Colloid Transport in Surface Runoff through Dense Vegetation

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Outline

• Introduction
• Theoretical Framework
• Study Contents
• Conclusions
Outline

• **Introduction**
  • Colloid & colloid-facilitated transport in water flow
  • Dense vegetation application
  • Objective

• **Theoretical Framework**

• **Study Contents**

• **Conclusions**
Colloid

- Colloids: particles with a diameter between 0.1 μm and 10 μm.
- "Solute": particles with a diameter of 0.01 μm.
- Suspended particles: 0.1 μm to 1 μm.
- Bed-load particles: 1 μm to 10 μm.
- Clay: 10 μm to 100 μm.
- Silt: 10 μm to 100 μm.
- Sand: 100 μm to 0.1 mm.
- Virus: smaller than 0.01 μm.
- Bacteria: 0.1 μm to 1 μm.
Colloid

- **Inorganic**
  
  All kinds of mineral particles with size smaller than 10 \( \mu m \) such as soil clay, industrial nanomaterials, etc.

- **Organic:**
  
  “Particulate” organic matter
  
  Bio-colloids: Viruses, bacteria, protozoa
Colloid & colloid-facilitated transport in ground water
Dense Vegetation

Natural grasslands, meadows
Implanted bands of vegetation located on land down-slope of agricultural fields, bordering surface waters
Schematic of lab-scale experiment

Runoff bromide distributor

Rainfall Simulator

Outflow

18 psi

2.0m

L = 1.531 m

L₄ = 1.52 m

Soil (sand)

Fraction sampler

Probe

Infiltrated water via drainage system

Computerized water depth recorder

n. of repetitions = 2
Dense Vegetation Effect on the Removal of Colloids

Bare Soil
Kaolinite (0.4 μm, 179mg/L, neg. charge)
- 51% Surface Recovery
- 23% Subsurface Recovery
- 26% Removed

Dense Vegetation System
Microspheres (0.3 μm, 10 mg/L, neg. charge)
- 67% Surface Recovery
- 29% Subsurface Recovery
- 4% Removed
Overall Objectives

- To explore through a combination of experimental and numerical tools the main factors involved in surface removal of colloids by dense vegetation
Outline

• Introduction

• **Theoretical Framework**
  - Mass transport
  - Classic colloid filtration theory
  - overland flow exchange

• Study contents

• Conclusions
Mass Transport

**Advection**

\[ \frac{\partial C}{\partial t} = -v \frac{\partial C}{\partial x} \]

**Saturated Porous Media**

\[ v = -\frac{K}{n_e} \frac{dh}{dl} \]

- \( n_e \): effective porosity;
- \( \frac{dh}{dl} \): hydraulic gradient (L/L);
- \( K \): hydraulic conductivity (L/T).

**Dense Vegetation**

\[ \frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = i_e(t) \]

\[ v = \frac{q}{h} ; v_g = \frac{v}{\theta_g} \]

- \( h \): surface water depth [L];
- \( q \): flow per unit width of the plane [L²T⁻¹];
- \( i_e \): rainfall rate [L/T];
- \( v_g, \theta_g \): “pore” velocity and vegetation porosity.

**Darcy’s Law**

The kinetic wave approximation of the Saint-Vennant’s equation (1881).
• **Hydrodynamic Dispersion**
  
  • Diffusion (Fick’s first Law)

\[ F = -D_d \frac{dC}{dx} \]

\( D_d \): diffusion coefficient (L^2/T)

• **Mechanical Dispersion**

  Coefficient of mechanical dispersion = \( \alpha_i v_i \)

• **Hydrodynamic Dispersion**

\[ D_L = \alpha_L v_i + D^* \]

\[ D_T = \alpha_T v_i + D^* \]

\[ D^* = \omega D_d \]

\( \omega \): related to tortuosity of the porous media or dense vegetation
Classic Filtration Theory (Porous Media)

**Transport to a surface**
- Interception
- Sedimentation
- Molecular diffusion

**Attachment**
- London-Van der Waals force
- Electrostatic forces

[Yao, 1973]
Factors Impacting the Colloid Filtration Theory

- Ionic strength
- Colloid characteristics
- Inflow rate
- Media surface characteristics

From porous media to vegetation?

