PHOSPHORUS IN THE AMAZON RIVER MAINSTEM: CONCENTRATIONS, FORMS AND TRANSPORT TO THE OCEAN

Allan H. Devol
Jeffrey E. Richey
Bruce R. Forsberg

1School of Oceanography WB-10, University of Washington, Seattle, Washington, 98195, USA
2Departamento de Ecologia, INPA, Estrada Alexio, Cx.P. 478, 69.011, Manaus, Am. Brazil

Introduction

The global biogeochemical P cycle begins with weathering and mobilization of primary rock phosphate and ends with permanent burial in marine sediments. Along the way P is cycled through the biosphere and involved in various inorganic reactions primarily in soils. Unlike the other bioactive elements - carbon, nitrogen and sulfur - P has no significant gaseous forms in the natural environment, therefore; the major conduit for the transport from the continents to the world's oceans is as dissolved and particulate phases in rivers. Although the contemporary riverine flux to the oceans is not well known, it has been variously estimated to be about 20 to 25 Tg/y (Tg=10^{12} g) and the pre-agricultural riverine flux is thought to be about half that (Meybeck, 1982; Froelich et al., 1982; Berner and Berner, 1987). For comparison, Richey (1983) and Graham and Duce (1979) have estimated the aeolian flux at about 5% of the riverine transport. The only other input of potential consequence is glacial scour but it is also small (Kempe, 1979).

The forms of P in transport in a river are generally classified according to the method used to determine them rather than by any strict chemical or physical definition. Thus, the total dissolved P (TDP) pool is frequently divided into soluble reactive P (SRP), which is normally assumed to be primarily PO_{4}^{3-}, and dissolved organic P (DOP). Although there are many different classifications of particulate P based on the numerous extraction methods, the most ecologically useful are probably particulate inorganic P and particulate organic P; the most unambiguous is total particulate P (TPP). The distinction between particulate and dissolved is defined by the nominal pore size of the filter used to separate them, usually 0.45 μm. (Thorough discussions of the different analytical methods for determination of the various P forms are given by Froelich (1988), and Strickland and Parsons (1967).)

The average TDP level in the world's unpolluted rivers is about 1 μM and that of TPP is 15 μM (Froelich 1988, Meybeck, 1982). However, in rivers draining highly industrialized or agriculturized areas P contents can increase dramatically, e.g. in the Thames (Great Britain) SRP values of 80 μM have been reported (Meybeck 1982).

Combining the annual river discharge of 3.2 X 10^{6} m^{3} s^{-1} (Berner and Berner, 1987) with average river concentrations yields the estimate of total, pre-agricultural P transport to the oceans of about 14 Tg/y. The difference between this number and that given above is the anthropogenic component. However, for several reasons, there are large uncertainties in these numbers: (1) the lack of information on the particulate forms
(Meybeck, 1982), (2) the difficulty of representatively sampling river particulate distributions that are not uniform either laterally or with depth (Curtis et al., 1979; Richey et al. 1986), (3) differences in analytical methodologies, especially for TPP, and (4) lack of good seasonal coverage of many rivers. This is especially true for the large tropical rivers which contribute a major fraction of the water and sediment discharge to the ocean.

In this report we present the results of a study undertaken to improve our understanding of temporal and spatial distributions of the different P forms, concentrations and fluxes in the Amazon river, the world's largest river. The study is part of the CAMREX (Carbon in the AMazon River EXperiment) project, which also investigated carbon and nitrogen. Results of the carbon and nitrogen investigations have been reported previously (Hedges, et al. 1986; Forsberg et al., 1988, Richey et al., in press). The total length of the Amazon river is about 3500 km and its drainage basin area is nearly 6 million km². The Amazon main channel receives input from major and minor tributaries. During its annual 10 meter rise and fall, the river also exchanges water and chemicals with its seasonally inundated floodplain or "varzea". The varzea acts as a large reservoir (100,000 km², Junk, 1985) for flood discharge and precipitation and, at times, as much as 30% of the water in transit in the river has passed through this reservoir (Richey et al., in press). With an average water discharge of about 200,000 m²s⁻¹, the Amazon accounts for fully 20% to the total annual water discharge to the oceans (Richey et al. 1986). Also, its sediment load of about 10⁹ Mg y⁻¹ constitutes slightly less than 10% of the total riverine transport (Milliman and Meade, 1983). Thus, a thorough knowledge of P transport in this mighty river is crucial to quantifying the global P budget.

