A MEAN RESIDENCE TIME RELATIONSHIP FOR LATERAL CAVITIES IN GRAVEL-BED RIVERS AND STREAMS:

INCORPORATING STREAMBED ROUGHNESS AND CAVITY SHAPE

Tracie Jackson
Roy Haggerty, Sourabh Apte, Ben O’Connor

Water Resources Engineering Program
Oregon State University

Jackson et al. [2013, WRR]
Surface Transient Storage

- STS is the short-term storage of solutes and suspended particulates in recirculating flow in the stream channel.

- Functional significance:
  - Refugia for aquatic communities
  - Improves water quality

Source: O’Connor et al. (2010)
Accurate estimates of mass-exchange parameters in TS zones needed to better understand and quantify solute transport and dispersion in riverine systems.
Motivation

To date, an accurate and reliable MRT relationship quantifying mass exchange in lateral cavities has not been identified:

$$\tau_L = \frac{W L d_c}{k U L d_E}$$
Variance in $k$ may be reduced if include effect of bed roughness and cavity shape.

$$\tau_L = \frac{WLDc}{kULd_E}$$
Study Objective

- To present 2 MRT relationships for lateral cavities in natural rivers and streams that incorporate streambed roughness and shape.
- Relationships developed using dimensional analysis and verified through comparison to previous laboratory and field studies.
Dimensional Analysis

- MRT can depend on following parameters:
  \[ \tau_1 = f(u_*, U, g, \nu, W, L, d_E, d_c) \]

- Buckingham Pi Theorem:
  \[ \frac{\tau_1 U}{L} = f\left(\frac{W}{L}, \frac{d_c}{d_E}, \frac{U d_E}{\nu}, \frac{U}{\sqrt{g d_E}}, \frac{u_*}{U}, \frac{\sqrt{Wd_c}}{L}\right) \]
MRT can depend on following parameters:

\[ \tau_1 = f(u_*, U, g, \nu, W, L, d_E, d_c) \]

Buckingham Pi Theorem:

\[ \frac{\tau_1 U}{L} = f\left(\frac{W}{L}, \frac{d_c}{d_E}, \text{Re}, \text{Fr}, \frac{u_*}{U}, \sqrt{\frac{W d_c}{L}}\right) \]

- Geometric Ratios
- Hydraulic Quantities
- Roughness Factor
- Shape Factor
\[ \frac{\tau_U L}{U} = \left[ \frac{U d_e}{\nu} \right]^{0.15} \cdot \left[ \frac{U}{\sqrt{g d_e}} \right]^{0.56} \cdot \left[ \frac{W^{3/2} d_c^{3/2}}{L^2 d_e} \right]^{0.44} \]

Normalized Mean Residence Time

- Lab: Pool-Riffle Sequences
- Elder Creek, CA
- Oak Creek, OR
- Soap Creek, OR
- John Day River, OR
- Lookout Creek, OR
- Elbe River, Germany*
- Elbe River, Germany**
- Danube River, Austria

\[ y = 28x - 5.0 \]
\[ R^2 = 0.83 \]
\[ \frac{\tau_1 U}{L} = \left( \frac{U d_E}{v} \right)^{0.13} \cdot \left( \frac{U}{\sqrt{g d_E}} \right)^{0.49} \cdot \left( \frac{W^{3/2} d_c^{3/2}}{L^2 d_E} \right)^{0.39} \cdot \frac{U}{u_*} \]

Normalized Mean Residence Time

Lab: Pool-Riffle Sequences
Elder Creek, CA
Oak Creek, OR
Soap Creek, OR
John Day River, OR
Lookout Creek, OR
Elbe River, Germany*
Elbe River, Germany**
Danube River, Austria

\[ y = 21x - 6.7 \]

\[ R^2 = 0.82 \]
Significance

- Tools hydrologists and water managers can use to predict conservative solute transport in natural systems with lateral cavities over a range of geometry (0.2 < W/L < 0.75), complex shapes, roughness, and flow conditions (1.0 × 10^4 < Re < 1.0 × 10^7).
- Few field-measurables (i.e., W, L, U, d_E, d_c, n, R, d_{50})

- **Examples:**
  - **Solute Transport:** predict solute MRT in lateral cavities within natural streams and rivers.
  - **Stream Restoration:** estimate MRT of in-stream structures emplaced to enhance stream biodiversity.
Considerations & Future Work

3 key considerations when using relationships:

1) Derived for gravel-bed systems:
   - May or may not hold for substrates other than gravel or heavily vegetated systems.

2) Channel roughness could be more significant than observed if roughness parameters are measured in cavity vicinity.
   - More detailed data of roughness parameters near shear layer needed to fully test hypothesis.

3) Relationship derived and tested for conservative solutes.
   - Additional term(s) needed (e.g., retention factor) to account for non-conservative solutes.
MRT relationships for lateral cavities in natural gravel-bed streams and rivers can be computed from 6 nondimensional groups:

- $Fr$
- $Re$
- $W/L$
- $d_c/d_E$
- Shape factor
- Roughness factor

2 empirical MRT relationships formulated.

Relationships valid for conservative tracers within a range of geometry ($0.2 < W/L < 0.75$) and flow conditions ($1.0 \times 10^4 < Re < 1.0 \times 10^7$).
Questions?
Roughness Parameters

\[ u_* = \sqrt{\frac{\tau_0}{\rho}} \quad \tau_0 = \rho g R S_f \quad S_f = n^2 U^2 / R^{4/3} \]

- **Shear velocity:**
  \[ u_* = \sqrt{g n^2 U^2 R^{-1/3}} \]

- **Chen and Cotton [1988] method (shallow flow < 1 m):**
  \[ n = \frac{(R / 0.3048)^{1/6}}{8.6 + 19.97 \log(R / d_{50})} \]

- **Henderson [1966] method (deeper flow > 1 m):**
  \[ n = 0.034 (3.28 d_{50})^{1/6} \]