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DE LA RECHERCHE À L'INDUSTRIE

# Estimation of the transverse mixing coefficients in shallow gravel-bedded rivers

RiverFlow 2020



INRAE



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## Goals:

- Understanding the contribution of mixing processes in a reach due to turbulent diffusion, secondary currents dispersion
- Determining a predicting formulation to estimate the mixing efficiency in a reach

## Applications:

- Predicting the spatial distribution of pollutants in a river downstream a disposal area
- Determining the «perfect transverse mixing length »



Fischer, 1979:  $L_y = \alpha \frac{UW^2}{E_y}$

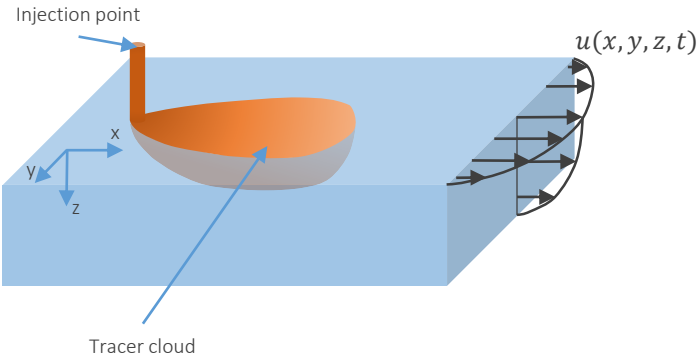
$L_y$ : perfect transverse mixing length

$U$ : bulk velocity of the stream

$W$ : width of the stream

$E_y$ : reach-averaged transverse mixing coefficient

When a cloud of particles is introduced in a stream, it spreads along the three spatial directions with increasing time:



For wide, shallow, uniform and stationary flows:

- velocity is mainly one directional ( $u = u(y)$ ,  $v = w = 0$ )
- vertical mixing is rapidly complete
- streamwise mixing is negligible
- we focus on transverse mixing



Simplified 1D depth-averaged advection-diffusion equation:

$$\frac{\partial hc}{\partial t} + u \frac{\partial hc}{\partial x} = uh \frac{\partial \left( uh^2 \varepsilon_y \frac{\partial c}{\partial q} \right)}{\partial q} \quad \text{①}$$

Yotsukura & Cobb (1972)

With:

- $h$  = local flow depth (m)
- $u$  = local depth and time-averaged velocity (m/s)
- $q = \int_0^y u(\delta)h(\delta)d\delta$  = cumulative discharge (m<sup>3</sup>/s)
- $\varepsilon_y$  = local mixing coefficient (m<sup>2</sup>/s)
- $c$  = local depth and time-averaged concentration (kg/m<sup>3</sup>)

In the case of a slug injection of a mass of tracer, we can integrate Eq.1 over the time following Beltaos (1980, 1984):

$$\frac{\partial \theta}{\partial x} = E_y \psi U H^2 \frac{\partial^2 \theta}{\partial q^2} \quad \textcircled{2}$$

With:

- $H$  = reach-averaged flow depth (m)
- $U$  = reach-averaged velocity (m/s)
- $E_y$  = reach-averaged coefficient (m<sup>2</sup>/s)
- $\psi = \frac{\frac{1}{Q} \int_0^Q \bar{u}(q) h(q)^2 dq}{UH^2}$  = velocity-shape profile
- $\theta$  = local depth-averaged dosage (kg.s/m<sup>3</sup>)

Solving Eq.2 in a reach from cross-section  $S_i$  to  $S_{i+1}$ :

$$\theta_0(x_{i+1}, q) = \int_0^Q \frac{\theta(x_i, q_0)}{\sqrt{4\pi E_{y,i,i+1} \psi U H^2 (x_{i+1} - x_i)}} \exp \left[ \frac{-(q \pm q_0)^2}{4 E_y \psi U H^2 (x_{i+1} - x_i)} \right] dq_0$$

Seo et al. (2006)

