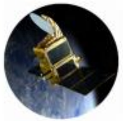
An index concentration method for suspended load monitoring in large rivers of the Amazonian foreland



william.santini@ird.fr

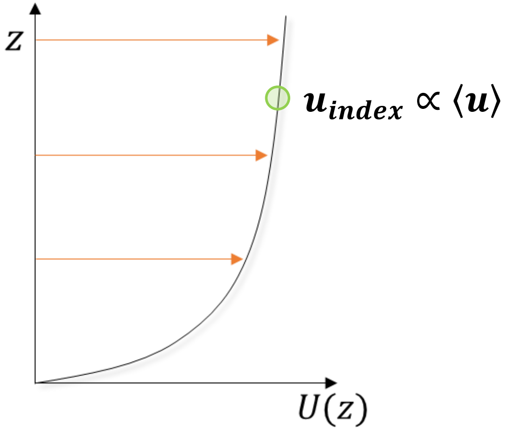
Why an index concentration?

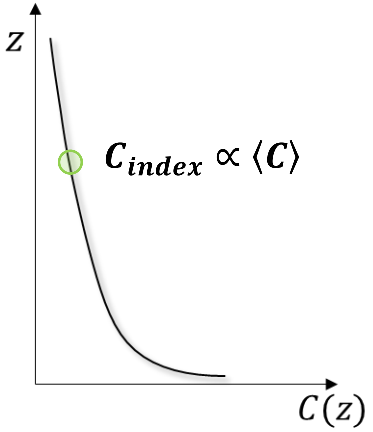
In the large tropical rivers, the measurement of cross-sectional average concentrations $\langle C \rangle$ [mg l^{-1}] remains a costly and time-consuming task

- Gauging stations can only be reached after several days of travelling on hard dirt roads or by the river
- There are no infrastructures on the rivers, and all operations are conducted using small boats
- The gauging section are very large
- The suspension regime is graded (sand, silts): the entire cross-section must be explored to provide a representative estimate of the mean concentration

For operational and cost rationalization purposes, index concentrations are often sampled in the flow and used as a surrogate of the cross-sectional average concentration.

Analogy: Index velocity





Ratio $\boldsymbol{\alpha}$ of mean concentration to index concentration

Sediment load

Mean concentration

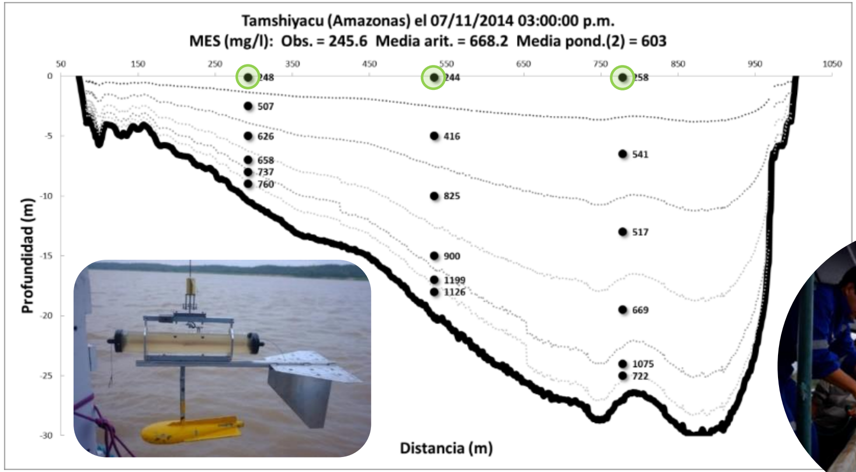
$$\langle C \rangle = Q_s / Q$$

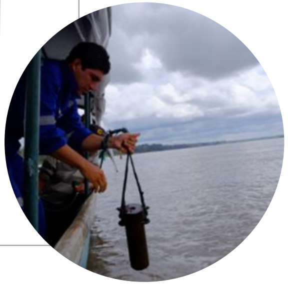
Discharge

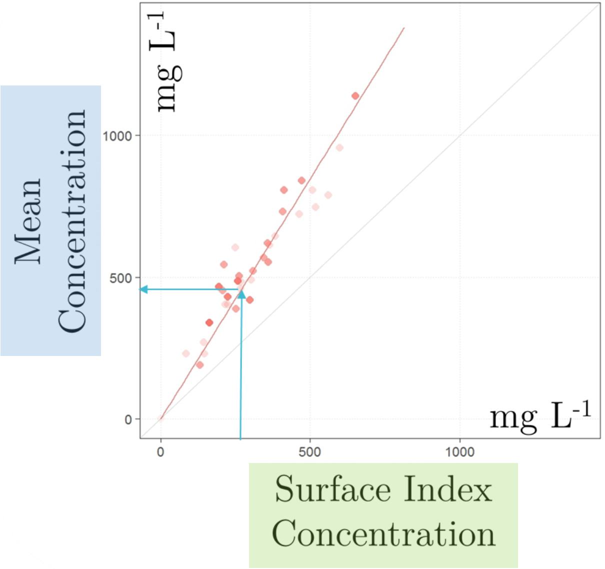
Index concentration

Sampling height (h: water surface)

$$\langle C \rangle = \boldsymbol{\alpha}\, C(z_\chi = h)$$

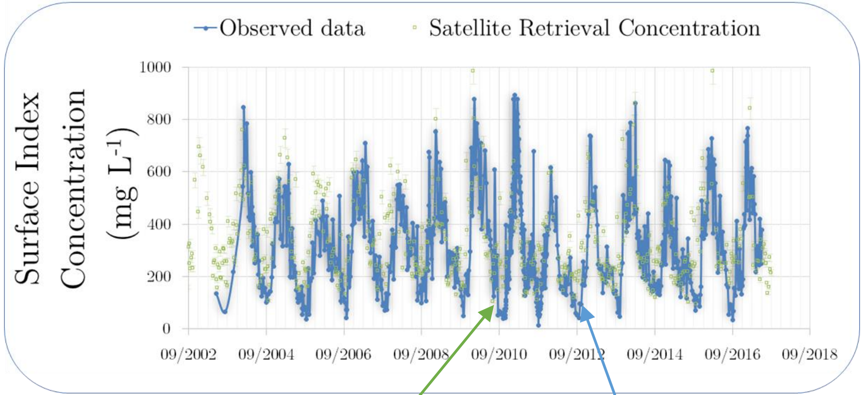


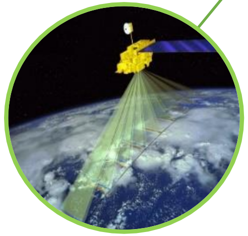




The CZO HyBAm strategy: a sharp temporal resolution of index concentrations

Time series of index concentration



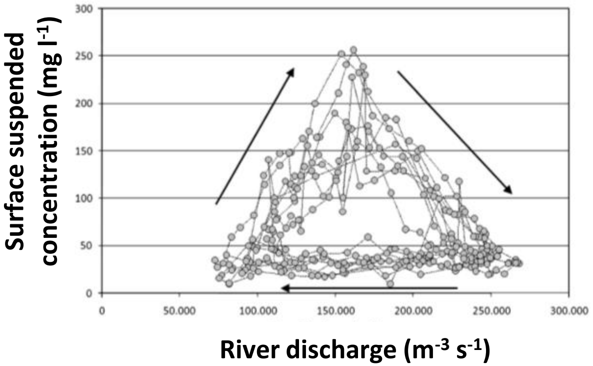


Remote sensing

In situ measurement

NB: There is no relation between discharge and concentration in the large Amazonian Rivers!