Remove colloidal particles with large particles

Remove colloidal particles with plants
Can we apply the transport/filtration theory in the porous media to dense vegetation?
Classic Filtration Theory

**Transport to a surface**
- Interception
- Sedimentation
- Molecular diffusion

**Attachment**
- London-Van der Waals
- Electrostatic forces
• **Solute Sorption**

\[
\frac{\partial C}{\partial t} = D_L \frac{\partial^2 y}{\partial x^2} - \nu \frac{\partial C}{\partial x} - \frac{B_d}{\theta} \frac{\partial C^*}{\partial t} + \Gamma
\]

**Solute**

• **Equilibrium Sorption Isotherm**
  • Linear Sorption Isotherm
  • Freundlich Sorption Isotherm
  • Langmuir Sorption Isotherm

• **Kinetic Sorption**
  • Irreversible first-order kinetic sorption model
  • Reversible nonlinear kinetic sorption model

• **Reaction**

  \( B_d \): bulk density of porous media ;

  \( \theta \): volumetric moisture content or porosity for saturated media

  \( \Gamma \): reactive term (=0 for tracer)

• **Colloid Deposition**

\[
\frac{\partial C}{\partial t} = D_L \frac{\partial^2 y}{\partial x^2} - \nu \frac{\partial C}{\partial x} - K_d C
\]

**Colloids**

**Colloid Filtration Theory**

In this classic “clean-bed” filtration model, the removal of suspended particles is described by first-order kinetics, resulting in concentrations of suspended and retained particles that decay exponentially with distance.

[Nathalie Tufenkji and Menachem Elimelech, 2004]
Soil Surface Exchange Mechanism

Diffusion Driven
Colloid Transport Conceptual Model

Kg: classic “clean-bed” filtration model, the removal of suspended particles is described by first-order kinetics
Outline

- Introduction
- Theoretical Framework
- **Study Contents**
  To illustrate colloid size, ionic strength, vegetation type and flow rate effects on the removal and transport of colloids in dense vegetation
- Conclusions
Process Controlling Colloid Mobility in Overland Flow through Dense Vegetation

- Solution composition
- Colloid size
- Water flow
- Vegetation type
Materials and Methods

• **Materials**
  • **Colloids:** 10 mg/L 0.3 μm Carboxylated polystyrene latex microspheres
  • **Tracer:** 40 ppm Sodium Bromide
  • **Soil bed:** 0.5 to 0.6 mm washed quartz sand
    porosity 0.43
    slope 1.7%, dimension (153.1 * 40.2 * 10 cm)

• **Environmental condition:**
  • **Inflow rate:** 0.62 L/min and 0.84 L/min
  • **Ionic strength:** regular tap water (0.558 mMol) and 100mM KCl
  • **Grass type:**
    • Bahia (*paspalum notatum*)
      • Density : Ss= 2 cm
      • Height: 8 cm
    • Rye (*Secale cereale*)
      • Density : Ss= 0.5 cm
      • Height: 8 cm
<table>
<thead>
<tr>
<th>Experiment No.</th>
<th>Solution</th>
<th>Ionic Strength$^1$</th>
<th>Colloid Size (µm)</th>
<th>Flow Rate (mL min$^{-1}$)</th>
<th>Grass Type</th>
</tr>
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<tbody>
<tr>
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<td>Bromide</td>
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<td>84</td>
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<td>2</td>
<td>84</td>
<td>Rye</td>
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</tbody>
</table>

$^1$Markku Yli-Halla, 1995
Schematic of small scale experimental setup
Colloid Transport Conceptual Model

Kg: classic “clean-bed” filtration model, the removal of suspended particles is described by first-order kinetics.
Colloid Transport Conceptual Model

\[ \frac{\partial C}{\partial t} = -v \frac{\partial C}{\partial x} + D \frac{\partial^2 C}{\partial x^2} - KgC - K_{ie}C + K_{oe}C_{sm} \]

Colloid Filtration Theory

Exchange Concept

\[ \frac{d_e \theta}{h} \frac{\partial C_{sm}}{\partial t} = \lambda K_{ie}C + K_{oe}C_{sm} \]

\[ \rho_s \frac{\partial C_{im}}{\partial t} = (1 - \lambda)K_{ie}C \]

VFSMOD-RSE
• Initial condition:
  \[ C(0, 0) = 0; \quad C(L, 0) = 0; \quad C_s(0) = 0; \]

• Boundary condition:
  \[
  C(0, t) = C_0 \quad t \leq 10 \text{ mins}; \\
  C(0, t) = 0 \quad 10 < t < 30 \text{ mins}.
  \]
**VFSMOD-RSE**

The Vegetative Filter Strip Modeling System, VFSMOD-W, is a field-scale, mechanistic, storm-based numerical model developed to route the incoming hydrograph and sediment from an adjacent field through a VFS and to calculate the resulting outflow, infiltration, and sediment trapping efficiency.