And using the mirror method to model the reflection at the banks:

$$\theta(x_{i+1}, q) = \theta_0(x_{i+1}, q) + \theta_0(x_{i+1}, q) + \sum_{n=1}^{\infty} \theta_0(x_{i+1}, 2n \pm q) \quad \textcircled{3}$$

- Many field and laboratory studies since 1960 (Elder, 1959; Fischer, 1969; ... ; Seo et al, 2016)
- Attempts to find correlation between the transverse mixing coefficient and parameters:  
$$\frac{E_y}{Hu^*} = f\left(\frac{U}{u^*}, \frac{W}{H}, S_n\right)$$
 with  $U/u^*$  the friction factor,  $W/H$  the aspect ratio and  $S_n$  the sinuosity
- Problem:
  - no clear correlation is yet found and the quantification of the transverse mixing coefficient remains an open question
  - most studies consider that the studied reaches follow the 1D model hypotheses, but natural reaches generally present significant longitudinal hydraulic and geometric variations (Jackson et al, 2013)
- Proposed solution:
  - Delineate a natural reach in smaller sub-reaches that would better follow the 1D hypotheses

➔ Choose a longitudinally varied reach, delineate it in sub-reaches with quasi-homogeneous roughness elements by measuring concentration cross-profile at each two ends

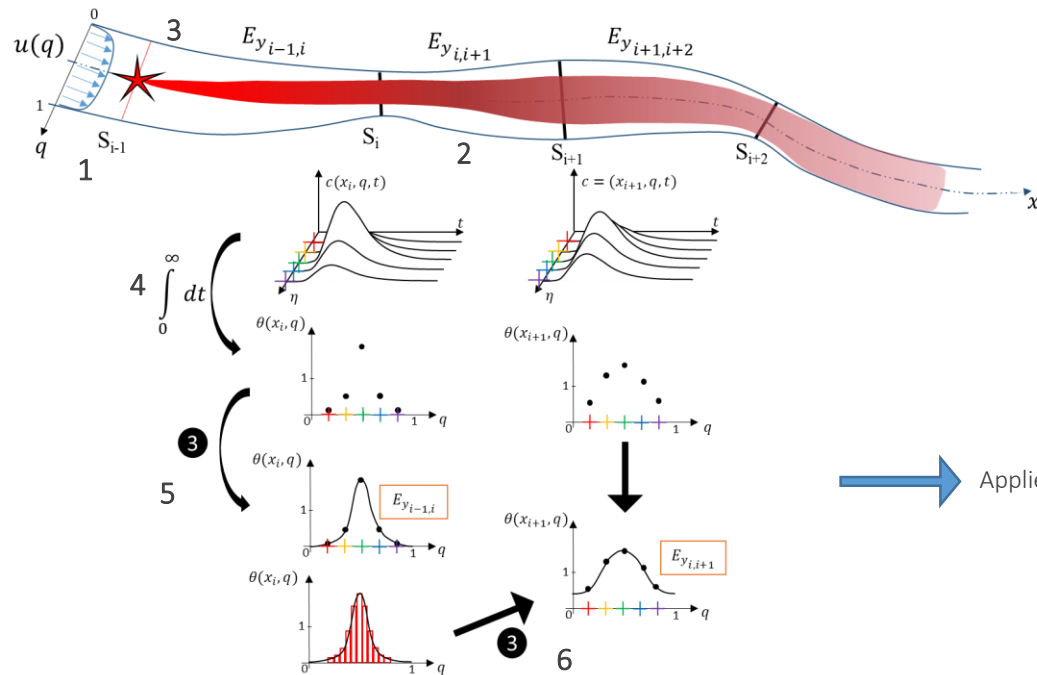
➔ Highlight the variability of the mixing coefficient in a short reach usually disregarded in past studies

➔ See if the delineation method gives useful correlations between the dimensionless mixing coefficient and hydraulic or geometric factors in order to use it for a predictive formulation