Example at Óbidos (Brazil):

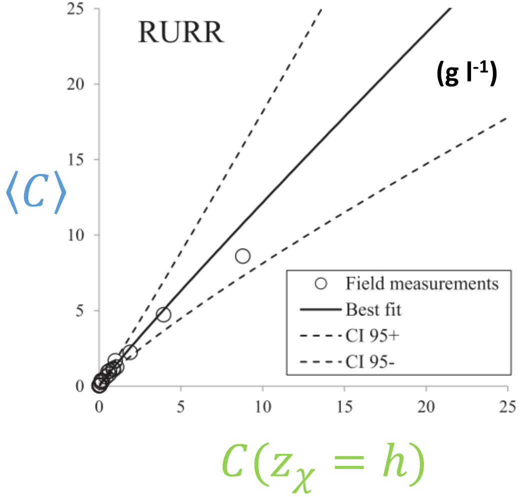


Martinez *et al.*,*Catena* ,2009

A substantial part of the uncertainties on the matter fluxes assessments are induced by these relationships

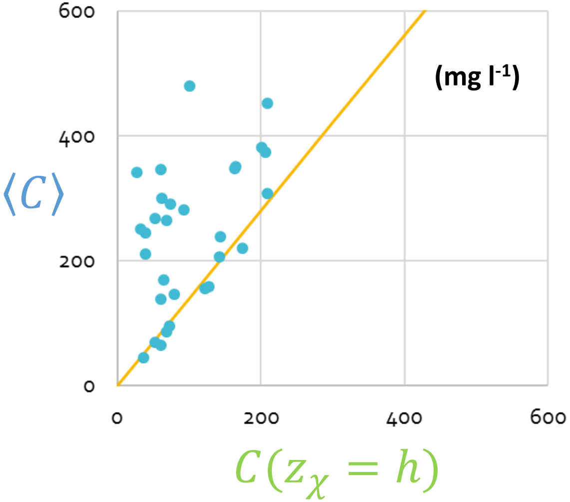
Example in Bolivia:

Rurrenabaque (Beni)



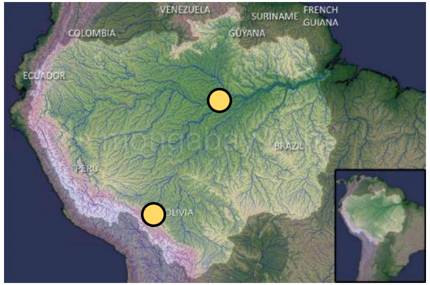
Example in Brazil:

Manacapuru (Solimões)



(Vauchel *et al.*, JH, 2017)

- **Extrapolation**: insufficient number of $\langle C \rangle$ measurements
- **Variability** of the hydrological conditions
- **Insufficient sampling** of the cross-section (few points)
- **Large uncertainties** on the surface concentration
- **Representability** of the surface concentration?



Needs

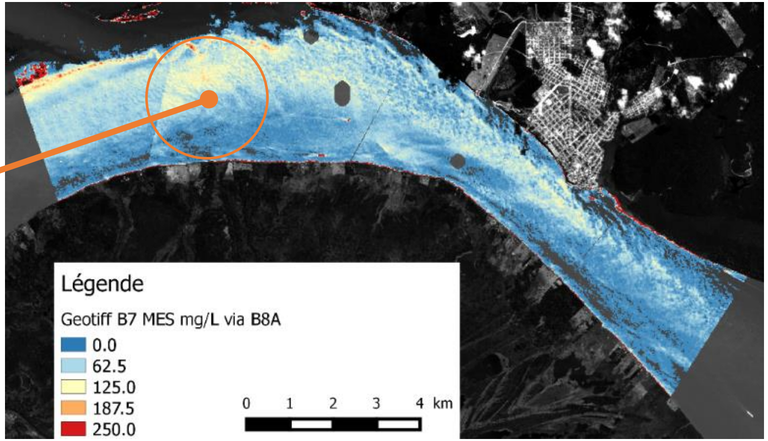
- Enhanced measurement protocols (rapidity, robustness…)
- Enhanced sediment load calculation, with uncertainties
- To link the concentrations derived from remote sensing data with the mean concentration transported by the river

The index sample representativeness becomes crucial as high-resolution imagery is increasingly used to link remote sensing reflectance data with suspended sediment concentration

In order to improve measurement, the relationships deserve more insight, and to be linked with the hydraulic theory

Index concentration

$C(z_\chi = h)$



Mean concentration

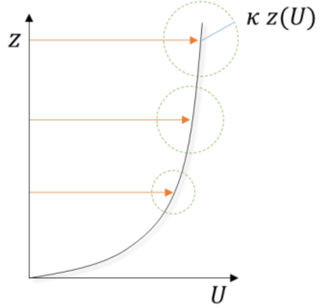
$$\langle C \rangle = \boldsymbol{\alpha}\, C(z_\chi = h)$$

$$\boldsymbol{\alpha} = ???$$

Hydraulic modelling

Theory for modeling vertical concentration profiles

Prandtl theory (mixing length)



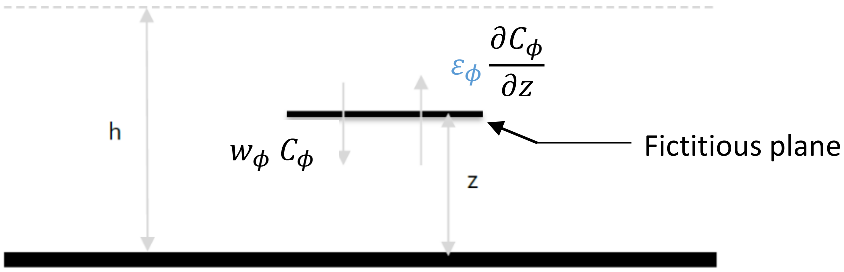
Sediment diffusivity

Concentration

$$\varepsilon_\phi \frac{\partial C_\phi}{\partial z} = -w_\phi\, C_\phi$$

Settling velocity (function of the mean diameter)

Schmidt (1925) and O'Brien (1933)



Rouse number

downward gravity forces

$$P_\phi = \frac{w_\phi}{\kappa\, \beta_\phi u_*}$$

upward turbulence forces

Mass

Sediment diffusivity

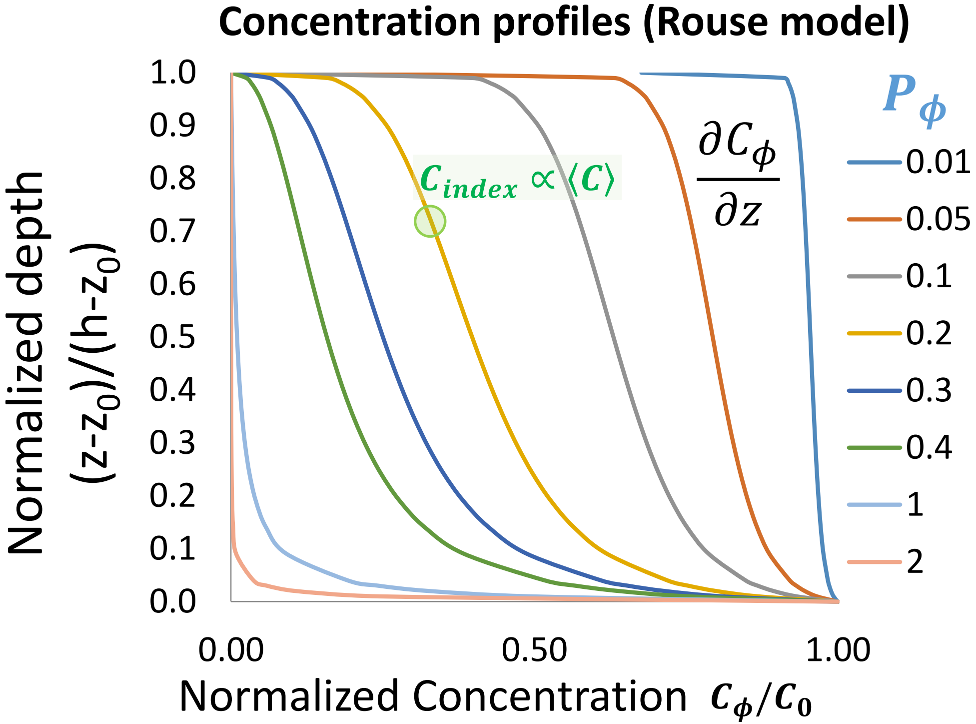
$$\frac{\varepsilon_\phi}{\varepsilon_m} = \beta_\phi$$

Fluid (momentum diffusivity)

Ratio of sediment to eddy diffusivity

! (Poorly understood physicochemical processes)

