Inland Water Dissolved Fluxes

Peter A. Raymond, Yale School of Forestry and Environmental Studies
Evolution of Inland Water C

Sarmiento and Gruber (2002)
Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO$_2$

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Extrapolation of CO$_2$ from Amazonian rivers and wetlands of the Amazon basin constitutes an important carbon loss process, equal to 1.2 ± 0.3 Mg C ha$^{-1}$ yr$^{-1}$. This carbon probably originates from organic matter transported from upland and flooded forests, which is then respired and outgassed downstream. Extrapolated across the entire basin, this flux—at 0.5 Gt C yr$^{-1}$—is an order of magnitude greater than fluvial export of organic carbon to the ocean$^8$. From these findings, we suggest that the overall carbon
Sabine et al. 2004
The boundless carbon cycle

Tom J. Battin, Sebastiaan Luyssaert, Louis A. Kaplan, Anthony K. Aufdenkampe, Andreas Richter and Lars J. Tranvik

Diagram showing the carbon cycle with various pathways and their associated carbon flows. The diagram includes the following components:

- Atmospheric accumulation (4.1)
- Land accumulation (2.2)
- Inland waters accumulation (0.6)
- Anthropogenic sources
- Ocean accumulation (2.2)
- Lithosphere

The diagram also includes labels for various processes such as GPP (Gross Primary Production) and R (Respiration) with specific values.
Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere

Anthony K Aufdenkampe¹, Emilio Mayorga², Peter A Raymond³, John M Melack⁴, Scott C Doney⁵, Simone R Alin⁶, Rolf E Aalto⁷, and Kyungsoo Yoo⁸

<table>
<thead>
<tr>
<th>Zone-class</th>
<th>Area of inland waters (1000s km²)</th>
<th>pCO₂ (ppm)</th>
<th>Gas exchange velocity (k100, cm hr⁻¹)</th>
<th>Areal outgassing (g C m⁻² yr⁻¹)</th>
<th>Zonal outgassing (Pg C yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>min—max</td>
<td>median</td>
<td>median</td>
<td>median</td>
<td>median</td>
</tr>
<tr>
<td>Tropical (0°—25°)</td>
<td></td>
<td></td>
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<tr>
<td>Lakes and reservoirs</td>
<td>1840—1840</td>
<td>1900</td>
<td>4.0</td>
<td>240</td>
<td>0.45</td>
</tr>
<tr>
<td>Rivers (&gt;60—100 m wide)</td>
<td>146—146</td>
<td>3600</td>
<td>12.3</td>
<td>1600</td>
<td>0.23</td>
</tr>
<tr>
<td>Streams (&lt;60—100 m wide)</td>
<td>60—60</td>
<td>4300</td>
<td>17.2</td>
<td>2720</td>
<td>0.16</td>
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<tr>
<td>Wetlands</td>
<td>3080—6170</td>
<td>2900</td>
<td>2.4</td>
<td>240</td>
<td>1.12</td>
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<tr>
<td>Temperate (25°—50°)</td>
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<tr>
<td>Lakes and reservoirs</td>
<td>880—1050</td>
<td>900</td>
<td>4.0</td>
<td>80</td>
<td>0.08</td>
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<td>Rivers (&gt;60—100 m wide)</td>
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<td>6.0</td>
<td>720</td>
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<td>Streams (&lt;60—100 m wide)</td>
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<td>3500</td>
<td>20.2</td>
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<td>0.08</td>
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<tr>
<td>Wetlands</td>
<td>880—3530</td>
<td>2500</td>
<td>2.4</td>
<td>210</td>
<td>0.47</td>
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<td>Boreal and Arctic (50°—90°)</td>
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<td>Lakes and reservoirs</td>
<td>80—1650</td>
<td>1100</td>
<td>4.0</td>
<td>130</td>
<td>0.11</td>
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<td>Rivers (&gt;60—100 m wide)</td>
<td>7—131</td>
<td>1300</td>
<td>6.0</td>
<td>260</td>
<td>0.02</td>
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<td>Streams (&lt;60—100 m wide)</td>
<td>3—54</td>
<td>1300</td>
<td>13.1</td>
<td>560</td>
<td>0.02</td>
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<tr>
<td>Wetlands</td>
<td>280—5520</td>
<td>2000</td>
<td>2.4</td>
<td>170</td>
<td>0.49</td>
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<tr>
<td><strong>Global</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.64</td>
</tr>
<tr>
<td>Percent of global land area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.30</td>
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<tr>
<td>Lakes and reservoirs</td>
<td>2800—4540</td>
<td>2.1%—3.4%</td>
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<tr>
<td>Rivers (&gt;60—100 m wide)</td>
<td>220—360</td>
<td>0.2%—0.3%</td>
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<tr>
<td>Streams (&lt;60—100 m wide)</td>
<td>90—150</td>
<td>0.1%—0.1%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Wetlands</td>
<td>4240—15 220</td>
<td>3.2%—11.4%</td>
<td></td>
<td></td>
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<tr>
<td><strong>All inland waters</strong></td>
<td>7350—20 260</td>
<td>5.5%—15.2%</td>
<td></td>
<td>3.28</td>
<td></td>
</tr>
</tbody>
</table>