➔ Usually  $\frac{E_y}{Hu^*} = f\left(\frac{U}{u^*}, \frac{W}{H}\right)$

With:

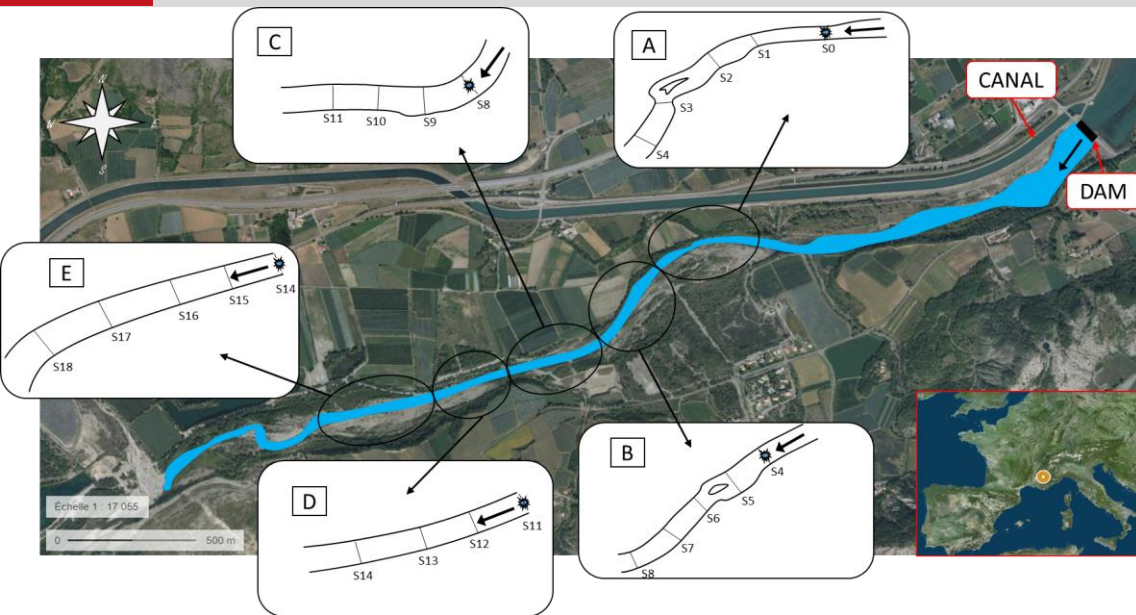
- $U/u^*$ : friction factor
- $W/H$ : aspect ratio



Applied to the Durance river, France

1. Position an injection point upstream
2. Measure hydraulics and position sensors along two successive cross-sections downstream
3. Inject a tracer
4. Gather data and integrate concentration profiles over time
5. Fit solution Eq.3 to determine  $E_y$  between the injection and the sub-reach's upstream cross-section
6. Discretize upstream profile and fit solution Eq.3 to determine  $E_y$  between the two cross-sections





Location: La Saulce, France

Dates: September 23-27 2019

➔ 5 injection zones, 18 cross-sections and sub-reaches



Complex succession of emerging blocks, riffle with island, and pool



Long sand bedded pool with vegetation



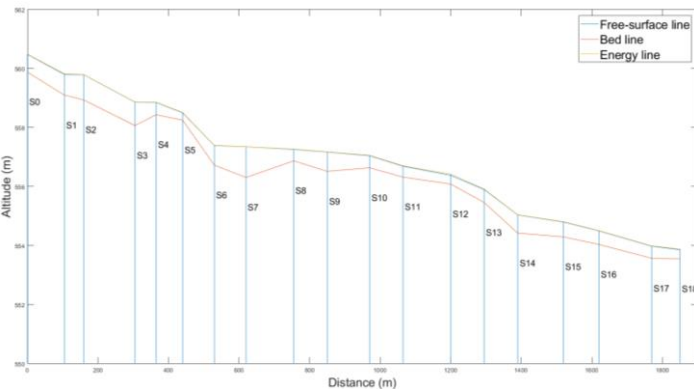
Patches of emerging blocks

ADCP measurements at every cross-sections: velocity field + bathymetry + sensors positioning