Methods

Measurements were made over a 1700 km reach of the river during 7 cruises of the Brazilian research vessel, R/V Amanai, between Vargem, Grande (3°16'S, 67°50'W) and Obidos (1°55'S, 55°29' W). On each cruise measurements were made at 9 mainstem stations plus stations on the 7 principal tributaries in the reach. All measurements were made between 1982 and 1984, and covered the different portions of the river hydrograph (Figure 1).

In order to derive a quantitative estimate of the amounts of dissolved and particulate P transported from the continent by the Amazon river it is first necessary to have a good estimate of the water discharge. Additionally, the cross sectional and depth distributions of both dissolved (Richey et al. 1988) and particulate phases (Meade, 1985) are not uniform so these must be determined also. To determine water discharges and cross-sectional distributions samples were taken with the integrating sampling array described by Richey et al. (1986). Briefly, the array consisted of a Price AA current meter that was lowered to the bottom and retrieved at a constant rate. Also attached to the array was a collapsible bag sampler that filled in proportion to the in situ current velocity. Thus, when lowered to the bottom and retrieved the sampler obtained a depth-integrated, flow weighted sample (profile) from one point in the river. At each mainstem station 18 such profiles were collected at equally spaced intervals across the river and tributaries were sampled using 12 profiles. The water discharge at the section was then calculated by integrating the individual velocity profiles across the river channel and a depth-
integrated, flow weighted water sample for chemical analysis was obtained by compositing the individual profile samples.

Prior to chemical analysis the composite water sample was passed through a 63 μm mesh screen to separate the coarse particulate fraction which was dried and weighed to determine coarse suspended sediment (CSS) concentration. A small portion of the sample (~300 ml) was then filtered through pre-weighed, 0.45 μm filters and stored for later, gravimetric determination of fine suspended sediment (FSS) concentration (Meade et al. 1979). The filtrate was saved for analysis of the dissolved chemical species (see below). The remainder of the composite sample (~30 l) was passed through a Sharples centrifuge operated continuously at 15,000 RPM to obtain the fine suspended sediment fraction for chemical analysis (Hedges et al., 1986).


Fine and coarse particulate organic carbon (FPOC, CPOC) and particulate nitrogen (FPN, CPN) were determined in duplicate with a Carlo-Erba elemental analyzer (model 1106) using the method of Hedges and Stern (1984). Fine and coarse total particulate P (FPP and CPP) were determined for sediment leachates that were first combusted at high temperature (550°C) and subsequently extracted with strong HCl for 24 h (Aspila et al.
1976). In addition to the total P analysis of bulk river sediments, the P content of both the woody and leafy tissue of the 20 most common floodplain plants was also determined. These analyses were made on samples previously analyzed for organic carbon and organic nitrogen (Hedges et al. 1986).

Total dissolved P and nitrogen concentrations were determined on the filtered samples using the persulfate digestion procedure of Valderama (1981). Soluble species — phosphate (SRP), nitrate, and nitrite — were determined with methods outlined in Strickland and Parsons (1972). Dissolved organic P was calculated as the difference between TDP and SRP. Although ammonium was routinely analyzed, it was never detected in significant amounts. Dissolved organic carbon was determined on acidified, nitrogen sparged, filtered samples by UV-enhanced persulfate oxidation (Ertell et al., 1986).

