

## Increase in suspended sediment discharge of the Amazon River assessed by monitoring network and satellite data

Jean-Michel Martinez, Guyot Jean-Loup, Naziano Filizola, Francis Sondag

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Title: Increase in suspended sediment discharge of the Amazon River assessed by monitoring network and satellite data

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Corresponding Author: Dr Jean-Michel Martinez,

Corresponding Author's Institution: IRD

First Author: Jean-Michel Martinez, PhD

Order of Authors: Jean-Michel Martinez, PhD; Jean-Loup Guyot; Naziano Filizola; Francis Sondas

Abstract: This study addresses the quantification of the Amazon River sediment budget which has been assessed by looking at data from a suspended sediment discharge monitoring network and remote sensing estimates derived from MODIS spaceborne sensor. Surface suspended sediment concentration has been sampled every 10 days since 1995 (390 samples available) by the international HYBAM program at the Óbidos station which happens to be the last gauged station of the Amazon River before the Atlantic Ocean. Remote sensing reflectance is derived from continuous time series of 554 MODIS images available since 2000 and calibrated with the HYBAM field measurements. Discharge shows a weak correlation with the suspended sediment concentration during the annual hydrological cycle, preventing us from computing sediment discharge directly from the water discharge. Accordingly, river sediment discharge is assessed by multiplying daily water discharge measurements by the suspended sediment concentration averaged on a monthly basis. Comparisons of annual sediment discharge assessed using both field and satellite datasets show a very good agreement with a mean difference lower than 1%. Both field and satellite-derived estimates of the sediment concentration of the Amazon River are

combined to get an uninterrupted monthly average suspended sediment discharge from 1995 to 2007. Unlike the water discharge which exhibits a steady trend over the same period at Óbidos, the 12-year suspended sediment discharge increases by about 20% since 1995, significant at the 99% level. In particular, the interannual variability is much more significant in the sediment discharge than in the river discharge.



1 **ABSTRACT**

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4 3 This study addresses the quantification of the Amazon River sediment budget which has  
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7 4 been assessed by looking at data from a suspended sediment discharge monitoring  
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10 5 network and remote sensing estimates derived from MODIS spaceborne sensor. Surface  
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12 6 suspended sediment concentration has been sampled every 10 days since 1995 (390  
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14 7 samples available) by the international HYBAM program at the Óbidos station which  
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17 8 happens to be the last gauged station of the Amazon River before the Atlantic Ocean.  
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19 9 Remote sensing reflectance is derived from continuous time series of 554 MODIS  
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22 10 images available since 2000 and calibrated with the HYBAM field measurements.  
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24 11 Discharge shows a weak correlation with the suspended sediment concentration during  
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26 12 the annual hydrological cycle, preventing us from computing sediment discharge  
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29 13 directly from the water discharge. Accordingly, river sediment discharge is assessed by  
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32 14 multiplying daily water discharge measurements by the suspended sediment  
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34 15 concentration averaged on a monthly basis. Comparisons of annual sediment discharge  
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36 16 assessed using both field and satellite datasets show a very good agreement with a mean  
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39 17 difference lower than 1%. Both field and satellite-derived estimates of the sediment  
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42 18 concentration of the Amazon River are combined to get an uninterrupted monthly  
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44 19 average suspended sediment discharge from 1995 to 2007. Unlike the water discharge  
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46 20 which exhibits a steady trend over the same period at Óbidos, the 12-year suspended  
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49 21 sediment discharge increases by about 20% since 1995, significant at the 99% level. In  
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51 22 particular, the interannual variability is much more significant in the sediment discharge  
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54 23 than in the river discharge.

