Quantifying Uncertainties in Pollutant Transport in Rivers

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Background

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River processes are complex and non-linear (e.g. soluble pollutants transport and transformation processes). An integrated approach is required for the proper management of rivers. Models are useful for predicting and/or simulating pollutant conditions (Bedri et al., 2014). Wye & Usk Foundation (WUF).

Large uncertainties are inherited while predicting or simulating soluble pollutant concentrations in rivers.
Aim and Objectives

**Aim:** To understand how the levels of uncertainty in the different models change, with changes in the spatial and temporal scales for a wide range of rivers.

**Objectives:**

1. Structural uncertainties analysis due to selection of pollutant transport and mixing model
2. Structural uncertainties analysis due to selection of biochemical processes model
3. Mixing parameters uncertainty analysis
4. Spatial and temporal extent of uncertainties dominance over total uncertainty
Methodology

• How do pollutants behave in rivers? What are the dominant processes?
• How do we model these processes?
• What/where are the uncertainties coming from?
• How do we measure them?
• How do we compare and evaluate them?
River dominant processes

Physical
- Advection
- Dispersion
- Transient storage

Biochemical
- Decay
- Respiration
- photosynthesis
- Eutrophication
- Sediment transport

(Kilpatrick and Wilson, 1989)

(Vanrolleghem, 2000)
\[ \frac{\partial c}{\partial t} = -u_x \frac{\partial c}{\partial x} - u_y \frac{\partial c}{\partial y} - u_z \frac{\partial c}{\partial z} + \frac{\partial}{\partial x} \left( D_x \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_y \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left( D_z \frac{\partial c}{\partial z} \right) + R(c, P) \]

Pollutant Modelling

Advection
Dispersion
Reactions

(LMNO Engineering, 2015)
Pollutant Modelling

\[
\frac{\partial c}{\partial t} = -u_x \frac{\partial c}{\partial x} - u_y \frac{\partial c}{\partial y} - u_z \frac{\partial c}{\partial z} + \frac{\partial}{\partial x} \left( D_x \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_y \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left( D_z \frac{\partial c}{\partial z} \right) + R(c, P)
\]

### Modelling reactions (RWQM1)

(Vanrolleghem, 2000)
Sources of uncertainty

• Input data
  – Data resolution
  – Outputs from other models (e.g. WWTP or Sewer models)

• Parameter selection
  – Empirical (e.g. dispersion coefficients in ADE)

• Structural
  – matching the model to the real processes of interest (Refsgaard et al., 2006)

• Model calibration
  – Parameters
  – Methods
  – Data
  – Objective functions
Modelling Framework

- Estimating pollutant concentrations in rivers for various models
- Quantifying structural and parameter uncertainties
- Studying the temporal and spatial scales where structural and parameter uncertainties are dominant

ADE 1D
\[ \frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} = 0 \]

Advection only

ADE 2D
\[ \frac{\partial u}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 0 \]

Advection and diffusion

Environmental River Processes - Solute Transport Course Notes (CIV6771/471)
River database and classification

82 rivers (Rutherford, 1994)

- Depth (H), width (B), mean velocity ($\bar{u}$), shear velocity ($u^*$), longitudinal dispersion ($D_x$), discharge ($Q$)
- Dominate the hydrology and geomorphology of rivers (Seo and Cheong, 1998)
Framework outputs
## Structural uncertainty analysis

### Narrow River vs. Wide River

<table>
<thead>
<tr>
<th></th>
<th>Yuma Mesa</th>
<th>Mississippi</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Depth (m)</strong></td>
<td>3.45</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Width (m)</strong></td>
<td>7.6</td>
<td>530</td>
</tr>
<tr>
<td><strong>Aspect ratio (-)</strong></td>
<td>2.2</td>
<td>173.8</td>
</tr>
<tr>
<td><strong>Mean velocity (ms⁻¹)</strong></td>
<td>0.68</td>
<td>0.08</td>
</tr>
<tr>
<td><strong>Shear velocity (ms⁻¹)</strong></td>
<td>0.047</td>
<td>0.0056</td>
</tr>
<tr>
<td><strong>Mean/shear velocity ratio (-)</strong></td>
<td>14.47</td>
<td>14.2</td>
</tr>
<tr>
<td><strong>Slope (-)</strong></td>
<td>0.000065</td>
<td>0.000001</td>
</tr>
<tr>
<td><strong>Dx (m²s⁻¹)</strong></td>
<td>0.961</td>
<td>0.098</td>
</tr>
<tr>
<td><strong>Dy (m²s⁻¹)</strong></td>
<td>0.024</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Pollutant mass (kg)</strong></td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Tau (s)</strong></td>
<td>125.9</td>
<td>1103.1</td>
</tr>
<tr>
<td><strong>Tbar (s)</strong></td>
<td>151.4</td>
<td>1311.8</td>
</tr>
</tbody>
</table>
Structural uncertainty analysis