Results and discussion

**Bulk P composition.** Before discussion of the patterns and transport of P in the Amazon river, it is instructive to look at the overall averages of the eight cruise (Figure 2). For both P and nitrogen the highest total levels were found in the mainstem, 9.2 μM for P and 51.8 μM for nitrogen. The average tributary total P value was only about half that of the mainstem, 4.1 μM, and concentrations were halved yet again, to 2.2 μM, in the varzea waters. Of the individual forms of P, TPP was by far the dominant form accounting for up to at least 75% of the total. The remainder was about equally split between DOP and PO₄. Individually, both particulate P and PO₄ concentrations also showed decreases from the mainstem to tributaries to the varzea. Although the lowest levels of DOP were also observed in the varzea, the tributaries actually showed slightly higher DOP concentrations than the mainstem. A similar pattern was noted for total nitrogen except that the decrease in overall concentration from the mainstem (51.8 μM) to the tributaries (35.5 μM) to the varzea (27.0 μM) was not as great. The nitrogen distributions differed from those of P, however, in that the dissolved forms of nitrogen, DON and NO₃, comprised the bulk of the nitrogen, >60%.

Although no attempt was made to determine the organic and inorganic components separately, indirect evidence indicates that much of the TPP is probably inorganic in nature. Hedges et al. (1986) plotted weight percent carbon vs. weight percent nitrogen for samples obtained on the first four cruises. There was a good linear relationship between the two for both the fine and coarse sediment fractions. Importantly, although the slopes, i.e. the C:N ratios, were different for the two fractions (C:N ratios by atoms for the fine and coarse fractions were 11 and 24 respectively) in both cases the intercepts were zero indicating that all the particulate nitrogen was organic. When a similar plot was constructed for P (Figure 3a) there was no significant relationship. Rather, for any given sample (mainstem or tributary) FPP and CPP were relatively constant. On the other hand, when FPP and CPP were plotted vs suspended sediment (Figure 3b) there was a significant relationship, both for the fine fraction (slope = 0.026, intercept=.19, R²=0.94) and the coarse fraction (slope=0.013, intercept=0.06, R²=0.82). Also in both cases, the intercepts of the regressions were not statistically different from zero. This lack of correlation with carbon but high correlation with total suspended sediment indicates that much of the suspended particulate P and, consequently, the majority of P in transport in the Amazon river is probably inorganic.
Figure 2. Concentrations of TPP (CPP plus FPP) and PON (solid), POP and DON (hatched), and PO₄ and NO₃ (cross hatched). Numbers near pie section give the actual concentration (µM) while total concentrations are given below. Phosphorus and nitrogen data from varzea waters are from Forsberg et al. 1988.

Downstream and seasonal patterns. Within any river, P, both particulate and dissolved, is transported by the water flow. Also, as tributaries contribute to the mainstem water flow they will either increase or decrease the P concentrations depending on their concentrations. Thus, in order to interpret the downstream and seasonal phosphorus patterns, it is important to know the river hydrology. The downstream patterns of water discharge for the Amazon river are shown in Figure 4. In this figure, and subsequent figures, the cruises are grouped according to flood stage; thus cruises 2, 5, and 8 were early falling water cruises, 3 and 6 were low water cruises and 4 and 7 were rising water cruises (see Figure 1).

Over the entire reach between Vargem Grande and Obidos, discharge showed the greatest increase, from about 40,000 m³s⁻¹ to about 180,000 m³s⁻¹, on the early falling water cruises, 2, 5, and 8. During this period, tributary discharges were still high and flood water stored on the varzea was presumably draining back into the river. Slightly smaller increases in water discharge occurred on the mid-rising water cruises, 4 and 7; 60,000 m³s⁻¹ to 160,000 m³s⁻¹. This is a period during which tributary flows were increasing but some water was being stored on the floodplain. The smallest increases in discharge, and also the smallest discharges, were observed on the two low water cruises, 3 and 6. Thus, as
tributary and varzea concentrations of the different P species were significantly different than those in the mainstem (Figure 2), tributary influences on mainstem concentration should be greatest on the early falling water cruises and least during the low water periods.