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56 24 **KEYWORDS :** Hydrology, sediment concentration, Amazon, remote sensing,  
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58 25 HYBAM, MODIS.  
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# 1 INTRODUCTION

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3  
4 3 With a drainage basin area of  $6.1 \cdot 10^6 \text{ km}^2$  (Goulding et al., 2003) and a mean annual  
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7 4 discharge estimated at  $209\,000 \text{ m}^3/\text{s}$  at the river mouth (Molinier et al., 1996), the  
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10 5 Amazon basin is the largest river system in the world. Given its large size, the Amazon  
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12 6 basin experiences significant climate variability (Marengo, 2004). At Óbidos, the most  
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14 7 downstream gauged station on the Amazon River in Brazil offering long term  
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16 8 hydrological monitoring, annual data for the 1903–1999 period indicate a steadily  
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18 9 increasing discharge trend (+9%) over the century, and a recent period of decrease over  
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20 10 the last decade of the past century (Callède et al., 2004). In recent decades, several  
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22 11 suspended sediment discharge budgets have been published for the Amazon (Dunne et  
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24 12 al., 1998; Filizola, 2003; Gibbs, 1967; Meade et al., 1985; Meade et al., 1979), but the  
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26 13 time variability of the sediment concentration, based on 10-day sampling has only been  
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28 14 recently made available thanks to the HYBAM program (<http://www.ore-hybam.org>).  
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36 16 Gibbs (1967) provides the first estimate of the sediment discharge of the Amazon River  
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38 17 at the Óbidos station of about 500 million tons per year using data from only two  
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40 18 sampling campaigns at low and high water levels. Using two additional sampling  
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42 19 campaigns conducted during a high water period, Meade (1979) got a higher sediment  
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44 20 discharge of 900 million tons per year. From the results of eight CAMREX sampling  
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46 21 campaigns, Meade et al. (1985) obtained an even higher sediment discharge value of  
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48 22 1200 million tons per year. More recently, using quarterly data from the Brazilian water  
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50 23 quality network, Bordas et al. (1988) and subsequently Filizola et al. (1999) derived a  
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52 24 new estimate for the annual sedimentary flux at the Óbidos station of 600 million tons  
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54 25 per year, a value close to the first estimate provided by Gibbs. Based on a 10-day  
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1 sampling from the HYBAM program, Guyot et al. (2005) suggest an increasing  
2 sediment discharge from 2000 to 2003 and also noted that the trend in suspended  
3 sediment concentration is not correlated with discharge. In other words, it is not  
4 possible to derive a simple relationship between river flow and suspended sediment  
5 concentration. It is therefore not possible to derive sediment discharge from the daily  
6 measurement of river water flow alone but instead, simultaneous monitoring of  
7 sediment concentration and of water discharge is required. In the current study, based  
8 on an updated HYBAM dataset (1995-2007) and surface suspended sediment  
9 concentrations calculated by MODIS reflectance inversion (Martinez et al., 2004) for  
10 the 2000-2007 period, new results are presented highlighting improved monitoring of  
11 suspended sediment. To quantify the Amazon River mean annual sediment discharge as  
12 well as the inter and intra-annual variability, various datasets from the Óbidos station  
13 have been used, namely :

14  
15 (a) 390 surface-suspended sediment (SSS) point samples collected every 10 days  
16 between 1995 and 2007 at Óbidos for the HYBAM program (Guyot et al., 1999);

17  
18 (b) intensive sampling of the river reach over the width and depth of the cross-section  
19 assessed during 18 field sampling campaigns allowing SSS estimates to be related to the  
20 river reach average suspended sediment concentration (Filizola, 2003);

21  
22 (c) 8-day estimates of the surface-suspended concentration over the river reach assessed  
23 from remote sensing images, i.e. 8-day composite MODIS images, calibrated and  
24 validated locally with the 10-day SSS measurements (Martinez et al., 2007).

1 Most past and present satellites are unsuited to water quality monitoring in rivers and  
2 lakes because the sensors used fail to offer an adequate tradeoff between spatial  
3 resolution, spatial coverage, revisit frequency and radiometric resolution. A significant  
4 amount of research has been devoted to the use of remote sensing data for monitoring  
5 inland water quality parameters. However, it is often limited to one-off studies based on  
6 high resolution imagery. In this study, we intend to make use of more robust remote  
7 sensing data offering daily coverage and for which we previously studied the possibility  
8 of retrieving suspended sediment concentration (Martinez et al., 2003; Martinez et al.,  
9 2004). The combination of field sampling and remote sensing data supports the  
10 provision of robust long term monitoring of the Amazon River sediment discharge for  
11 the 1995-2007 period.