Gives  $U, H, \psi$  and sensors position in cumulative discharge

Free surface elevation measurements with a DGPS Leica along the left bank



Gives  $u^* = \sqrt{gHJ_e}$

With:

- $g$  = gravitationnal acceleration ( $m^2/s$ )
- $J_e$  = energy line slope ( $m/m$ )

Chosen tracer: Liquid rhodamine WT 20% → Fluorescent tracer, small quantities needed, low toxicity

Measured with:

GGNU-FL30 Albillia



TQ-tracer (Sommer Messtechnik)



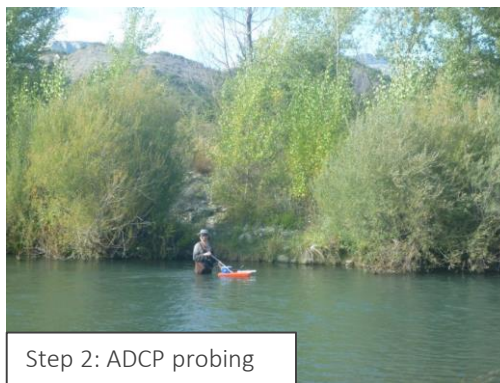
Positioned along the cross-sections every 7<sup>th</sup> of the total discharge



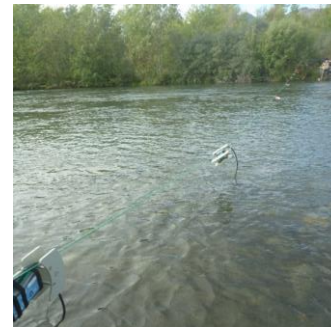




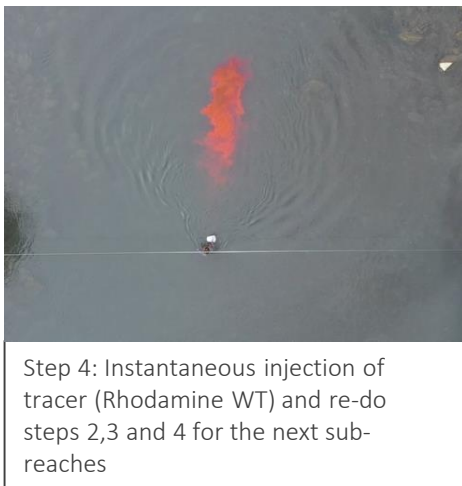
Step 1: Calibration



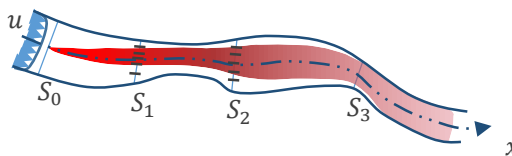
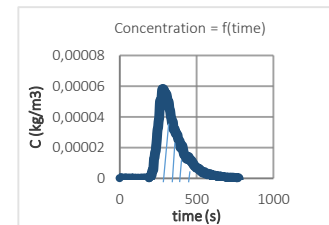
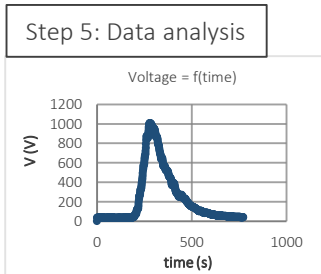
Step 2: ADCP probing