The TRT program solves the Advection-Dispersion-Reaction Equation (ADR) using a split operator scheme of the type Transport-Reaction-Transport at each time step, which means that the pollutant is transported using half of the time step, then is reacted for the full time step, and then transported for the remaining time step.
VFSMOD: dynamic flow and sediment


http://abe.ufl.edu/carpena/vfsmod
## Results

<table>
<thead>
<tr>
<th>Experiment conditions</th>
<th>Optimized model parameters^3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solution</strong></td>
<td><strong>Concentration(ppm)^1</strong></td>
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<tr>
<td>Parameter constrains^2</td>
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<tr>
<td>Bromide</td>
<td>40</td>
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<tr>
<td>Colloid</td>
<td>11 (2.6×10^9)</td>
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<tr>
<td>Colloid</td>
<td>11 (2.6×10^9)</td>
</tr>
<tr>
<td>Colloid</td>
<td>11 (7.6×10^{11})</td>
</tr>
<tr>
<td>Colloid</td>
<td>11 (1.8×10^7)</td>
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<tr>
<td>Bromide</td>
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<tr>
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<tr>
<td>Bromide</td>
<td>40</td>
</tr>
<tr>
<td>Colloid</td>
<td>11 (2.6×10^9)</td>
</tr>
</tbody>
</table>
Ionic Strength Effect

Promoting effect of ionic strength on colloid removal in dense vegetation system

<table>
<thead>
<tr>
<th></th>
<th>Low Ionic Strength</th>
<th>High Ionic Strength</th>
<th>Bromide</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Recovery</td>
<td>69.78%</td>
<td>65.40%</td>
<td>79.43%</td>
</tr>
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</table>
Colloid Size Effect

Increase in particle size enhanced the removal of colloids

<table>
<thead>
<tr>
<th>Colloid Size</th>
<th>% Recovery</th>
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</thead>
<tbody>
<tr>
<td>0.3 um</td>
<td>72.03%</td>
</tr>
<tr>
<td>2 um</td>
<td>69.78%</td>
</tr>
<tr>
<td>10.5 um</td>
<td>56.75%</td>
</tr>
<tr>
<td>Bromide</td>
<td>79.43%</td>
</tr>
</tbody>
</table>
**Flow Rate Effect**

<table>
<thead>
<tr>
<th></th>
<th>Low Flow Rate</th>
<th>High Flow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Recovery</td>
<td>62 ml/min</td>
<td>84 ml/min</td>
</tr>
<tr>
<td>Bromide</td>
<td>77.24%</td>
<td>79.43%</td>
</tr>
<tr>
<td>Colloids</td>
<td>63.94%</td>
<td>72.03%</td>
</tr>
</tbody>
</table>

Lower flow rate enhances the removal rate.
Vegetation Types Effect

Performance of the dense vegetation system varies with vegetation types.

<table>
<thead>
<tr>
<th>% Recovery</th>
<th>Bahia</th>
<th>Rye</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bromide</td>
<td>79.43%</td>
<td>86.90%</td>
</tr>
<tr>
<td>Colloids</td>
<td>69.78%</td>
<td>65.57%</td>
</tr>
</tbody>
</table>
Summary of trends of colloid recovery rates under the different effects studied
Conclusion

- Increases in solution ionic strength and increases in particle size can enhance the removal of colloids in dense vegetation systems.

- Performances of the dense vegetation systems varied with vegetation types.

- A numerical model that incorporated classic filtration theory and solute exchange concept was used to interpret the removal of colloids in the dense vegetation.

- VFSMOD-RSE successfully simulated the observed colloid transport through dense vegetation.
QUESTIONS AND COMMENTS?