## 13 **DATA AND METHODS**

### 15 *Surface-Suspended Sediment Estimates*

17 The Óbidos hydrological station managed by the Brazilian water agency  
18 ([www.ana.gov.br](http://www.ana.gov.br)) has been furnishing uninterrupted data since 1968. At Óbidos, the  
19 watershed covers  $4.8 \times 10^6$  km<sup>2</sup> and the river mouth is located 900 kilometers  
20 downstream (Figure 1). Discharge has been derived from the rating curve established  
21 within the HYBAM project (Callede et al., 2002; Callède et al., 2001). Figure 2 shows  
22 the monthly average Amazon River discharge from 1968 to 2007. The Amazon River  
23 average annual discharge is 173,000 m<sup>3</sup>/s, with, during the last decade, a noteworthy dry  
24 year (-15%) in 1997/1998 marked by a strong El Niño episode. The river discharge



1 shows a very stable value over the period considered for the study of sediment  
2 discharge : 1995-2007.

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7 From March 1995 to December 2007, 390 500-ml SSS samples were collected.  
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10 Suspended sediment concentration at the river surface has been sampled by local  
11 operator in a small boat every 10 days at a fixed point, near the middle of the river reach  
12 where the stream is about 2-km wide. Bottles were stored and sent approximately every  
13 6 months for filtering to the UnB (Brasilia National University 1995-2003) and recently  
14 to the Amazonas State University at Manaus. In the laboratory, the samples were  
15 filtered using 0.45  $\mu\text{m}$  cellulose acetate filters, previously dried for 24 hours at 50°C and  
16 weighted. The weight difference before and after filtration allows the amount of  
17 suspended matter to be determined by unit of liquid.

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31 Figure 3 displays the clockwise hysteresis in the relation between SSS concentration  
32 and river discharge from 1995 to 2003. It shows that there is no simple and robust  
33 relationship between river flow and the suspended sediment. The concentration peak  
34 occurs two to three months before the annual flood peak during the rising water stage.  
35  
36 Around the flood peak, the SSS concentration reaches a minimum. During each year,  
37 the SSS concentration is highly variable, from 9 to 260 mg/l. Nevertheless, the pattern is  
38 relatively stable from year to year. A specific sampling campaign was conducted to  
39 assess the SSS concentration heterogeneity across the river reach. From 66 samples  
40 collected on a regular grid of 250 by 250 meters, we calculated a coefficient of variation  
41 of 18 %.

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58 *Average suspended sediment concentration*

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2 Eighteen sampling campaigns were conducted between 1995 and 2003 to relate the 10-  
3 day surface samples to the average suspended sediment (ASS) concentration across the  
4 whole river reach. During these campaigns, the discharge was measured with Acoustic  
5 Doppler Current Profilers (ADCP). Fifteen 10-liter water samples were collected at  
6 three verticals and five different depths using horizontal oceanographic bottles suitable  
7 for the Amazon River's operational and environmental conditions (Filizola and Guyot,  
8 2004). Each sample was first filtered through 62  $\mu\text{m}$  filters to remove the coarser  
9 material. Then, each sample was processed using the same protocol as for the 10-day  
10 HYBAM measurement network. Comparison of the results derived with our technique  
11 and a depth integration method used by the USGS and the Brazilian Water Agency  
12 during the same sampling campaign indicated a difference of less than 5% (Filizola and  
13 Guyot, 2004).

14  
15 From the 320 samples collected over the whole river reach at Óbidos, we calculated a  
16 ASS concentration of 150 mg/l, which is twice the mean SSS concentration of 72 mg/l  
17 for 390 samples. Figure 4 shows the SSS concentration as a function of the ASS  
18 concentration for the 18 campaigns. A good agreement is found and makes it possible to  
19 assess the ASS concentration for the whole river reach from the 10-day SSS  
20 measurement network or from satellite data (Guyot et al., 2005). For calculation of  
21 sediment discharge we will make use of the following equation relating the average  
22 concentration to the surface concentration:

$$\text{ASS} = 1.24 \cdot \text{SSS} + 43.5 \quad (1)$$

1 The same equation will be used to derive ASS concentration from SSS concentration  
2 over the whole period considered (1995-2007).