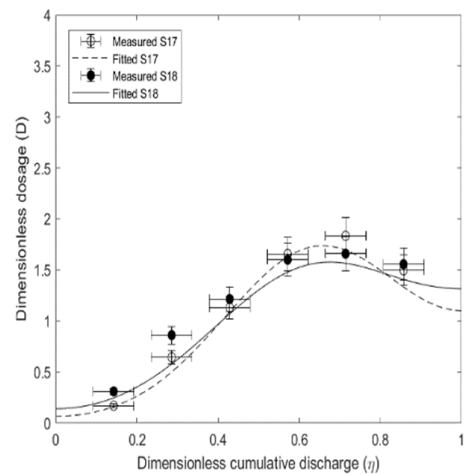
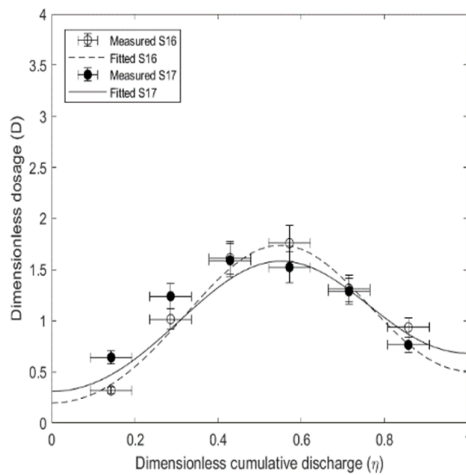
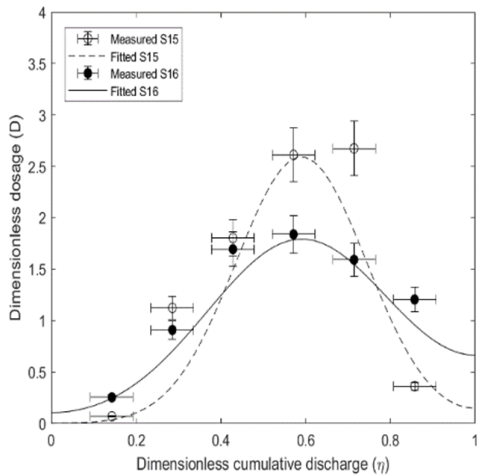
Step 3: Probes positioning on two consecutive cross-sections



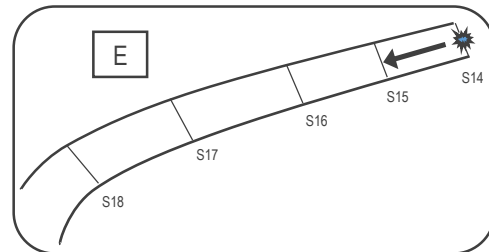
Step 4: Instantaneous injection of tracer (Rhodamine WT) and re-do steps 2,3 and 4 for the next sub-reaches