Notes: see WebPanelI for associated references.
Atmosphere 589 ± 230 ± 10
(average atmospheric increase: 4 (PgC yr⁻¹))

Net ocean flux

2.3 ± 0.7

Ocean-atmosphere gas exchange
80 = 60 ± 20
78.0 ± 17.7

Freshwater outgassing
1.0

Net land flux
2.6 ± 1.2

Volcanism
0.1

Rock weathering
0.3

Rock weathering
0.1

Export from soils to rivers
1.7

Gross photosynthesis
12.3 ± 10.8 ± 14.1

Net land use change
1.1 ± 0.8

Total respiration and fire
11.6 ± 7.0 ± 11.6

Fossil fuels (coal, oil, gas)
cement production
7.8 ± 0.6

Burial
0.2

Soils
1500 - 2400

Vegetation
450 - 650

Permafrost
−1700

Units
Fluxes (PgC yr⁻¹)
Stocks (PgC)

Surface ocean
900

Intermediate & deep sea
37,100

Dissolved organic carbon
700

Marine biota
50

Rivers
2

Ocean floor surface sediments
1,750

1.7

0.9

0.2
Active Pipe Model

- Inland Waters historically seen as “passive pipe”
- Currently trying to work out fluxes of “active pipe” model
Global Inland Water CO₂ Evasion

CO₂ Concentration Gradient

Stumm and Morgan

Surface Area

Gas Transfer Velocity

Benstead and Leigh, 2012
River CO2

- 6,709 sites with CO$_2$ calculated from alkalinity and pH
- Not correlated strongly with anything
- Regional CO$_2$ was interpolated from individual sites
- Global average $\sim 3500$ µatm (used medians)

Raymond et al. 2013
• 6,709 sites with CO₂ calculated from alkalinity and pH
• Not correlated strongly with anything
• Regional CO₂ was interpolated from individual sites
• Global average= ~3500 µatm (used station medians)
Stream Surface Area

• Very few estimates of global stream and river surface area. *No spatially resolved estimate.*
• Estimated from length and width by stream order
• Length gathered from HydroSHEDS
• Width from discharge and hydraulic equations
• Corrected for stream drying and freezing
Stream Surface Area - Length

- Use digital elevation maps
- Global: HydroSHEDS for length (Lehner et al. 2008).
- United States: National Hydraulic Data set (NHD)
- NHD has a better resolution than HydroSHEDS

Benstead and Leigh 2012
Stream Surface Area - Width
Comparing Two Data Sets

![Graph showing the relationship between In Width (m) and ln Q (m³ s⁻¹). The equation y = 0.51x + 1.86 with r² = 0.89 and p < 0.0001 is shown.]