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7 4 *Remote sensing images*  
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11 6 Numerous papers deal with the sensitivity of remote sensing reflectance to the  
12 suspended sediment concentration in oceanic and inland waters. A significant number  
13 of researchers have reported a strong positive correlation between surface suspended  
14 concentrations and spectral radiance (Bhargava and Mariam, 1990; Bhargava and  
15 Mariam, 1991; Doxaran et al., 2002; Hinton, 1991; Martinez et al., 2004; Mertes et al.,  
16 1993; Novo et al., 1989a; Novo et al., 1989b; Ritchie and Cooper, 1988; Ritchie et al.,  
17 1987) and have noted that the relation may depend on the range of concentration, water  
18 types and suspended matter origin. Most studies agree that the best correlation between  
19 reflectance and SSC is between 700 and 800 nm in turbid inland waters. In this study  
20 we propose to use data from the latest generation of spaceborne sensors such as MODIS  
21 that are promising in terms of inland water monitoring because they offer the spatial  
22 resolution and spatial coverage that are compatible with the dimensions of river systems  
23 while allowing for fine temporal resolution.  
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46 20 The Collection 5 atmospherically-corrected surface reflectance products from the Terra  
47 and Aqua MODIS spaceborne sensors are utilized in this study. The MODIS data  
48 product MOD09Q1 (Terra on-board sensor) and MYD09Q1 (Aqua on-board sensor)  
49 provides calibrated reflectance for two radiometric bands measured at a 250 m pixel  
50 resolution while offering near-daily time coverage over tropical areas  
51 (<http://modis.gsfc.nasa.gov>). Band 1 is centered at 645 nm and band 2 at 858.5 nm  
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1 (infrared). MODIS surface reflectance 8-day composite data were acquired between  
2 March 2000 and October 2007 from the NASA Earth Observing System (EOS) data  
3 gateway. We chose composite images because i) the 8-day composite is compatible  
4 with the 10-day field measurement sampling frequency; ii) it reduces the amount of data  
5 to be analyzed as a large number of daily images cannot be used in view of the  
6 persistent cloud cover and iii) it significantly reduces the directional reflectance effects  
7 and atmospheric artifacts. For each date, the composites from Terra and Aqua are  
8 automatically scanned and the image with the lowest cloud coverage is selected. When  
9 both composites exhibit low cloud coverage, the composite acquired with the lowest  
10 satellite viewing angle is preferred.

11  
12 A pixel-based river mask covering nearly 10,000 pixels is manually outlined over the  
13 Óbidos station to automatically extract the reflectance in each MODIS image. Retrieval  
14 of river stream reflectance using MODIS data however, is greatly hampered by the low  
15 spatial resolution that may result in few pure (non-mixed) water pixels, depending on  
16 the river width and image acquisition geometry. Along the river bank, the occurrence of  
17 multiple materials such as water, vegetation and sand results in a composite pixel with a  
18 mixed spectral signal. Starting with the spectra of each pure component or  
19 “endmember”, the pixel value observed in any spectral band is usually modeled by a  
20 linear combination of the spectral responses of the components. The spectra of the  
21 vegetation and sand endmembers may be directly assessed from each image from stable  
22 and large targets. River pixels are partitioned into homogeneous clusters using the K-  
23 means algorithm (Martinez et al., submitted). The fraction of each endmember in each  
24 cluster is obtained by applying a least squares technique to minimize the unmodeled  
25 residual. The set of linear equations is then solved by testing every cluster as a possible

1 “pure” water endmember. The cluster leading to the lowest residual is retained as the  
2 water endmember (Martinez et al., submitted).