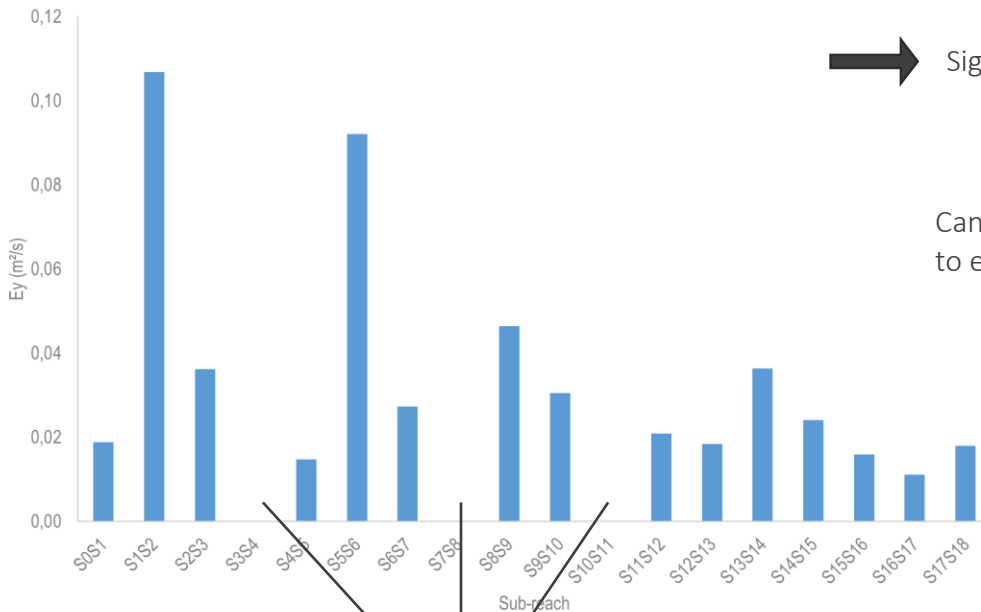


Integrate to get:  $\theta = \int_{t=0}^{t=\infty} c dt$



Example for injection zone E:  
(straight channel with patches of emerging blocks)





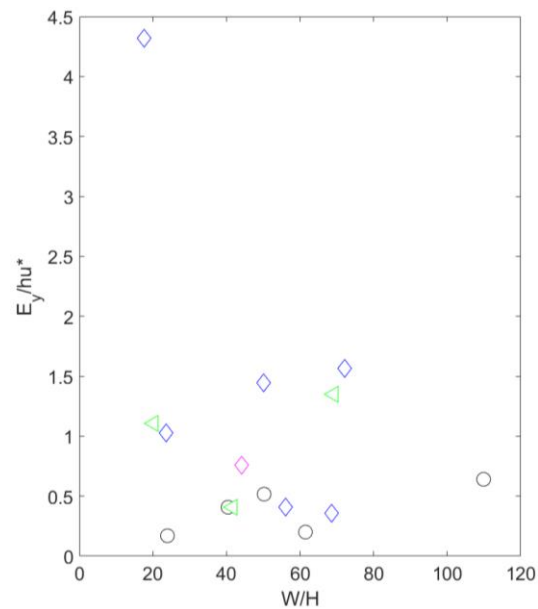
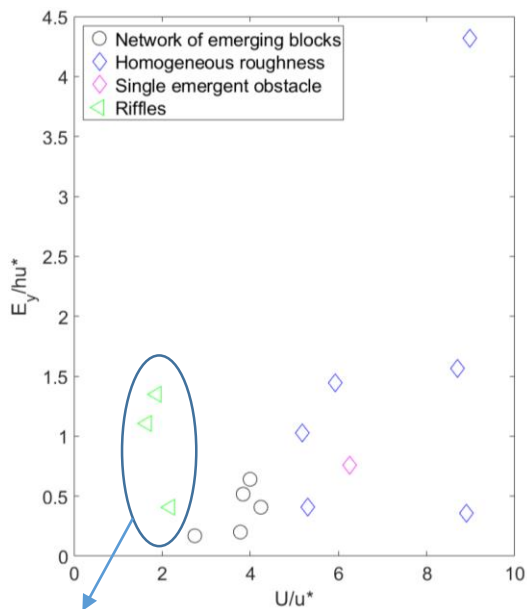
Significant longitudinal variability



Can we find interesting correlations to explain it?

Complete mixing reached

$$\frac{E_y}{Hu^*} = f\left(\frac{U}{u^*}, \frac{W}{H}\right)$$



Values of  $Hu^*$  poorly representative of the riffles hydraulics (measurements upstream and downstream of it)

➔ No clear correlation observed even when a reach is delineated in quasi-homogeneous sub-reaches



- We applied tracing experiments in a river presenting strong variations in bed morphology; we delineated the chosen reach in sub-reaches with quasi-homogeneous roughness elements
- We used a simple 1D-diffusion model with simplificative hypotheses to determine the transverse mixing coefficient of each sub-reaches and show significant variations of the mixing coefficient in a natural reach
- We found no clear correlation of the dimensionless mixing coefficient against the usual factors defined in the literature

## Perspective:

- A new parameter seems needed to explain the variations in our data, and eventually explain those in the literature; a new analysis of the data considering the non-uniformity of the flow may reveal interesting results
- Laboratory measurements are planned to study the influence of the relative roughness height on the transverse mixing (including emerging obstacles)

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