The Rouse number, a shape factor for the concentration profiles



Washload $P_\phi \ll 1$

Graded suspension $P_\phi < 1$

Mixed load $\sim 1 < P_\phi < 6$

Bedload/saltation $P_\phi > 6$

$$\langle C \rangle = \frac{1}{(h-z_0)} \int_{z_0}^{h} C(z)\, dz$$

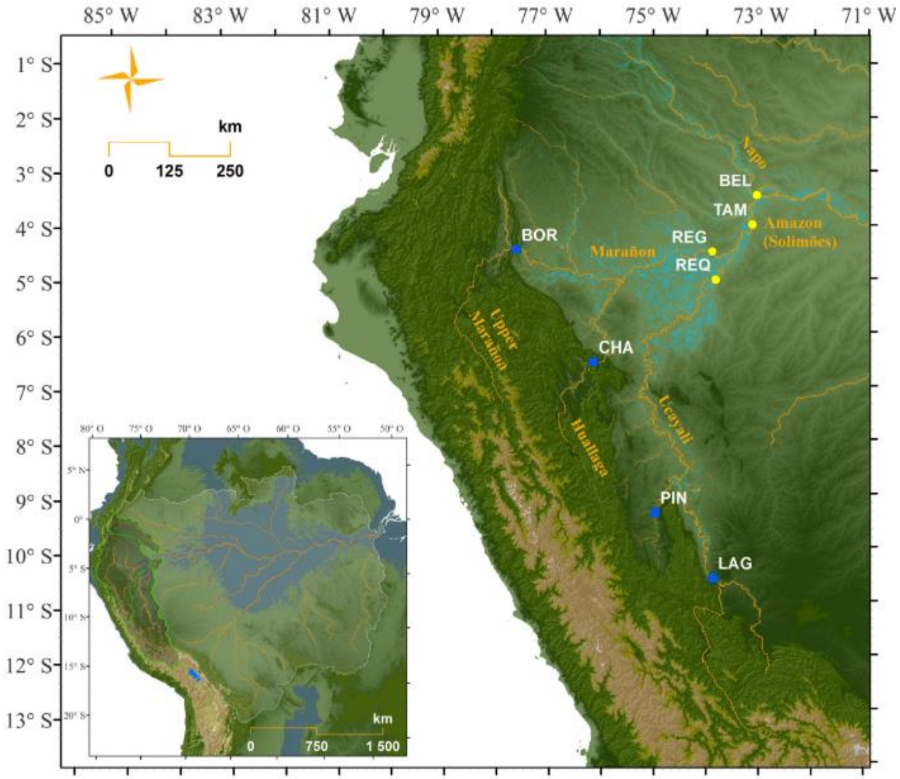
Model

Previous studies showed that the Rouse model (Rouse, 1937) can describe the suspension of sediments in large tropical rivers well

(Vanoni, 1979, 1980; Bouchez et al., 2011; Lupker et al., 2011; Armijos et al., 2016)

However, the Rouse model **predicts a concentration of zero at the water surface**, which is where the index concentration is often sampled

Location of the sampling sites



Data summary

8 sites (North Amazonian Foreland Basin)
820 000 km²
37 700 $m^3 s^{-1}$
Period: 2010 – 2017

1330 water samples
249 concentration profiles

Concentration ranges: 1 – 3700 mg l^{-1}

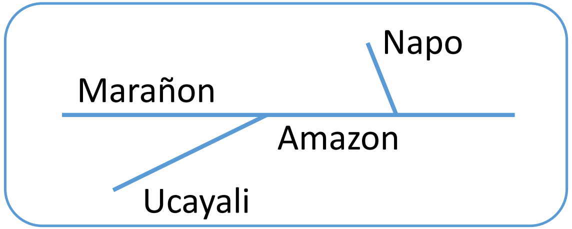
14 PSD profiles
88 PSD

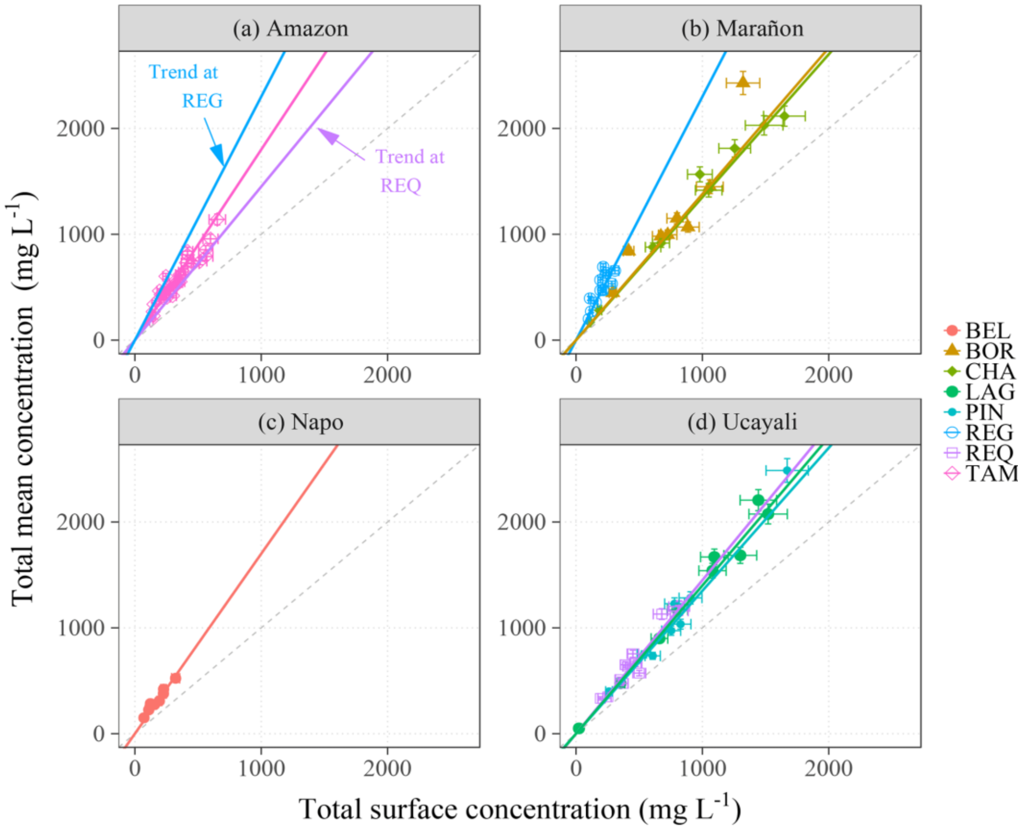
Variability of the ratio of mean concentration to index concentration

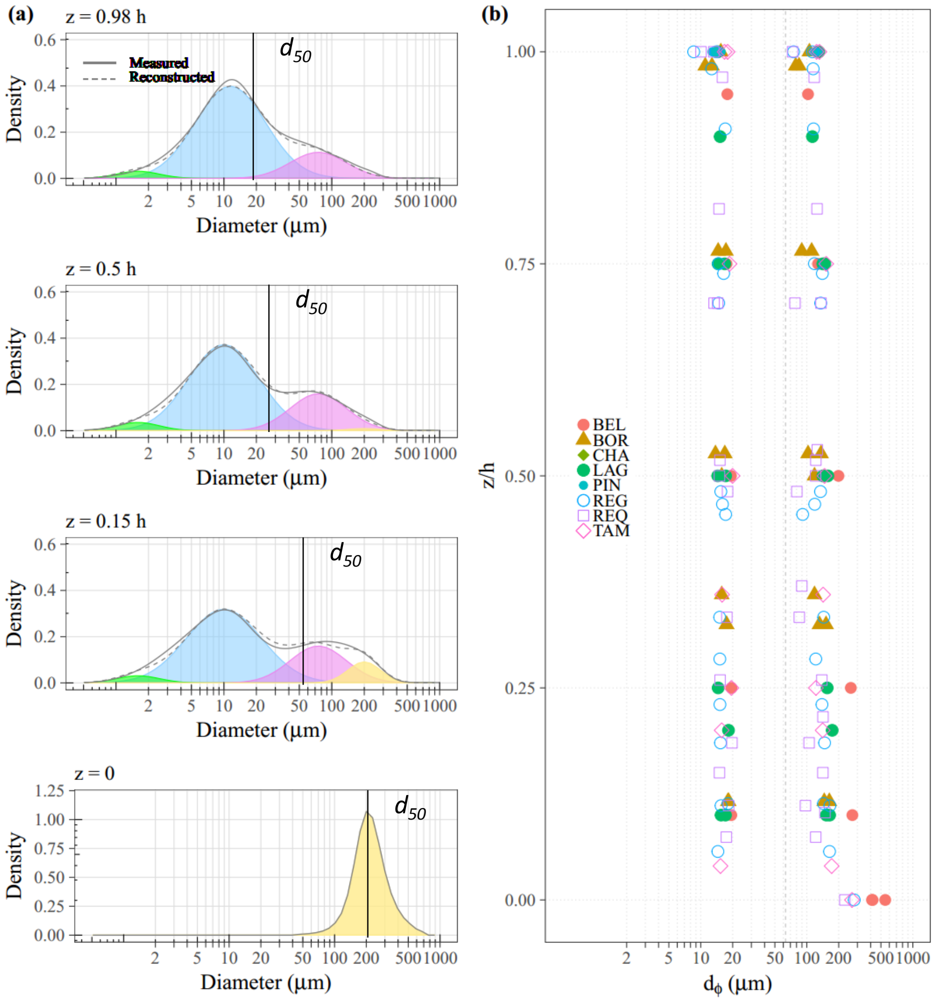
The ratio α of mean concentration to index concentration is:

- Location and source dependent (basin characteristics, confluences, sediment properties: grain size, shape, density…)

- Flow condition dependent (u_*)







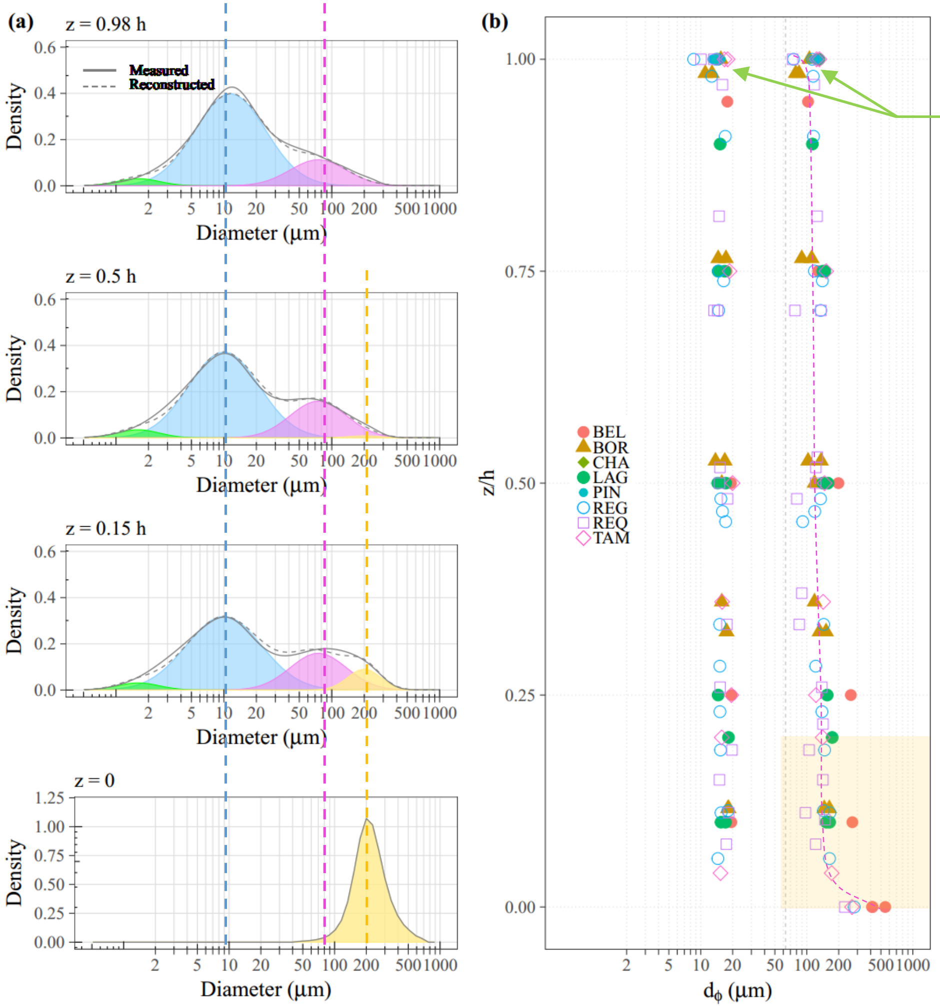
A proper model for the PSD

The d_{50} shifts with depth, i.e. with X_s, but it does not mean that there is any change in the physical properties (e.g. diameter, density and shape) of the sand fraction.
This shift directly affects α, as the vertical concentration gradient depends on the balance between the turbulence strength and the settling velocity

A key issue is to provide a proper model of the PSD using a limited number of sediment classes ϕ

$$\alpha = \sum_{\phi=1}^{n} \alpha_\phi \, X_\phi$$

Mass fraction [0 – 1]



Strong grain size sorting at the air/water interface

Choice: 2 particle size groups, fine sediments and sand were considered for the large rivers of the Peruvian Amazon