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7 We calibrate the reflectance – surface suspended sediment concentration by comparing  
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10 MODIS images and SSS measurements assessed every 10 days between 2000 and 2007.  
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12 Strong cloud cover typical of tropical areas makes it difficult to have the MODIS  
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14 acquisition date matching the field sampling date which likely introduces a significant  
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16 bias in the comparison between both datasets. To reduce this bias, monthly average  
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18 estimates of the SSS concentration (3 samples each month) and 8-day composites  
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20 (between 3 and 4 reflectance estimates each month) are used. Because MODIS images  
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22 have only been available since March 2000, a total of 93 months can be theoretically  
23  
24 used for comparison purposes. Nevertheless, because the 10-day measurement dataset  
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26 has suffered various interruptions, a total of 77 out of 93 months was selected for  
27  
28 calibration and validation of the reflectance – SSS concentration relationship. Samples  
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30 have not been stratified in relation to the season of the year in order to assess the  
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32 robustness of the relationship.  
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41 Figure 5 shows the relationship between the water endmember reflectance extracted  
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43 from the MODIS infrared band and the monthly average SSS concentration  
44  
45 measurements derived from the 10-day samples. The reflectance shows an increasing  
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47 reflectance as a function of SSS concentration with no saturation up to 200 mg/l. A  
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49 reflectance / SSS concentration linear model has been calibrated using bootstrap  
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51 resampling techniques and York least square regression (York et al., 2004) that  
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53 accounts for uncertainties in both variables.  
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1 The general bootstrap approach involves resampling of the dataset with repeated  
 2 replacements (Wehrens et al., 2000) to generate an empirical estimate of the sampling  
 3 distribution. Accordingly, a large number of ‘bootstrap samples’ is generated, each with  
 4 the same size as the original dataset. For each bootstrap sample, a linear model using  
 5 York regression is built and tested against those objects present in the sample to  
 6 compute the RMSE  $\delta$  and the objects omitted from the resampled set to compute the  
 7 RMSE  $\varepsilon$ . To achieve a better estimate of the prediction error, we use the *0.632*  
 8 *bootstrap*  $b_{632}$ . Practical and theoretical evidence suggests that this is a very reliable  
 9 estimator (Efron and Tibshirani, 1993). The final bootstrap estimate is the average value  
 10 of  $b_{632}$  over N iterations of the procedure :

$$b_{632} = \frac{1}{N} \sum_{i=1}^N (1 - 0.632) \delta_i + 0.632 \varepsilon_i$$

14 The factor 0.632 is used because it corresponds to the probability of getting an  
 15 observation in a bootstrap sample. Although two hundred bootstrap samples are usually  
 16 sufficient, two thousand bootstrap samples have been routinely used. The dataset for  
 17 regression and validation consists of 77 reflectance/SSS estimates, from 17 to 235 mg/l  
 18 with a mean value of 75 mg/l. Based on this dataset the  $b_{632}$  estimate of the retrieval is  
 19 29 mg/l (36 % relative error). Field assessment of SSS concentration heterogeneity  
 20 during one sampling campaign showed a CV of 18 % using 66 samples. Comparison of  
 21 both estimates highlights the fact that a significant part of the difference between field  
 22 measurements and satellite-derived estimates should be attributed to SSS concentration  
 23 heterogeneity across the river reach.

## 1 RESULTS

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4 Figure 6 compares the monthly average SSS concentration measurements with the  
5 satellite-derived SSS estimates over the 2000-2007 period at the Óbidos station. A very  
6 good agreement is found between satellite-derived and ground-derived monthly  
7 averages. The automatic reflectance retrieval procedure appears to produce robust  
8 estimates over the 7 consecutive hydrological cycles.

9 Figure 7 shows the monthly average sediment discharge at the Óbidos station computed  
10 with field measurements and satellite images. Monthly average sediment discharge is  
11 calculated multiplying monthly average discharge records times monthly average ASS  
12 concentration. Monthly average discharge is calculated by averaging the daily discharge  
13 records. ASS concentration data are assessed from SSS concentration estimates using  
14 equation (1). Monthly average ASS concentration is calculated by averaging either the  
15 HYBAM 10-day estimates or the MODIS-derived 8-day estimates. Direct comparison  
16 of both sediment discharge budgets can be carried out on 2 cycles (2001 and 2005) for  
17 which complete records are available for both field measurements and satellite images.  
18 The relative difference is -3.0 % (sediment discharge of  $788.10^6$  tons with field  
19 measurements and of  $811.10^6$  tons using satellite images) for the hydrological cycles of  
20 2001 (November 2000 – October 2001) and +1.8 % for 2005 (sediment discharge of  
21  $797.10^6$  tons with field measurements and of  $782.10^6$  tons using satellite images). Field-  
22 derived and satellite-derived SSS estimates complement each other for monitoring the  
23 suspended sediment discharge. On the one hand, the field measurements provide  
24 estimates at fixed and regular dates but fail to provide an assessment of the sediment  
25 concentration heterogeneity across the river surface. Additionally, the monitoring