Raymond et al. submitted from USGS data

\[ W = aQ^b \]

Raymond et al. 2012

Fig. 1 Hydraulic geometry relationships for streams and rivers of this study. Presented are the relationships between discharge and velocity (A), depth (B), and width (Q).
Global surface area by stream order

- Large differences due to equations
- Importance of small streams
Climatic Regulation of Surface Area

- Greater surface area in wetter regions.
- Width relationship with Precip, stronger than length Density
River Surface Area

- Total Surface area of 624,000km² (0.5% earth surface)
- Aufdenkampe 2011: 320,000-510,000km²
- Downing et al. 2012: 485,000-662,000km²
- Approximately 88,000km² is blocked by ice
- Approximately 84,000km² not active due to drying
Stream Gas Transfer Velocity ($k_{600}$)

- $k_{600}$ is a function of turbulence at the surface of streams
- Calculated from slope and velocity (Raymond et al. 2012) from 563 independent measurements
- Velocity estimated from discharge and hydraulic equations
- Slope gathered from Hydrosheds
  \[ V = cQ^d \]

### Table 2: Fitted equations for predicting the $k_{600}$ (m d⁻¹) based on stream velocity ($V$, in m s⁻¹), slope ($S$; unitless), depth ($D$, in meters), discharge ($Q$, in m³ s⁻¹), and the Froude number ($Fr = V/(gD)^{0.5}$). Also displayed are the standard deviations (±1 SD) for the equation parameters, $r^2$, slope (±SE), and y-intercept (±SE for regressions of the equation output vs. actual values; Fig. 3). All $p$-values for the regressions are 0.0001.

<table>
<thead>
<tr>
<th>Model equation</th>
<th>$r^2$</th>
<th>Slope</th>
<th>y-Intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. $k_{600} = (VS)^{0.09±0.020} \times D^{0.54±0.030} \times 5037 ± 604$</td>
<td>0.72</td>
<td>0.92 ± 0.024</td>
<td>0.98 ± 0.17</td>
</tr>
<tr>
<td>2. $k_{600} = 5937 ± 606 \times (1 - 2.54 ± 0.223 \times Fr^2) \times (VS)^{0.89±0.017} \times D^{0.58±0.027}$</td>
<td>0.76</td>
<td>0.94 ± 0.022</td>
<td>0.76 ± 0.16</td>
</tr>
<tr>
<td>3. $k_{600} = 1162 ± 192 \times S^{0.77±0.028} \times (VS)^{0.85±0.045}$</td>
<td>0.54</td>
<td>0.91 ± 0.036</td>
<td>0.91 ± 0.24</td>
</tr>
<tr>
<td>4. $k_{600} = (VS)^{0.76±0.027} \times 951.5 ± 144$</td>
<td>0.53</td>
<td>0.82 ± 0.037</td>
<td>0.92 ± 0.24</td>
</tr>
<tr>
<td>5. $k_{600} = VS \times 2841 ± 107 ± 2.02 ± 0.209$</td>
<td>0.55</td>
<td>1.0 ± 0.038</td>
<td>$-4.8 \times 10^{-3} ± 0.26$</td>
</tr>
<tr>
<td>6. $k_{600} = 929 ± 141 \times (VS)^{0.75±0.027} \times Q^{0.011±0.016}$</td>
<td>0.53</td>
<td>0.92 ± 0.036</td>
<td>0.81 ± 0.24</td>
</tr>
<tr>
<td>7. $k_{600} = 4725 ± 445 \times (VS)^{0.86±0.016} \times Q^{-0.14±0.012} \times D^{0.66±0.029}$</td>
<td>0.76</td>
<td>0.95 ± 0.023</td>
<td>0.57 ± 0.17</td>
</tr>
</tbody>
</table>
Global Stream/River Evasion

- 1.8Pg yr$^{-1}$ (2.2 with lakes and reservoirs)
- 70% of CO2 from 20% of Earth surface
- High Fluxes from Southeast Asia, Amazonia, Central America, Europe, regions of South America west of the Andes, Southeast Alaska, western Africa, and the eastern edge of East Asia
(hypothetical) Sources of 2.2 Pg yr$^{-1}$

- **Soil CO$_2$**
  - Assume all soil water entering inland waters (40,000 km$^3$ yr$^{-1}$) has CO$_2$ concentration of 50,000 µatm that evades = 1.0 Pg yr$^{-1}$. 
(hypothetical) Sources of 2.2 Pg yr$^{-1}$

- Soil CO$_2$.  **1 Pg yr$^{-1}$**

- Terrestrial OM Decomposition
  - Assume lateral transport of soil OM is twice as large as what is exported to the ocean and that this OM is oxidized and evaded as CO$_2$. ~0.4Pg yr$^{-1}$
(hypothetical) Sources of 2.2 Pg yr\(^{-1}\)

