogeneous and generally behaves as a mixed material.

Sewer Type	Primary Sediment Composition	Characteristics
Combined	Sand/grit + fine organics	Strong cohesive–noncohesive interaction
Sanitary	Predominantly cohesive	Biofilms, flocs, fine particles
Storm	Predominantly noncohesive	Sand, silt, road dust

Role of Cohesion

Cohesion arises from:

- Organic matter
- Biological activity
- Electrochemical interactions

Consequences include:

Aggregation

Formation of flocs through:

- Aggregation

- Breakage
- Biofilm growth

Time-Dependent Strength

As sediment deposits remain undisturbed:

- Consolidation increases
- Resistance to erosion increases

Higher Erosion Threshold

Cohesive sediment beds require greater mobilization energy than equivalent noncohesive beds.

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3. Physical Mechanisms of Transport

Transport processes are controlled by interactions among:

Flow velocity: U
Shear stress: τ
Critical shear stress: τ_c

Dry-Weather Deposition

During dry-weather flow:

$$U \downarrow$$

If:

$$\tau < \tau_c$$

deposition occurs.

Primary causes:

- Oversized sewer design
- Low flow rates

- Flat slopes

First-Flush Phenomenon

As storm runoff begins:

$$U \uparrow$$

and

$$\tau > \tau_c$$

stored material becomes rapidly mobilized.

Pollutant Spike

A large fraction of pollutant load may occur before peak discharge:

$$Q$$

First Flush Index (FFI)

$$FFI = \frac{M_{0-30\%}}{M_{\text{total}}}$$

where:

$M_{0-30\%}$ = load during first 30% of runoff volume

M_{total} = total event load

Typical values:

$$0.6 \leq FFI \leq 0.9$$

Hysteresis and Asymmetry

Deposition and resuspension exhibit strong asymmetry.

Observed values:

Settling:

$$V < 0.27 \text{ m/s}$$

Resuspension:

$$V \approx 0.44 \text{ m/s}$$

Thus:

$$\tau_{\text{resuspension}} > \tau_{\text{deposition}}$$

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4. Sediment Transport Theory

Transport Modes

Bed Load

- Rolling
- Sliding
- Saltation along the pipe bed

Cohesion may increase threshold conditions through consolidation and armoring.

Suspended Load

Fine particles maintained in suspension through turbulence.

Often modeled using the **Rouse Profile**.

Wash Load

Very fine particles:

- Clay
- Fine silt
- Organic flocs

Typically supply-limited.

Dissolved Load

Transport of:

- Nutrients
- Dissolved ions

Not sediment, but important for water quality.

Key Mathematical Relations

Settling Velocity

For small particles (Stokes regime):

$$v_s = \frac{(s-1)gd^2}{18\nu}$$

Critical Velocity

Approximate criterion:

$$V_c \sim \sqrt{gH(s-1)}$$

where:

H = flow depth
s = specific gravity of solids

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5. Modeling and Engineering Controls

Modeling Approaches

Model	Key Capability	Limitation
SWMM	Hydraulics + sediment + water quality	Limited cohesive processes
MIKE URBAN	Sediment routing	Limited floc dynamics
Delft3D-FLOW	Cohesive transport	Computationally intensive
InfoWorks ICM	Integrated sewer/catchment modeling	Simplified cohesive representation

Empirical Deposition Models

Daily solids loading:

$$TS \propto L^{1.06} S^{-0.43} Q^{-0.51}$$

where:

L = sewer length
S = slope
Q = per-capita flow

This relation emphasizes that:

- Lower slope increases deposition
- Lower flow increases deposition

Hydraulic Design: Self-Cleansing Velocity

A commonly used design criterion is:

$$V_{\text{self-cleansing}} \approx 0.60 \text{ m/s}$$

For a circular pipe flowing half-full:

$$R = \frac{D_p}{4}$$

where:
R = hydraulic radius
D_p = pipe diameter

Integrated Control Strategies

Effective sediment management generally requires three levels of control:

Source Control

- BMP implementation
- Reduction of external solids inputs

Hydraulic Design

- Appropriate pipe slope
- Adequate flow velocity

In-Sewer Control

- Flushing systems
- Periodic sediment removal

Key Takeaways

- Sewer systems behave as **non-equilibrium sediment systems**
- Sewer sediments are commonly **mixed cohesive–noncohesive materials**
- Deposition and resuspension exhibit **hysteresis**
- First flush can dominate event pollutant loading
- Effective management requires integrated hydraulic and sediment control approaches