1 network is prone to many potential sources of failure including variable sampling  
2 location, operator reliability or loss of samples. When a problem occurs, it may take a  
3 few weeks or even months before it can be fixed, resulting in a significant loss of data.  
4 On the other hand, satellite measurements must first be calibrated using field  
5 measurements and availability depends primarily on the weather. Furthermore, during  
6 the rainy season, a clear sky is a remote possibility which may lead to interruptions in  
7 the monitoring service. Nonetheless, MODIS images were constantly available for 93  
8 consecutive months. This shows that the daily coverage offered by the MODIS sensor is  
9 a prerequisite for long term monitoring of tropical areas by remote sensing means.  
10 Finally, satellite imagery provides unprecedented knowledge of the surface  
11 heterogeneity for much larger areas than a monitoring network would allow.

12  
13 Yearly averaged field and satellite-derived suspended sediment discharges were merged  
14 to produce a continuous assessment of the inter-annual variability of the sediment  
15 discharge of the Amazon River. When available and complete, field-based data records  
16 were considered while the remote sensing data was used for the period without  
17 complete field measurements (2002, 2003, 2004, 2006 and 2007 cycles). Thus, a  
18 complete and continuous assessment of the sediment discharge of the Amazon River  
19 was obtained from 1995 to 2007, representing twelve consecutive hydrological cycles  
20 (with the beginning of a hydrological cycle in November). Yearly average discharge  
21 and yearly average sediment discharge were calculated summing the monthly estimates  
22 for each variables. Over this period, the mean river discharge has been 173,000 m<sup>3</sup>/s  
23 with a coefficient of variation of 6.2 %. Between 1996 and 2007, the annual mean  
24 sediment discharge is about 754.10<sup>6</sup> tons / year with a coefficient of variation of 8.6 %.  
25 This value is consistent with previous studies by Bordas et al. (1988), Filizola (2003)



1 and Guyot et al. (2005) and much higher than the river bed transport, assessed to be of  
2 about  $4.7 \cdot 10^6$  tons / year at this station (Strasser et al., 2002). The 1997/1998  
3 hydrological cycle shows a very low discharge (-15 % relative to the rest of the time  
4 series). If we remove this particular hydrological cycle from the statistics, the mean  
5 river discharge remains almost constant at 175,000 m<sup>3</sup>/s but the coefficient of variation  
6 falls to 4.1 %. Clearly, the sediment discharge exhibits a much greater variation over  
7 time than the discharge. Finally, the intra-annual variation in sediment discharge is  
8 much more regular than inter-annual variation. For example, half the annual sediment  
9 budget (51 % on average) is discharged between January and April for every year  
10 considered.

11  
12 Over the 1996-2007 period, an increasing trend of sediment discharge significant at the  
13 99% level can be noticed. More specifically, the Amazon River sediment discharge time  
14 series exhibits two contrasting periods, that is, before and after the 2001 hydrological  
15 cycle. Before 2001, the annual mean sediment discharge was approximately  $688 \cdot 10^6$   
16 tons / year (coefficient of variation of 4.4 %). Then the annual mean sediment discharge  
17 increased to  $801 \cdot 10^6$  tons / year (coefficient of variation of 4.0 %) accounting for an  
18 increase of 16 % in terms of absolute sediment discharge between both periods. These  
19 observations suggest a significant change in the sediment transport regime of the  
20 Amazon River even though the river discharge fails to exhibit a specific trend and the  
21 time series is not long enough to reach a definitive conclusion on this topic.

22  
23 An increase in sediment discharge may be attributed to stronger erosion processes  
24 caused either by a global change (rainfall), or regional changes (land cover change  
25 resulting from deforestation for example) or both. On the one hand, Callède et al.