Yuma Mesa (narrow) River

Concentration 50 m downstream of release

Mississippi (wide) River

Concentration 50 m downstream of release

Absolute Concentration Deltas

Absolute Concentration Deltas
## Structural uncertainty analysis

### Slow vs. fast river

<table>
<thead>
<tr>
<th></th>
<th>Punehu</th>
<th>Coachella</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Depth (m)</strong></td>
<td>0.28</td>
<td>1.56</td>
</tr>
<tr>
<td><strong>Width (m)</strong></td>
<td>5.0</td>
<td>24.0</td>
</tr>
<tr>
<td><strong>Aspect ratio (-)</strong></td>
<td>17.9</td>
<td>15.4</td>
</tr>
<tr>
<td><strong>Mean velocity (ms⁻¹)</strong></td>
<td>0.26</td>
<td>0.71</td>
</tr>
<tr>
<td><strong>Shear velocity (ms⁻¹)</strong></td>
<td>0.2098</td>
<td>0.0428</td>
</tr>
<tr>
<td><strong>Mean/Shear velocity (-)</strong></td>
<td>1.24</td>
<td>16.5</td>
</tr>
<tr>
<td><strong>Slope (-)</strong></td>
<td>0.347</td>
<td>0.0001</td>
</tr>
<tr>
<td><strong>Dx (m²s⁻¹)</strong></td>
<td>0.395</td>
<td>0.395</td>
</tr>
<tr>
<td><strong>Dy (m²s⁻¹)</strong></td>
<td>0.008</td>
<td>0.010</td>
</tr>
<tr>
<td><strong>Pollutant mass (kg)</strong></td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Tau (s)</strong></td>
<td>330.2</td>
<td>127.8</td>
</tr>
<tr>
<td><strong>Tbar (s)</strong></td>
<td>394.7</td>
<td>142.9</td>
</tr>
</tbody>
</table>
Structural uncertainty analysis

Punehu (slower) River

Coachella (faster) River

Concentration 50 m downstream of release

Absolute Concentration Deltas
Parameter Uncertainty Analysis

Elder (1959) (E) \[ D_L = 5.93HV. \]

Fischer (1975) (F) \[ D_L = 0.011 \left( \frac{V}{V_*} \right)^2 \left( \frac{B}{H} \right)^2 hV. \]

McQuivey and Keefer (1974) (M&K) \[ D_L = 0.058 \frac{HV}{\sqrt{S_c}} \]

Liu (1977) (L) \[ D_L = 0.18 \left( \frac{V}{V_*} \right)^{0.05} \left( \frac{B}{H} \right)^2 HV. \]

Iwasa and Aya (1991) (I&A) \[ D_L = 2HV. \left( \frac{B}{H} \right)^{1.5} \]

Magazine et al. (1988) (M) \[ D_L = 75.86 \left( 0.4 \frac{V}{V_*} \right)^{-1.632} R_h V \]

Koussis and Rodriguez-Mirasol (1998) (K&R-M) \[ D_L = 0.6HV. \left( \frac{B}{H} \right)^2 \]

Seo and Cheong (1998) (S&C) \[ D_L = 5.92 \left( \frac{V}{V_*} \right)^{1.43} \left( \frac{B}{H} \right)^{0.62} HV. \]

Deng et al. (2001) (D) \[ D_L = \frac{0.15}{8 \varepsilon_{c1}} \left( \frac{V}{V_*} \right)^2 \left( \frac{B}{H} \right)^{1.67} HV. \text{ with } \varepsilon_{c1} = 0.145 + \left( \frac{V}{V_*} \right) \left( \frac{B}{H} \right)^{1.38} / 3520 \]

Kashefi and Falconer (2002) (K&F) \[ D_L = 10.612 \left( \frac{V}{V_*} \right) HV \text{ for } B/H > 50 \]

\[ D_L = \left[ 7.428 + 1.775 \left( \frac{B}{H} \right)^{0.62} \left( \frac{V}{V_*} \right)^{0.572} \right] \left( \frac{V}{V_*} \right) hV \text{ for } B/H < 50 \]

\[ \text{mean to } \]

\[ D_x \text{ (m}^2\text{s}^{-1}) \]

- \[ D_x = 0.6 \]
- \[ D_x = 10.3 \]
- \[ D_x = 2.6 \]
- \[ D_x = 9.0 \]
- \[ D_x = 19.8 \]
- \[ D_x = 46.9 \]
- \[ D_x = 37.7 \]
- \[ D_x = 33.6 \]
- \[ D_x = 27.1 \]
- \[ D_x = 4.7 \]
- \[ D_x = 15.7 \]

(El Kadi Abderrezak et al., 2015)
Conclusions

• For narrow and wide river, there is a difference in the models’ estimations
• For slow versus fast river, no evident difference was observed in models’ estimations
• Modelling framework is useful!

Future Work

• Implement uncertainty analysis module in framework
  – Residuals from peak concentrations
  – Bayesian uncertainty analysis
• Analyse uncertainties due to output variables (e.g. peak concentrations vs. average concentrations)
Future Work

• Sensitivity analysis of model parameters
• Models evaluation for study case in Haute-Sûre catchment in Luxembourg
• Implementation of additional models (e.g. transient storage and biochemical models)

Thank you

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References


Boxhall, J. B. *Environmental River Processes - Solute Transport Course Notes (CIV6771/471).* University of Sheffield.