Figure 3. (A) Weight percent P vs. weight % carbon for Amazon river particulate material. (B) Particulate P concentration, FPP or CPP, vs. suspended sediment concentration in the corresponding size fraction. The different symbols identified on (B) also apply to (A).

Figure 4. Water discharge vs. distance downstream from Vargem Grande.
The distributions of PO₄, DOP and TPP with respect to distance downstream are shown in Figure 5. The highest concentrations of PO₄ were observed on the two low water cruises, 3 and 6. On both cruises concentrations were high upriver, about 1.1 μM and remained so with distance downstream, decreasing only slightly near Obidos. In contrast, during the three early falling water cruises, 2, 5, and 8, PO₄ concentrations were also high upriver, about 1 μM, but they then decreased rather regularly to values at Obidos of about 0.6 μM at Obidos. On the two rising water cruises, upriver concentrations were somewhat lower than during the other cruises, between 0.4 μM on cruise 4 and 0.8 μM on cruise 7. Whereas concentrations remained about constant on cruise 4, they decreased significantly on cruise 7 to about 0.5 μM at Obidos.

To understand the downstream and seasonal changes of PO₄, it must be realized that most of the inorganic solutes in the Amazon river are derived from sources in the Andes mountains (Gibbs, 1967, Stallard and Edmond, 1983). Consequently, waters originating in the Andes have much higher concentrations of inorganic nutrients than rivers draining primarily lowland and shield areas (Forsberg et al. 1988). This, for the most part, explains why the average mainstem PO₄ concentration is higher than that of the average tributary, which, in turn, is higher than the varzea (Figure 2). Thus, the two low water cruises had the highest PO₄ values because, at this time, at Vargem Grande the river contained relatively more Andean water and the amount of dilution by subsequent tributary inputs was small compared with other periods. During the early falling water cruises the PO₄ levels at Vargem Grande were also relatively high. However, draining varzea waters and large tributary inputs between Vargem Grande and Obidos resulted in the largest increases in water discharge and, concomitantly, dilution of PO₄. An intermediate situation was observed on the two rising water cruises, with somewhat lower PO₄ concentrations upstream and also somewhat smaller increases in discharge and dilution downstream to Obidos. Thus, much of the pattern of seasonal and downstream changes in the PO₄ can be explained by dilution of mainstem water with PO₄-poor tributary and varzea waters.

Although on any given cruise there were large fluctuations in the DOP concentration downstream, in general, there was no overall trend of either increase or decrease (Figure 5). There were however, some interesting differences between the concentrations of DOP on the different cruises. The highest DOP concentrations, about 1 μM were observed on the early rising water cruises, 4 and 7, while the lowest values, about 0.3 μM, were seen on the low water cruises, 3 and 6. The early falling water cruises had intermediate values of about 0.6 μM. The lack of a distinct downstream trend is explained by the fact that there are apparently no systematic differences between mainstem and tributary concentrations of DOP. Instead, differences are relatively random (probably dependent on local geology, vegetation and climate) and such that the resultant addition of tributary water to the mainstem, while producing fluctuations, does not change the overall DOP concentration. The differences between cruises are more difficult to explain. As pointed out above, the low water cruises had the least dilution by lowland tributary input. This would indicate that water of Andean origin should have low values of DOP (average low water DOP=0.22 μM). The highest DOP concentrations were encountered on the rising water cruises (average DOP=0.97 μM). Why rising water concentrations were higher than early falling water concentrations (average DOP=0.47 μM) is not clear at present.
Figure 5. Concentration vs. distance downstream (in thousands of km) for particulate P, TPP, dissolved organic P, DOP, and PO₄. Cruise number and line type given in upper left panel apply to all panels.