1 (Callède et al., 2004) assessed the Amazon river discharge at Óbidos and observed a  
2 rather stable river discharge since the seventies. However, for the same period, the  
3 runoff coefficient, assessed from discharge and rainfall records for the whole basin, is  
4 shown to increase, thereby pointing to a possible impact of land cover change (Callede  
5 et al., 2008). On the other hand, Espinoza Villar et al. (Submitted) showed that the  
6 stability of the mean discharge on the river main stem at Óbidos may be accounted for  
7 by opposite regional features upstream : a decrease in low stage runoff, particularly in  
8 the southern sub-basins, and an increase in high stage runoff in the north-western  
9 region. The same authors (Espinoza Villar et al., 2008) also point out a stronger intra-  
10 annual variability of rain causing more extreme events in terms of discharge even  
11 though the mean discharge tends to remain stable over time. Stronger rainfall variability  
12 upstream may support a more efficient production and transportation of sediments.  
13 Thus, a change in rainfall pattern may account as well for sediment discharge variation.

## 14 **CONCLUSION**

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17 This study contributes to the quantification of erosion processes in one of the main  
18 surviving natural ecosystems. Although our work only covers the last 12 years, it  
19 demonstrates the interest of new techniques such as remote sensing for long term  
20 monitoring of inland waters. The surface reflectance data appears to be robustly linked  
21 with the suspended sediment concentration at the river surface over a large range of  
22 concentration and for several consecutive hydrological cycles. By combining an  
23 excellent temporal resolution and a fine calibration quality, MODIS data may be used  
24 operationally along field observations to provide more observations in poorly gauged  
25 basins, such as the large-scale river basins. However, the quest for a universal algorithm

1 for suspended sediments retrieval from satellite data is never likely to succeed because  
2 the scattering efficiency of suspended particles is very much a function of average  
3 particle size that is quite variable from one catchment to another. Thus, local calibration  
4 of satellite data would have to be developed and tested for each river basin.

5  
6 Our results confirm the independence of river discharge and suspended sediment  
7 concentration at the Óbidos station. No major trend during the 1996-2007 period has  
8 been found for the river discharge. On the contrary, there exists a significant increase in  
9 the sediment budget of the Amazon with a suspended sediment discharge 20 % higher  
10 in 2007 relative to 1996. To get further insights into these results, the inter-annual  
11 budget of the Amazon River's two main tributaries in terms of sediment discharge i.e.,  
12 the Madeira River and the Solimões River, that drain the southern and northern part of  
13 the Andean Cordillera respectively, will be assessed.

## 14 15 **ACKNOWLEDGMENTS**

16  
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1 **FIGURE CAPTIONS**

2  
3 Figure 1 : Location of Óbidos on the Amazon River, 900-km upstream from the river  
4 mouth. At Óbidos, the Amazon River has received most of its tributaries including the  
5 Madeira River (the main tributary in terms of suspended sediment concentration) and  
6 the Negro river (volumetrically the main tributary). At Óbidos, the drainage area is 4.8  
7  $10^6$  km<sup>2</sup>.  
8

9 Figure 2: Monthly average river discharge of the Amazon River at Óbidos. Over the  
10 period considered in this study (1968-2007), the average discharge is 173,000 m<sup>3</sup>/s.  
11

12 Figure 3 : Surface suspended sediment concentration at Óbidos as a function of the  
13 Amazon river discharge. Suspended sediment concentration measurements have been  
14 collected every 10 days by the HYBAM program since 1995.  
15

16 Figure 4 : Average suspended sediment concentration as a function of the surface  
17 suspended sediment concentration assessed during 18 field sampling campaigns.  
18 Sampling within the water column was based on 15 point samples at 3 different  
19 verticals and 5 increasing depths. Error bars stand for the standard deviation of all  
20 points collected at a given campaign, either at the river surface (3 points) or within the  
21 water column (12 points).  
22

23 Figure 5 : Surface reflectance of the Amazon River water derived from MODIS 8-day  
24 composite (Terra and Aqua Satellite) as a function of the surface suspended sediment  
25 concentration. Surface reflectance was extracted from the infrared channels available in  
26 the 250-meter resolution mode. Measurements represent monthly average values and  
27 error bars stand for the standard deviation each month.  
28

29 Figure 6 : Comparison of surface suspended sediment concentration derived from the  
30 10-day HYBAM samples and of satellite-derived estimates previously calibrated with  
31 field measurements. Error bars for the satellite-derived estimates stand for the 95%  
32 confidence interval of the prediction previously calibrated with field measurements.  
33

