Analysis of timescales of mixing at the Negro/Solimões confluence

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Outline

- Research background on mixing at river confluences
- Field measurements
- Basic results on confluence hydrodynamics and mixing
- A conceptual model for mixing
- Conclusions

Analysis of timescales of mixing at the Negro/Solimões confluence
Confluences are nodes in fluvial networks characterized by complex 3D changes in flow hydrodynamics and bed morphology and important ecological functions. These changes are located in the so-called Confluence Hydrodynamic Zone (CHZ).

Hydrodynamics and morphodynamics at confluences are influenced by:
- the junction angle and, more generally, the confluence planform;
- the momentum flux ratio $M_R$;
- the degree of concordance of the channel beds at the entrance to the confluence;
- eventually, differences in water density.
Research background – 2

Slightly modified from Best (1987)

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Research background - 3

Few studies have investigated river confluences with a significant difference in density between the merging rivers. These studies confirmed the role of $M_R$ on mixing and, more importantly, agreed that relevant density contrasts are able to create an underflow of the denser waters, affecting mixing rates. However, some points still need to be clarified.

**Scientific questions**

- how large seasonally and annually variations in the discharge ratio may impact the mixing interface dynamics at a very large confluence?;
- is it possible to comparatively identify the contribution of difference in velocity and density, bed friction and channel width change to mixing?;
- how these contributions are evolving along the CHZ in response to any adjustment in confluence hydrodynamics, bed morphology and channel geometry?

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Let’s consider the Negro/Solimões confluence in the Amazon Basin.

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Gualtieri et al. 2017
The location of the mixing interface on the water surface can be identified at a first look by the strong difference in colour (Encontro das Aguas). But in reality the mixing between the rivers is much more complicated....
Hydrodynamics

**Acoustic Doppler Current Profiler (ADCP)**

- measurement of the 3 components of the velocity
- definition of bed position
- estimation (after calibration) of the concentration of suspended sediments

Four beams ADCP

ADCP profiling

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Field measurements - 4

Water chemistry

Water sampling and Multiparametric probe profiling

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Field measurements - 5

FS–CNS1 – October 2014

FS–CNS2 – April/May 2015

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The field surveys were conducted in low flow (FS \( \text{FS} - \text{CNS1} \)) and relatively high flow conditions (FS \( \text{FS} - \text{CNS2} \)) to investigate hydrodynamics, morphodynamics and mixing.

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Basic results - 2

Table 1 – Main flow properties and water chemistry characteristics of Negro and Solimões Rivers during FS–CNS1/FS–CNS2

<table>
<thead>
<tr>
<th>Field trip</th>
<th>Basin area (km²)</th>
<th>Q (m³/s)</th>
<th>W (m)</th>
<th>h_{med} (m)</th>
<th>V_{avg} (m/s)</th>
<th>Dir (°)</th>
<th>T (°C)</th>
<th>ρ (Kg/m³)</th>
<th>Cond. (μS/cm)</th>
<th>TSS (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Negro</td>
<td>687000</td>
<td>24510</td>
<td>2830</td>
<td>24.4</td>
<td>0.37</td>
<td>59</td>
<td>30.3</td>
<td>995.50</td>
<td>7</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>33501</td>
<td>2875</td>
<td>31.3</td>
<td>0.37</td>
<td>58</td>
<td>29.0</td>
<td>995.90</td>
<td>13</td>
<td>4.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>63380</td>
<td>1589</td>
<td>27.2</td>
<td>1.42</td>
<td>289</td>
<td>29.6</td>
<td>995.82</td>
<td>79</td>
<td>185.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>105205</td>
<td>1925</td>
<td>28.6</td>
<td>1.65</td>
<td>255</td>
<td>28.0</td>
<td>996.26</td>
<td>80</td>
<td>108.6</td>
<td></td>
</tr>
</tbody>
</table>

Legend: Q = discharge; W = channel width; h_{med} = median depth; V_{avg} = median of the cross-sectional velocity (Q/A); Dir = median of flow direction from North; T = water temperature; ρ = water density (based on water temperature and TSS concentration); Cond. = water conductivity; TSS = total suspended sediments

Table 2 – Density difference, reduced gravity, internal Froude number, discharge, velocity and momentum flux ratios during FS–CNS1/FS–CNS2

<table>
<thead>
<tr>
<th>Field survey</th>
<th>Δρ/ρ₀</th>
<th>g' (m²/s)</th>
<th>Fr₁</th>
<th>Qᵣ</th>
<th>Vᵣ</th>
<th>Mᵣ</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS–CNS1</td>
<td>3.19E-04</td>
<td>3.12E-03</td>
<td>3.09</td>
<td>0.39</td>
<td>0.26</td>
<td>0.10</td>
</tr>
<tr>
<td>FS–CNS2</td>
<td>3.63E-04</td>
<td>3.56E-03</td>
<td>3.10</td>
<td>0.32</td>
<td>0.22</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Gualtieri et al., JoH 2019

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Basic results - 3

*Kelvin-Helmholtz waves* along the laterally stratified mixing interface were observed during the field studies.