In all cases TPP concentrations were greatest at Vargem Grande and decreased down river. Concentrations and downstream patterns were very similar on all three early falling water cruises. Concentrations were greatest upstream, 6 μM to 10 μM, and decreased to about 4 μM over the first 1000 km, beyond which they remained relatively constant. In contrast, the two rising water cruises had much higher concentrations upstream, 12 μM to 15 μM, and these concentrations decreased more or less continuously to between 10 and 6 μM at Obidos. The two low water cruises were distinctly different with cruise 3 showing a pattern similar to the rising water cruises and cruise 6 resembling the early falling water cruises. Due to the close correlation between TPP and TSS, the downstream
distributions and seasonal variations in TPP will parallel those of the bulk suspended sediment, and the hydrology of deposition and resuspension will control the distributions. The TPP is discussed further below.

The downstream patterns presented above present 7 "snapshots" of the P distributions in the Amazon over a two year period. They probably set a reasonable range for concentrations expected at other times of the year and they are of great value for the calculation of weathering rate and riverine transport of P to the ocean. However, the explanations of the seasonal and downstream patterns are tentative and more data on seasonality, especially in the tributaries, is necessary to complete the analysis.

*Phosphorus mass balance of the river.* As seen above, it is possible to qualitatively explain much of the seasonal and downstream pattern of the dissolved components in the Amazon river simply by mixing of mainstem waters and tributary waters. However, mixing is not the only process affecting concentrations, in situ reaction could also be important. For example, PO₄ participates in many inorganic reactions (House and Casey, 1989) and is returned to solution during the decomposition of organic matter. The importance and nature of such in situ processes in the Amazon River can be investigated through the use of mass balances similar to those constructed for C (Richey, et al. in press) and O₂ (Devol et al. 1987).

Mass balances were done over the entire study reach. The mass flux into the reach at Vargem Grande, Fᵢ, and the mass flux out of the reach at Obidos, Fₒ, were calculated from the product of the water discharge (m³s⁻¹) and concentration (mass m⁻³). Individual tributary inputs to the mainstem were calculated in a similar manner, and summed to arrive at the total tributary flux, Fᵣ. In addition to the major tributaries, water also entered the mainstem via minor tributaries and varzea drainage. Although these water amounts were not directly measured, they could be estimated by taking the difference between the water outflow at Obidos and the sum of the measured water inflows, i.e. Vargem Grande plus tributaries. The mass fluxes of these diffuse inputs, Fᵥ, could then estimated from the average varzea concentrations (Figure 2). The mass fluxes were then used to calculate a balance parameter $\beta$:

$$\beta = \frac{\text{observed}}{\text{expected}} = \frac{Fᵢ + Fᵣ + Fᵥ}{Fₒ} - 1$$

Thus, if the sum of the inputs equals the flux out at Obidos $\beta=0$. This indicates a balance and no in situ production or consumption is required. However, positive values of $\beta$ require an in situ source, while negative values require a sink.

The mass balance parameter, $\beta$, for the fine particulate phases of total suspended matter, carbon and P are shown in Figure 6. Some interesting patterns are evident. (The same patterns hold for fine fraction PON and all the coarse fraction components). First, as would be expected from their rather constant ratios with total particulate material (Figure 3), both P and carbon mirror the trends shown by FSS, even though they are only small components of the FSS (C ~1.0 wt% and P ~0.01 wt%). Secondly, the data again tend to differentiate according to flood stage. On all three early falling water cruises, mass balances are positive and near 1.0. Essentially, this means that on these cruises about twice as much material was leaving the river reach at Obidos as was entering. This material must have been supplied either by resuspension of sediments stored within the river channel itself, or by erosion of the river banks.
Conversely, on all other cruises the mass balance was either negative or zero. During these cruises net deposition within the channel is required to balance the excess of input over output. Thus, as noted above, the hydrology of sediment deposition and resuspension control both the downstream and seasonal pattern of particulate concentration in the Amazon River.

![Graphs showing mass balances for FSS, FPOC, and PP(0)](image)

Figure 6. Mass balances, $\beta$, for fine suspended sediment (FSS), fine particulate organic carbon (FPOC) and fine particulate P (PP(0)). Positive values of $\beta$ indicate a within river source, while negative values indicate a sink.