Fine sediments

Clays

Small aggregates

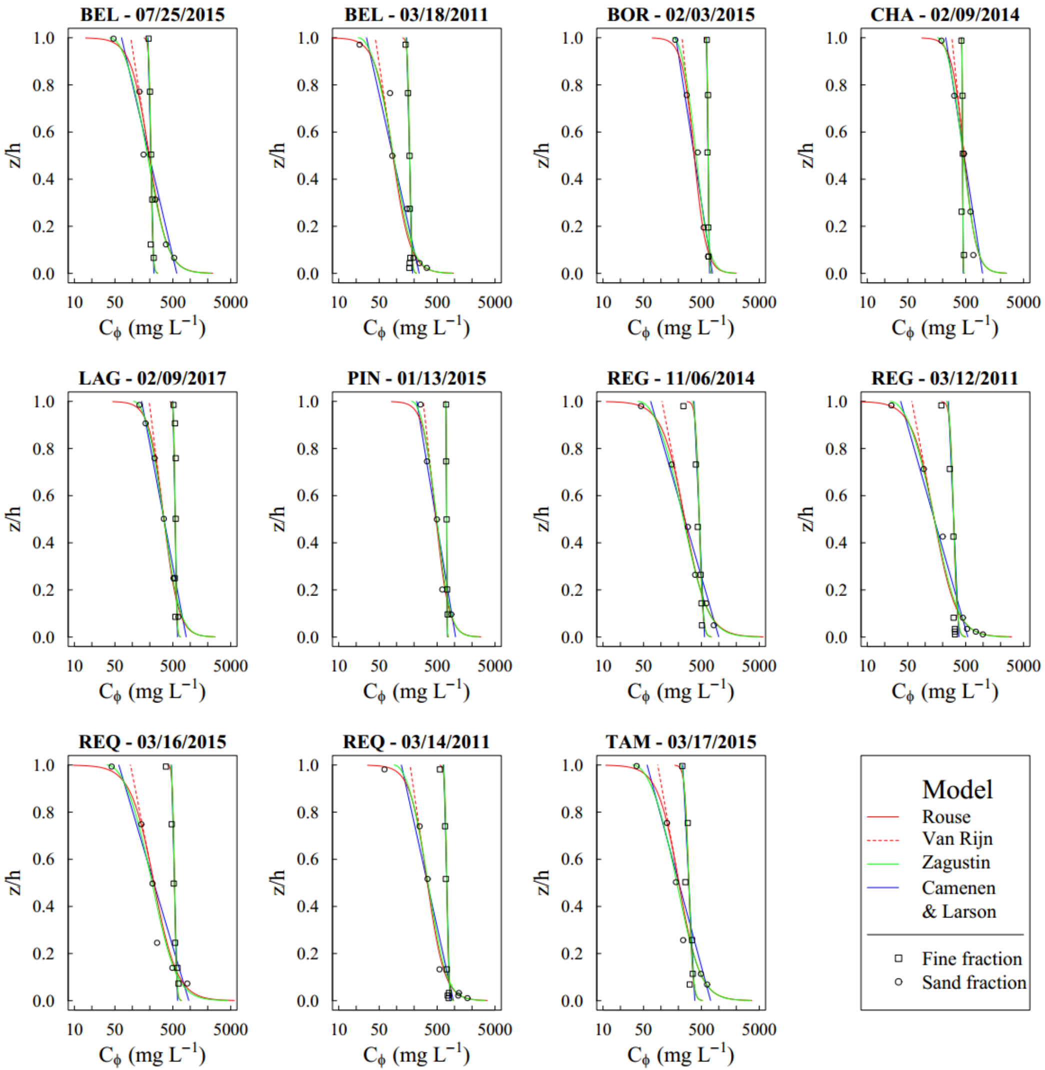
Silts

Sands

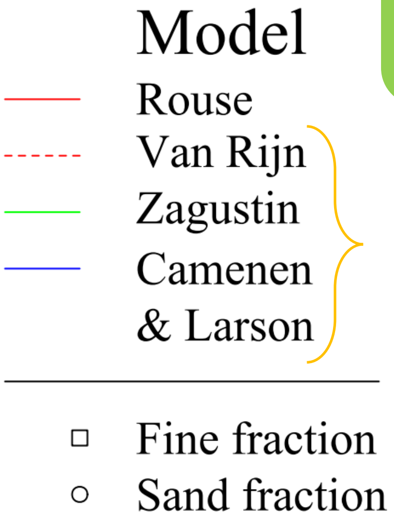
Non-cohesive

$$\alpha = X_f\ \alpha_f + X_s\ \alpha_s$$

Bed material influence on the vertical distribution of sand particle concentration



The Rouse model predicts a concentration of zero at the water surface

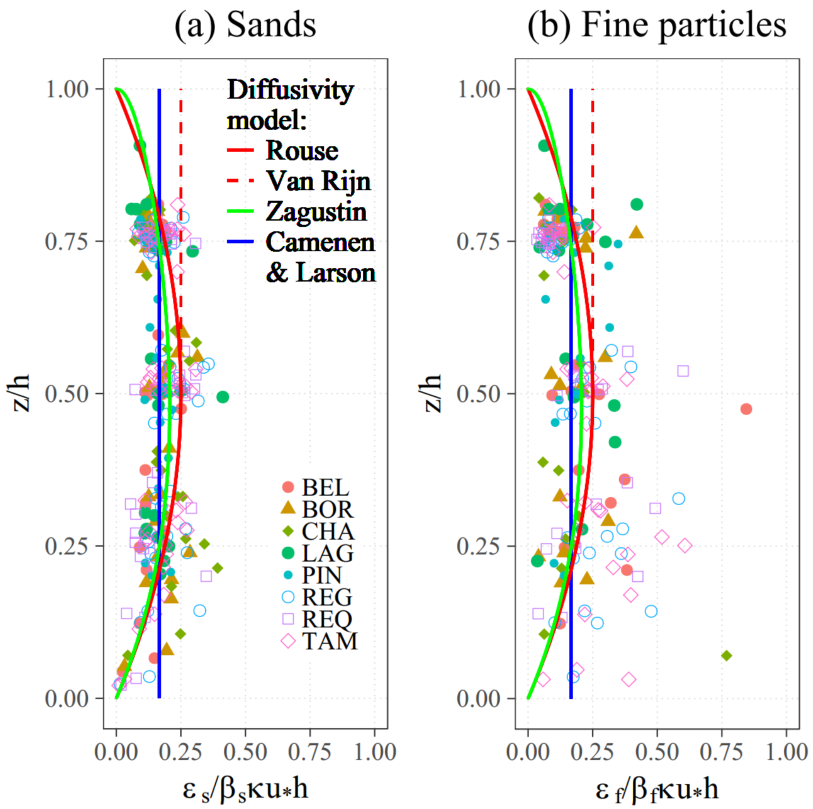


Other formulations with **finites values** at the water surface

(Zagustin, 1968; Van Rijn, 1984; Camenen and Larson, 2008)

1330 water samples
249 concentration profiles

Dimensionless Sediment diffusivity profiles: $\varepsilon_\phi(z)$



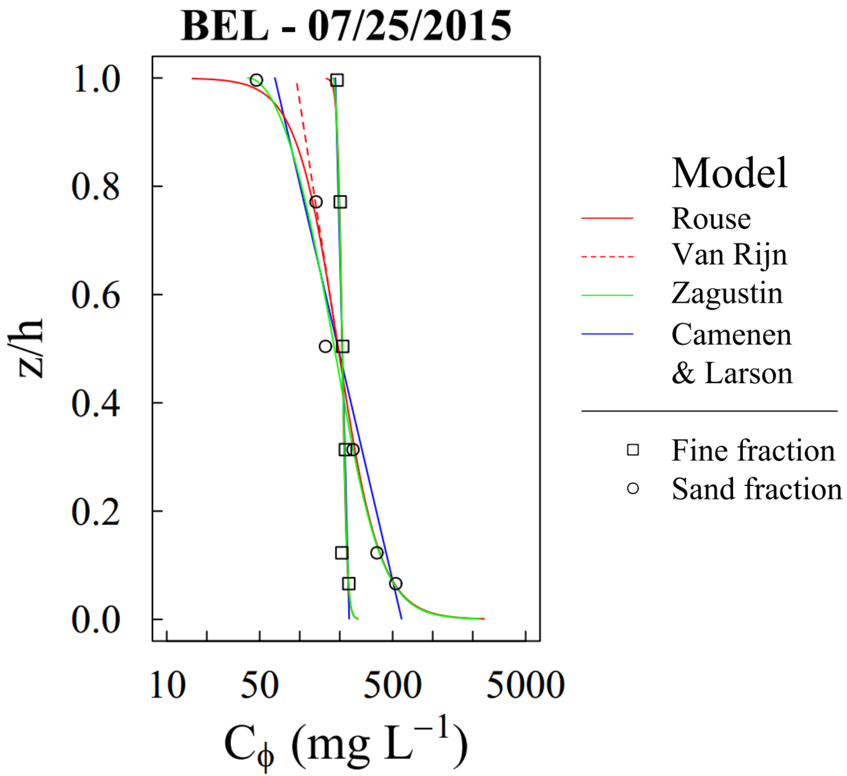
$\varepsilon_\phi(z)$ profiles were derived from the measured concentration profiles

The overall shapes of the derived $\varepsilon_\phi(z)$ profiles were in good agreement with the Rouse and Zagustin theories

Camenen and Larson's expression (2008) of depth-averaged diffusivity is a reasonable approximation, except near the bottom and top edges

The constant diffusivity value suggested by Van Rijn (1984) for the upper half of the water column clearly overestimates the diffusivity for z > 0.75 h

Model expression: a simple function of the Rouse number



$$\langle C \rangle = \boldsymbol{\alpha}\, C(z_\chi)$$

$$\boldsymbol{\alpha} = ???$$

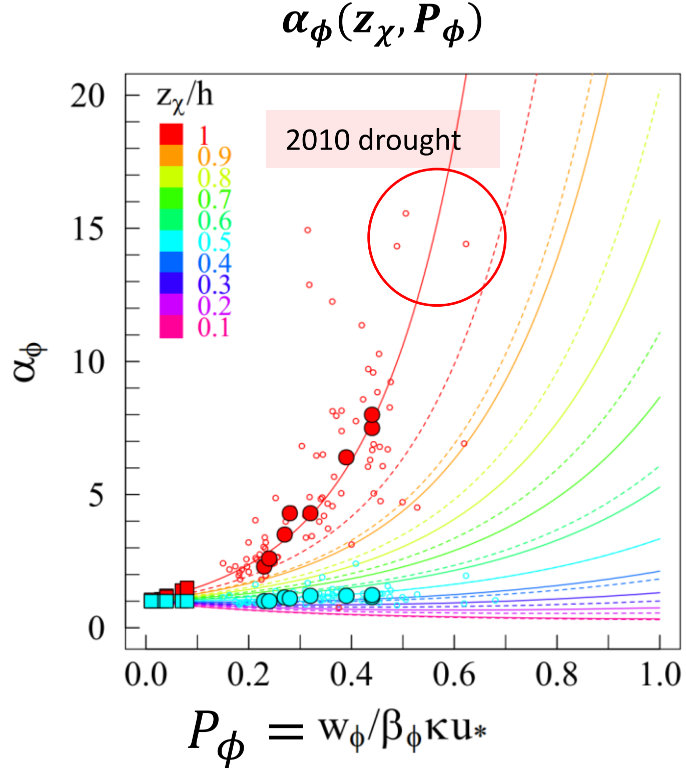
Model 1:

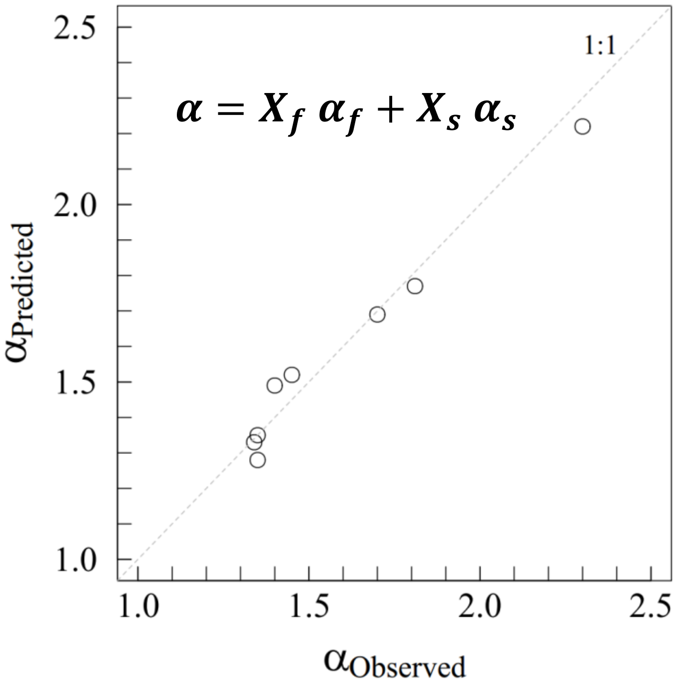
$$\alpha_\phi(z_\chi, P_\phi) = \frac{\exp(3\,P_\phi)\,(1-\exp(-6\,P_\phi))}{6\,P_\phi\,\exp\left(0.93\,P_\phi\left(\Phi(\frac{h}{2})-\Phi(z_\chi)\right)\right)}$$

Model 2:

$$\alpha_\phi(z_\chi, P_\phi) = \frac{1}{6\,P_\phi}\,\exp\left(6\,P_\phi\,\frac{z_\chi}{h}\right)\left(1-\exp(-6\,P_\phi)\right)$$

Model validation





But…how to get the parameters?

- What we need to predict the Rouse Number:

$$\alpha_\phi(z_\chi, P_\phi) = \frac{\exp(3\,P_\phi)\,(1-\exp(-6\,P_\phi))}{6\,P_\phi\,\exp\left(0.93\,P_\phi\left(\Phi(\frac{h}{2})-\Phi(z_\chi)\right)\right)}$$

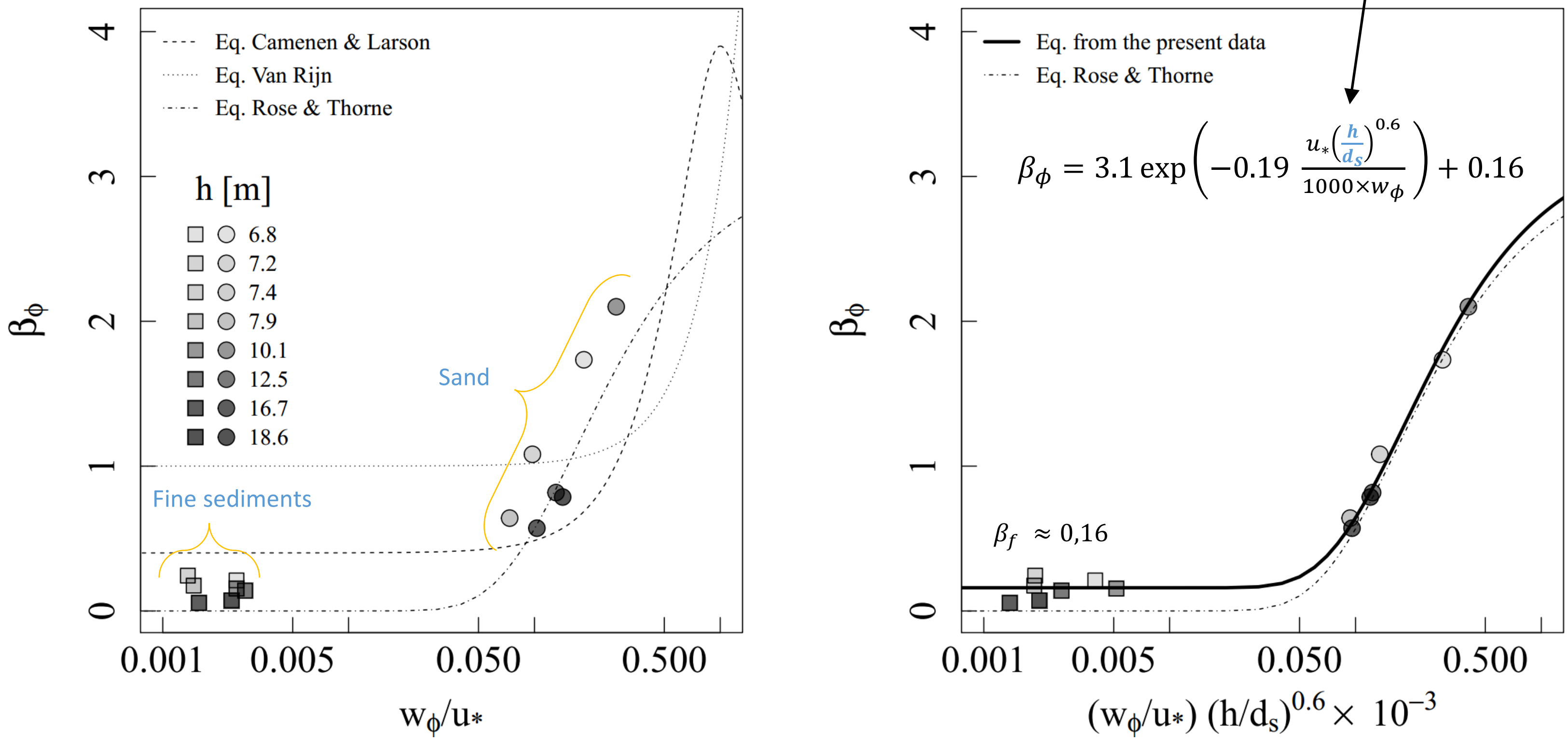
Settling velocity (function of the mean diameter)

$$P_\phi = \frac{w_\phi}{\kappa\,\beta_\phi u_*}$$

Ratio of sediment diffusivity to momentum diffusivity

Ratio of sediment to eddy diffusivity β_ϕ as a function of the ratio w_ϕ / u_*

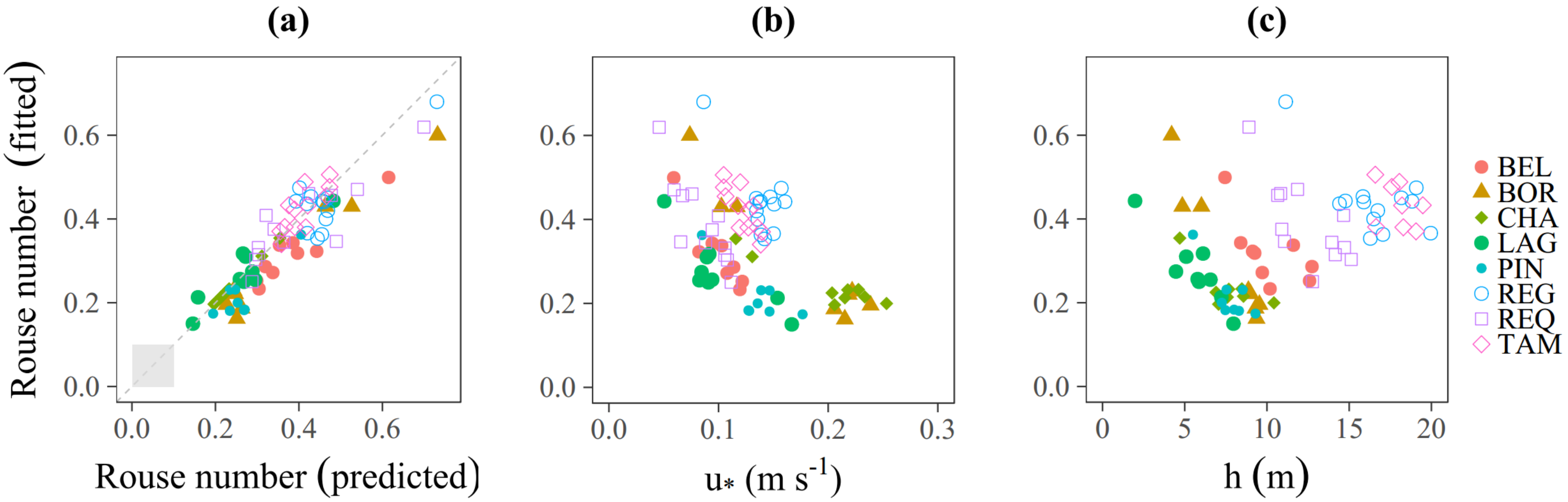
Departures from log –vel profiles (u)?
Errors on w_ϕ and u_* ?