Analysis of timescales of mixing at the Negro/Solimões confluence

Gualtieri et al., JoH 2019
Basic results - 4

We can study the development of the Kelvin-Helmholtz waves in the CHZ using a dimensionless stability number

\[ S_{ml} = c_f \frac{\delta}{H} \frac{U_c}{\Delta U} \]

c_f friction coefficient and \( U_c \) is a characteristic velocity scale

\( S_{ml} < 0.09 \) Friction is negligible and the Kelvin-Helmholtz waves can develop in the mixing layer

\( S_{ml} > 0.09 \) Friction dominates and growth of waves is not allowed

Analysis of timescales of mixing at the Negro/Solimões confluence
Basic results - 5

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Rapid/slow transfer of momentum in low flow/relatively high flow conditions

$S_{ml}$ is $<0.09$ up to 6 Km downstream of junction (A4), hence KH waves can develop, in agreement with visual observations.

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Basic results - 6

Entrainment of Solimões waters rich of sediments into the Negro side

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Basic results - 7

Gualtieri et al., JoH 2019

Analysis of timescales of mixing at the Negro/Solimões confluence

CNS6

1.53 Km downstream of junction

A13

2.73 Km downstream of junction
Conductivity was used to evaluate mixing. Conductivity was vertically constant everywhere.

Analysis of timescales of mixing at the Negro/Solimões confluence.

1.35 Km downstream of junction.
Basic results - 9

Conductivity was still vertically constant on both the Negro and the Solimões sides. But in the **mid of the channel**, conductivity was larger close to the bed.

The Solimões waters are entering in the Negro pool.

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Gualtieri et al., JoH 2019

2.48 Km downstream of junction
Basic results - 10

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Location of MI on the bed for relatively high flow conditions

Location of MI on the water surface for low flow conditions

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The distance from the Negro bank decreased as $Q_R$ decreased and the mixing interface width was the largest at the lowest $Q_R$.

The width increased with the distance from the junction and it was larger at the lowest $Q_R$.

Analysis of timescales of mixing at the Negro/Solimões confluence.
A conceptual model - 1

- Which are the processes potentially involved in the mixing of the two rivers?
  - **Difference in velocity**, i.e. shear, between the rivers (shear layer)
  - **Difference in density**, possibly increased by lateral forces (gravity current)
  - **Bed friction** and **change in channel width** (backwater effect)

Analysis based upon 4 **time scales**

- Difference in velocity $T_{shear}$
- Difference in density $T_{gc}$
- Bed friction $T_{friction}$
- Channel width $T_{width}$

FS–CNS1    FS–CNS2

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Down to 1.5–2.0 km from the junction, $T_{\text{shear}} \approx T_{\text{gc}}$, while $T_{\text{friction}}$ and $T_{\text{width}}$ were larger. Farther downstream, $T_{\text{shear}} > T_{\text{gc}}$. About the entrance of the Amazon river (2.5 km), $T_{\text{friction}} \approx T_{\text{shear}}$. Downstream of the scour hole (>4.7 km), where large bedforms were found, $T_{\text{friction}} \approx T_{\text{gc}}$

Any adjustment of confluence hydrodynamics, bed morphology and channel geometry can modify the relative importance of each contribution to mixing.

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Conclusions

- The dimensionless stability number $S_{ml}$ was applied to check the development of Kelvin-Helmholtz waves. It was found that, consistently with the theory, these waves can develop in the central CHZ in both flow conditions;
- The location of the mixing interface was found to be closely related to the discharge ratio between the tributaries. As much the discharge in the Solimões was larger than that in the Negro, the mixing interface was closer to the Negro bank. Finally, the width of the mixing interface increased with the distance from the junction and it was the largest at the lowest discharge ratio;
- Four timescales related to difference in velocity and density, bed friction and channel width change were applied to study mixing at the Negro/Solimões confluence. The longitudinal distribution of these timescales along the CHZ demonstrated that any adjustment of confluence hydrodynamics, bed morphology and channel geometry can modify the relative importance of each contribution to mixing.

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References


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Thank you – Merci – Obrigado - Grazie
Any Questions?

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