The mass balances for the dissolved P (Figure 7) forms differed significantly from those seen for the particulate phases (Again, although not shown, dissolved nitrogen species mirror those of P.) Even though the absolute magnitude of DOP changed from cruise to cruise, the mass balance parameter, $\beta$, for DOP was near zero on all cruises. This good overall balance suggests that DOP in the Amazon River is conservative and is not produced or consumed in any significant amount. This conclusion is in agreement with that of Richey et al. (in press) who suggest that the majority of DOC in transport is also refractory.

In contrast to DOP, the opposite situation was observed for PO$_4$. On all cruises there was an excess of PO$_4$ over what could be explained by the sum of the inputs. Because the mass balance accounts for fluvial inputs, this excess PO$_4$ probably comes from in situ reaction; either through: 1) dissolution of primary and secondary minerals or, 2) desorption of PO$_4$ associated with clay minerals and metal oxides or, 3) liberation of organically bound PO$_4$ during organic matter oxidation.

In addition to positive values of $\beta$ for PO$_4$, there were also positive mass balances for NO$_3$ and, after accounting for gas exchange, for total CO$_2$ (Richey et al. in press). If the excess CO$_2$, NO$_3$ and PO$_4$ are due to decomposition of organic matter then the ratio of the excess fluxes (Moles time$^{-1}$) should give the elemental ratios of the organic matter being oxidized. However, if the excess PO$_4$ results primarily from dissolution or desorption of mineral phases then the C:N ratio of the dissolved species will remain constant and the C:P ratio will decrease. The apparent C:N, N:P and C:N:P ratios of the flux excess along with the corresponding ratios of the potential source materials are given in Table 1.
The C:N and N:P ratios of the apparent flux excess were 54:1 and 34:1, respectively. In contrast, the apparent C:N and N:P ratios of the bulk suspended sediment were 10:1 and 4:1, respectively. Hedges et al. (1986) and Richey et al. (in press) have shown that there are virtually no inorganic forms of carbon or nitrogen contained within the bulk suspended sediment — in other words, all the C and N is organic. Thus, oxidation of the bulk organic matter in suspension would result in a C:N flux excess of the dissolved species that is much lower than that observed. Similarly, although we do not know the relative contributions of organic and inorganic P to the overall bulk suspended P, stoichiometric conversion to dissolved forms would result in low apparent flux excess N:P ratios also. Again, these were not observed. Thus, it is unlikely that the observed flux excess results from stoichiometric decomposition of the bulk suspended matter only. Indeed, the observed excess C:N and N:P ratios are more similar to those of the potential organic substrates, which strongly suggests that the majority of the flux excess is derived from oxidation of organic substrates such as wood, leaf and macrophyte tissue as well DOC. Furthermore, although we can not rule out dissolution and desorption of inorganic P phases as a significant source of P, we feel that it is unlikely because of the similarity of the N:P ratios of the flux excess and the potential substrates. Dissolution and desorption of mineral phases would result in lowered C:P and N:P ratios relative to the known organic substrates. For dissolution and desorption to be important contributors to the flux excess and still produce the observed C:N:P flux excess ratios requires either a yet unidentified organic substrate rich in C and N relative to P, or preferential liberation C and N relative to P during oxidation of the known organic forms. Thus, we conclude that the excess PO₄ in the Amazon river is generated primarily by organic matter decomposition and that dissolution and desorption of inorganic P is probably of only minor importance. However, identification of the actual organic matter undergoing decomposition is not possible from the apparent flux excess because the C:N ratio does not match any of the identified organic matter pools. The excess may arise from mineralization of a mixture of the pools, from the mineralization of a subcomponent of one of the pools or a combination of these processes.
Table 1. The apparent elemental ratios (by atoms) calculated from the average flux imbalances. The total CO₂ balance included respiration and was taken from Richey et al. (in press). Also listed are the elemental ratios of common organic tissues found on the floodplain as well as the riverine DOM and TSS