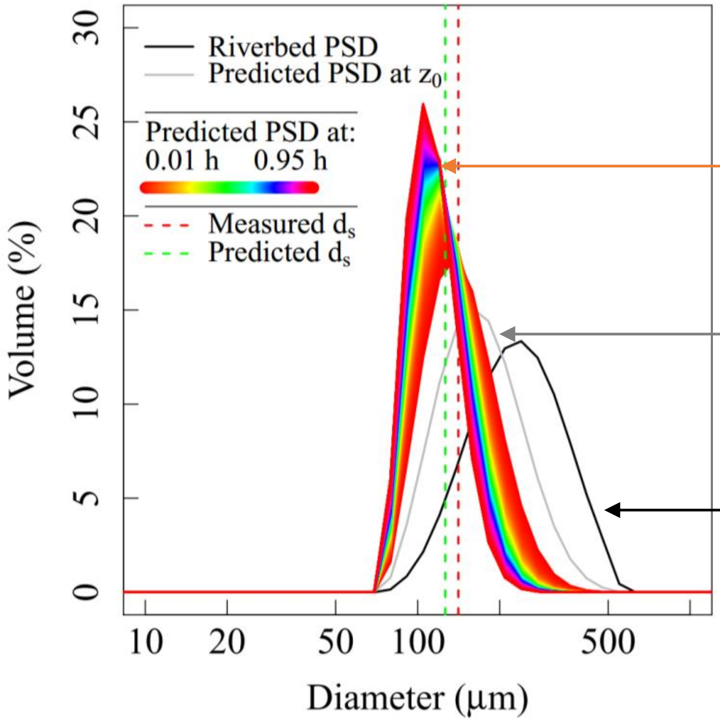
Rouse number variability (sands)

The shear velocity mainly controls the Rouse number variability at a given site

The variations in particle size are therefore a second order factor



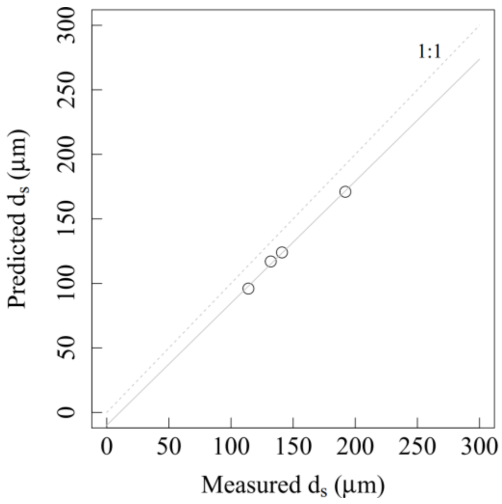
Mean diameter assessment (sand)

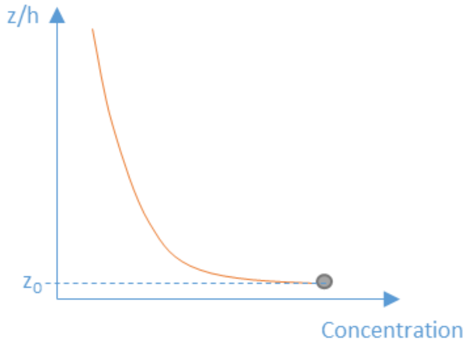


Predicted PSD at z:
Concentration distribution model
(Zagustin model, 1968)

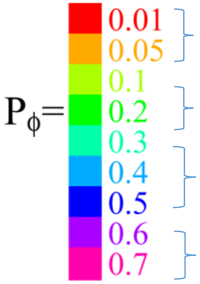
Predicted PSD at z_0
Bedload transport model
Camenen *et* Larson (2005)

Measured PSD (riverbed)





Which protocols are suitable to the Amazonian Rivers?



Nominal conditions for fine sediments

Nominal conditions for sand particles (piedmont)

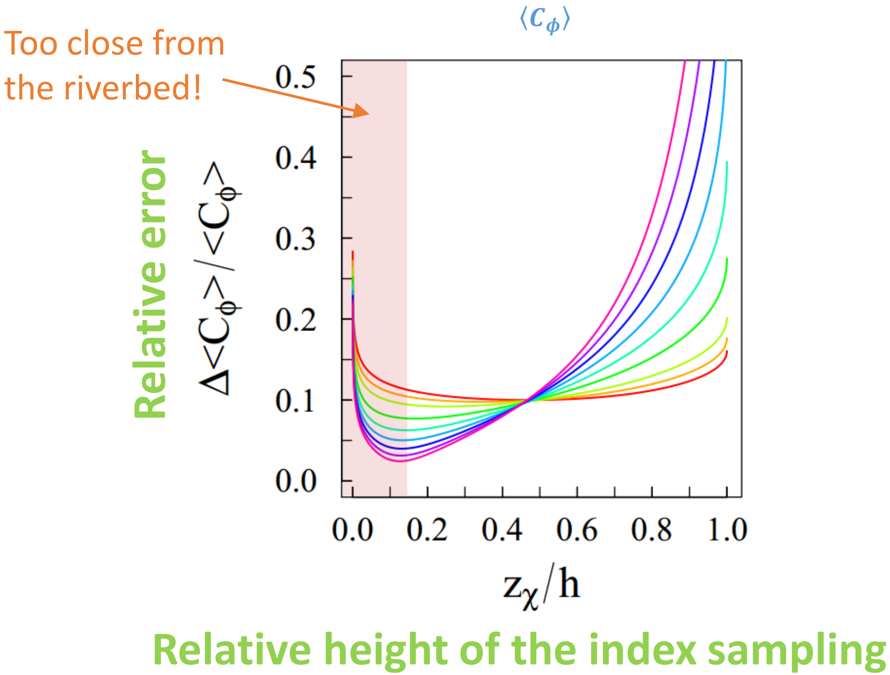
Nominal conditions for sand particles (lowland)

Extreme drought (sands)

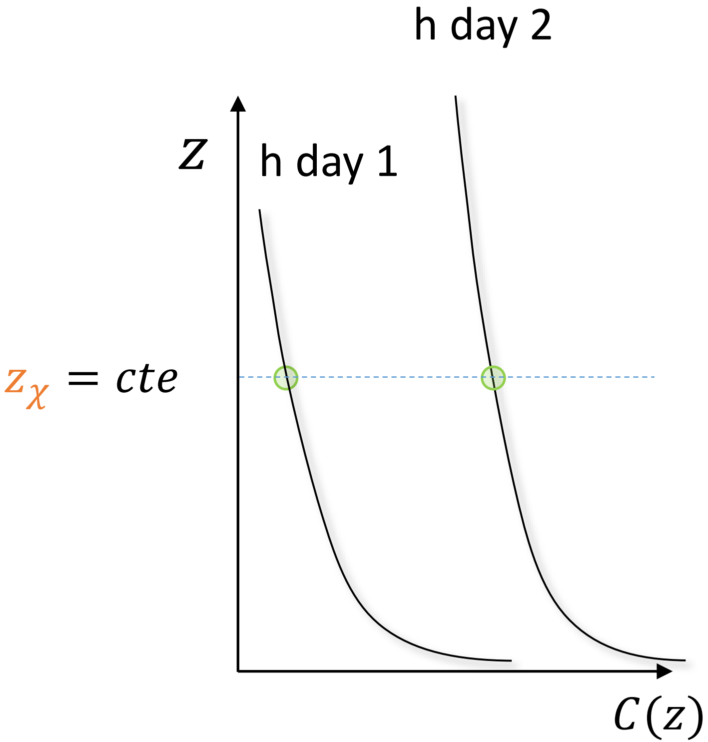
- For fine sediments ($P_f < 0.1$), the most accurate $\langle C_f \rangle$ is obtained when sampling the water column at approximately $0.5\ h$.
  The sampling can also be achieved at the water surface with a good estimation of $\langle C_f \rangle$ (±15%)
  → OK for *Remote sensing*

- **For the sand fraction at the piedmont stations** ($P_s < 0.3$), sampling in the $[0.2\ h, 0.8\ h]$ region is recommended to keep the errors of $\langle C_s \rangle$ below ±20%. A sampling at the water surface is still possible, but there will be uncertainties between ±20-40% for $\langle C_s \rangle$.