- Soil CO\(_2\). 1 Pg yr\(^{-1}\)
- Terrestrial OM Decomposition. 0.4 Pg yr\(^{-1}\)
- Wetland and riparian root respiration.
  - Assume 20% of wetland NPP (6 Pg yr\(^{-1}\)) is transferred laterally as C and evaded as CO\(_2\)
(hypothetical) Sources of 2.2 Pg yr\(^{-1}\)

- Soil CO\(_2\).  1 Pg yr\(^{-1}\)
- Terrestrial OM Decomposition.  0.4Pg yr\(^{-1}\)
- Wetland and riparian root respiration.  1.2Pg yr\(^{-1}\)
• Significantly lower estimate
  – 0.65 vs 1.3 Pg yr\(^{-1}\)
• Significantly higher estimate
  – 0.4 vs 0.1 Pg yr\(^{-1}\)
How much riverine DOC makes it to the ocean?

- There are now numerous estimates
- They are a bit incestuous in the data they utilize (still room for improvement)
- Annual variation of ~25%

<table>
<thead>
<tr>
<th>Study</th>
<th>Estimate (Pg yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schlesinger and Melack (1981)</td>
<td>0.37-0.41</td>
</tr>
<tr>
<td>Ludwig et al. (1996)</td>
<td>0.21</td>
</tr>
<tr>
<td>Meybeck (1993)</td>
<td>0.20</td>
</tr>
<tr>
<td>Aitkenhead and McDowell (2000)</td>
<td>0.36</td>
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<tr>
<td>Meybeck (1982)</td>
<td>0.22</td>
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<tr>
<td>Harrison et al. (2005)</td>
<td>0.17</td>
</tr>
<tr>
<td>Seitzenger et al. (2005)</td>
<td></td>
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<tr>
<td>Mayorga et al. (2010)</td>
<td>0.16</td>
</tr>
<tr>
<td>Dai et al. (2012)</td>
<td>0.21-0.22</td>
</tr>
<tr>
<td>Raymond and Spencer (2014)</td>
<td>0.25</td>
</tr>
</tbody>
</table>
DOC flux for top 30 rivers ranked by discharge

• 36% of land draining into ocean
• 50% of global ocean discharge

Raymond and Spencer (2014)
DIC/Alkalinity Fluxes

- Facilitated by strong relationship between fluxes and climate/lithology
- 70% of flux, 10% area
- \( \sim 0.35 \) Pg C yr\(^{-1} \) (as bicarbonate)
Active Pipe Model-Global

174 J. J. Cole and others

\[
\begin{align*}
\text{a} & \\
\text{Land} & \rightarrow 0.9 \rightarrow \text{Inland waters} \rightarrow 0.9 \rightarrow \text{Ocean} \\
\text{CO}_2 \text{ evasion} \\
\text{b} & \\
\text{Land} & \rightarrow 1.9 \rightarrow \text{Inland waters} \rightarrow 0.9 \rightarrow \text{Ocean} \\
\text{Sediment storage} & \rightarrow 0.23 \rightarrow 0.6
\end{align*}
\]
Aquatic carbon cycling in the conterminous United States and implications for terrestrial carbon accounting

David Butman\textsuperscript{a,b,1}, Sarah Stackpoole\textsuperscript{c}, Edward Stets\textsuperscript{e}, Cory P. McDonald\textsuperscript{d}, David W. Clow\textsuperscript{c}, and Robert G. Striegl\textsuperscript{a}

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Edited by William H. Schlesinger, Cary Institute of Ecosystem Studies, Millbrook, NY, and approved November 12, 2015 (received for review June 29, 2015)
Regnier et al. 2013
Thank you

- Funding: NASA grant (NNX11AH68G)
- Jens Hartmann, Ronny Lauerwald, Sebastian Sobek, Cory McDonald, Mark Hoover, David Butman, Rob Striegl, Emilio Mayorga, Christoph Humborg, Pirkko Kortelainen, Hans Durr, Michel Meybeck, Philippe Ciais, Peter Guth
- Rob Spencer