<table>
<thead>
<tr>
<th></th>
<th>C:N</th>
<th>N:P</th>
<th>C:N:P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent flux excess ratio</td>
<td>54:1</td>
<td>34:1</td>
<td>1840:34:1</td>
</tr>
<tr>
<td>Average varzea wood tissue</td>
<td>54:1</td>
<td>38:1</td>
<td>5940:38:1</td>
</tr>
<tr>
<td>Average varzea leaf tissue</td>
<td>28:1</td>
<td>36:1</td>
<td>1000:36:1</td>
</tr>
<tr>
<td>Average macrophyte tissue</td>
<td>32:1</td>
<td>36:1</td>
<td>1160:36:1</td>
</tr>
<tr>
<td>Mainstem TSS</td>
<td>10:1</td>
<td>4:1</td>
<td>40:4:1</td>
</tr>
<tr>
<td>Mainstem DOM (DOC:DON:DOP)</td>
<td>23:1</td>
<td>27:1</td>
<td>607:27:1</td>
</tr>
</tbody>
</table>

Table 2. Concentrations and transports of nitrogen and P species of the Amazon river and their global significance. World average rivers are from Meybeck (1982) and are for natural rivers

<table>
<thead>
<tr>
<th>Concentration (µM)</th>
<th>Transport (Tg y⁻¹)</th>
<th></th>
<th></th>
<th>% Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amazon</td>
<td>World</td>
<td>Amazon</td>
<td>World</td>
</tr>
<tr>
<td>TPP</td>
<td>6.2</td>
<td>17.0</td>
<td>1.23</td>
<td>19.0</td>
</tr>
<tr>
<td>DOP</td>
<td>0.5</td>
<td>0.9</td>
<td>0.10</td>
<td>1.0</td>
</tr>
<tr>
<td>PO₄</td>
<td>0.8</td>
<td>0.4</td>
<td>0.13</td>
<td>0.4</td>
</tr>
<tr>
<td>PON</td>
<td>19.9</td>
<td>--</td>
<td>--</td>
<td>1.62</td>
</tr>
<tr>
<td>DON</td>
<td>13.7</td>
<td>27.0</td>
<td>0.62</td>
<td>14.7</td>
</tr>
<tr>
<td>NO₃</td>
<td>12.0</td>
<td>7.0</td>
<td>0.83</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Nitrogen and P transport from the continent to the ocean. From the P and nitrogen concentrations determined at the downstream station, Obidos, during the seven CAMREX cruises it is possible to calculate average concentrations that can then be compared to "world average" river values reported by Meybeck (1982). Furthermore, when combined with Obidos water discharge measurements it is possible to quantitatively evaluate the transport of these elements from the continents to the oceans by the world's largest river. The results of both calculations are shown in Table 2. (The average concentrations given in Table 2 are slightly different from those of Figure 2 because the values in Figure 2 include all mainstem stations, not just Obidos.)

Comparison of the concentrations of dissolved and particulate phases of nitrogen and P in the Amazon river with those of the "world average" river reveals that although they may vary by a factor of 2, the Amazon is chemically quite ordinary. For both elements, particulate and organic concentrations are lower than the world average while the inorganic forms
are higher. However, because the water discharge of the Amazon is so large, the overall transport of nitrogen and P from the continent to the ocean is a significant fraction of the total riverine transport. The Amazon river alone is responsible for about 7% of the particulate P transport, about 10% of the DOP transport and about one third of the total natural PO₄ transport. The river is also highly significant in global nitrogen transport. Thus, in terms of overall transport, chemically the Amazon river is quite typical; nevertheless its great water discharge makes it significant in the global cycles of nitrogen and P.

Acknowledgement

We wish to thank the crew of the Brazilian research vessel L/M Amanai and our colleagues at the Instituto Nacional de Pesquisas da Amazonia and at the Centro de Energia Nuclear na Agricultura; especially Dr. L.A. Martinelli and Dr. R. Victoria. Contribution # 40 from the CAMREX project.

References


Stallard, R.F. and J.M. Edmond. 1983. Geochemistry of the Amazon 2. The
influence of geology and weathering environment on the dissolved load.