- **For enhanced monitoring of the sand concentration at the lowland stations** ($P_s > 0.3$), the $[0.2\ h, 0.8\ h]$ zone is preferred over the water surface



Example of a simple and operational protocol: sampling at fixed depth



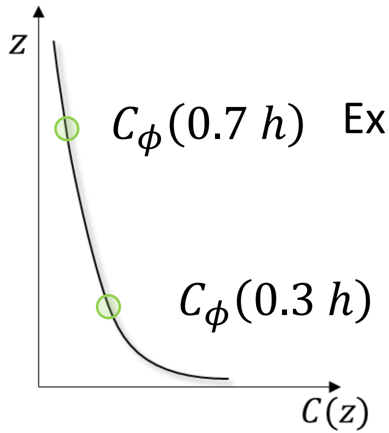
$$\alpha_\phi(z_\chi, P_\phi) = \frac{\exp(3\ P_\phi)\ (1-\exp(-6\ P_\phi))}{6\ P_\phi\ \exp\left(0.93\ P_\phi\ \left(\Phi(\frac{h}{2})-\Phi(z_\chi)\right)\right)}$$

Example of protocol: 2 x n index concentrations on the same vertical

Ex: $P_\phi = 0.59\ln\big(C_\phi(0.3\,h)/C_\phi(0.7\,h)\big)$

It can be shown that:

$$P_\phi = \frac{\ln\left(\dfrac{C_\phi\left(z_{\chi_1}\right)}{C_\phi\left(z_{\chi_2}\right)}\right)}{\ln\left(\dfrac{z_{\chi_2}}{z_{\chi_1}}\dfrac{\left(h-z_{\chi_1}\right)}{\left(h-z_{\chi_2}\right)}\right)}$$

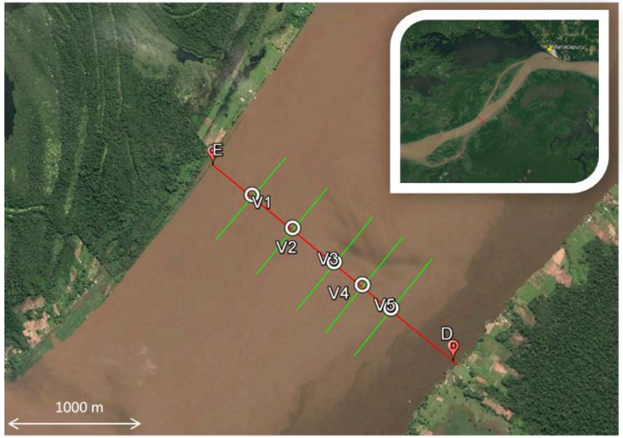


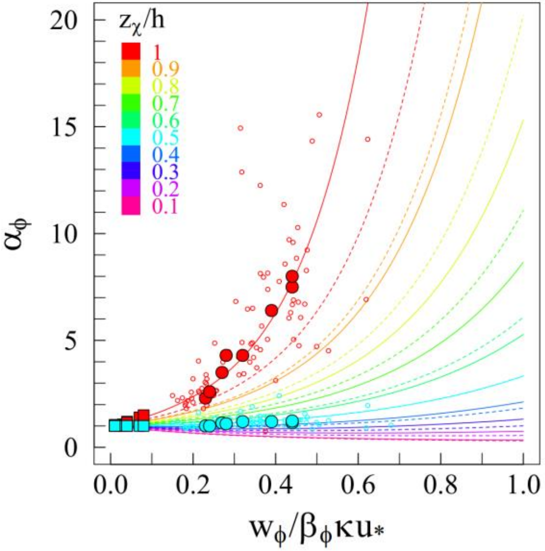
Ex: 3 samples (replicates)

Ex: 3 samples

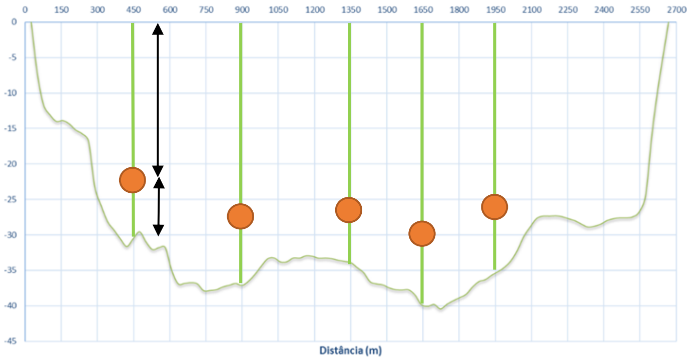
→ Time fluctuations
→ Consistent for sand concentration
→ No need to estimate β_ϕ

Example of rapid assessment protocol, for very large cross-sections

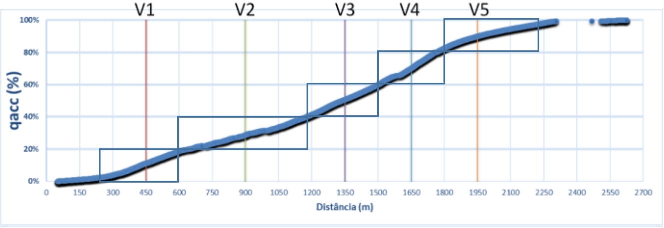




Manacapuru, Solimões



$$\frac{h}{e} \cong 0{,}37h$$



Mean concentration

Mean velocity

$$q_{s\phi} = \langle C_\phi \rangle \times \langle u \rangle \cong C_\phi\left(\frac{h}{e}\right) \times u\left(\frac{h}{e}\right) \pm 10\%$$

Sediment load (grain size group ϕ)

Index concentration

Euler number

Index velocity

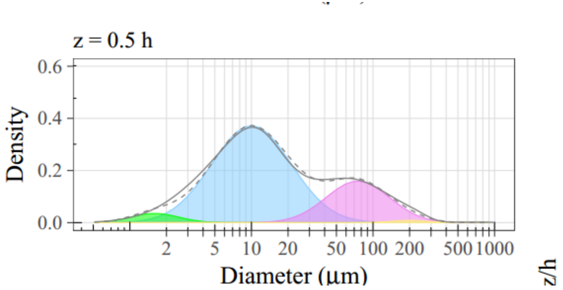
Global strategy: 2 classes of sediments

Ex: SENTINEL mission

Reflectance measurements for fine sediment concentration monitoring

Ex: SWOT mission

Satellite altimetry measurements to force the model



C_{index}

$\langle C_f \rangle = \alpha\, C_{index} \rightarrow$ **hydraulic Model** (Santini *et al.*, 2019)

$\langle C_s \rangle \rightarrow$ **sediment transport model** (ex: Camenen *et* Larson, 2008, Molinas *et* Wu, 2001)

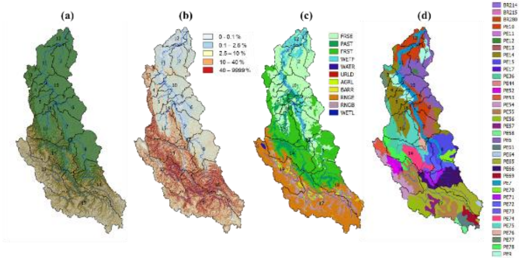
h

Hydrological modelling

$\langle \boldsymbol{u} \rangle, \boldsymbol{h}, \boldsymbol{u_*}$

See next presentation on Wednesday

SWAT model



Thanks, Obrigado, Gracias, Grazie
Merci!

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