34 Figure 7 : Comparisons of monthly average river discharge with suspended sediment  
35 discharge derived from field measurements and MODIS images.  
36

37 Figure 8 : Annual Amazon river discharge and sediment discharge between 1996 and  
38 2007 at Óbidos.  
39

Figure 1  
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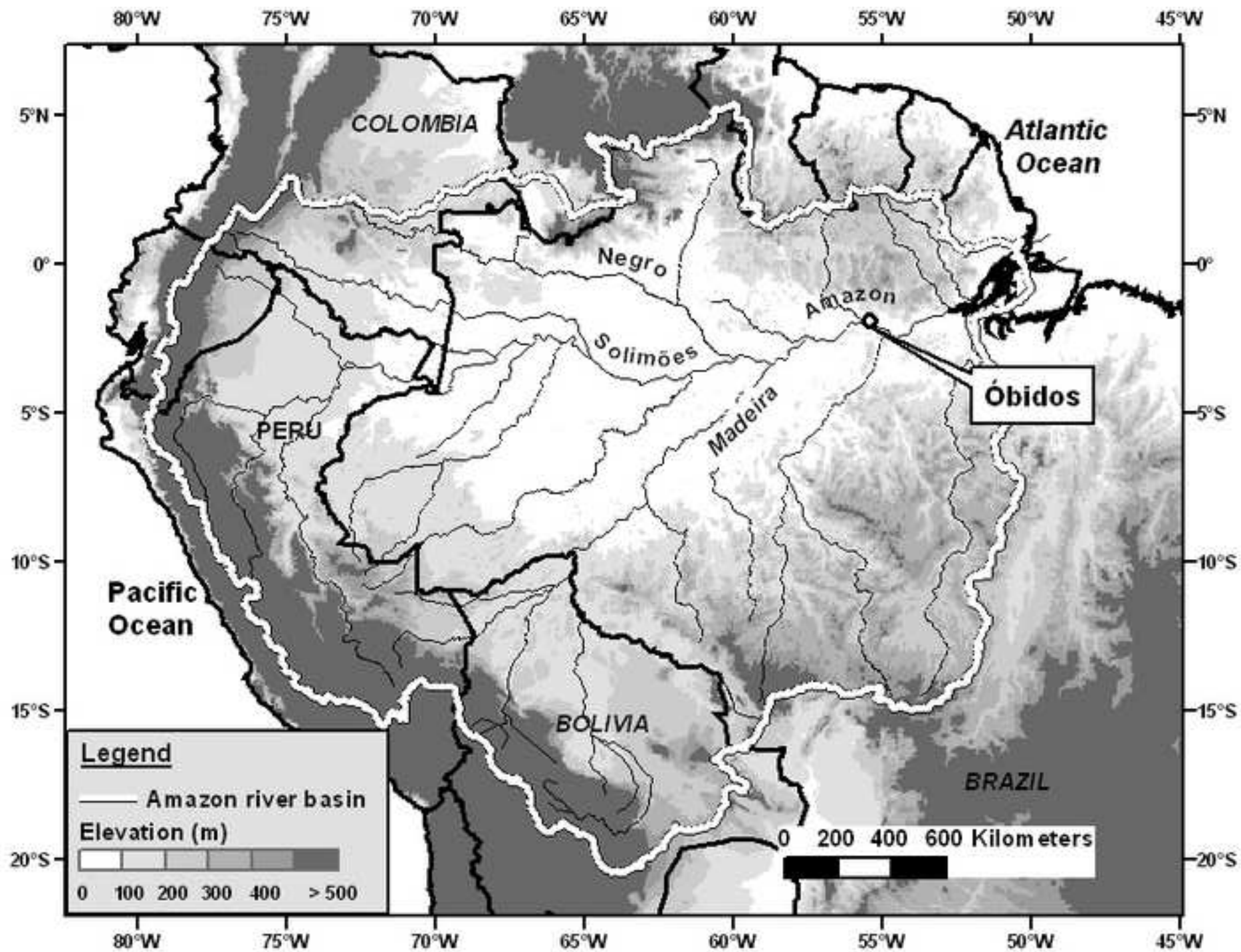


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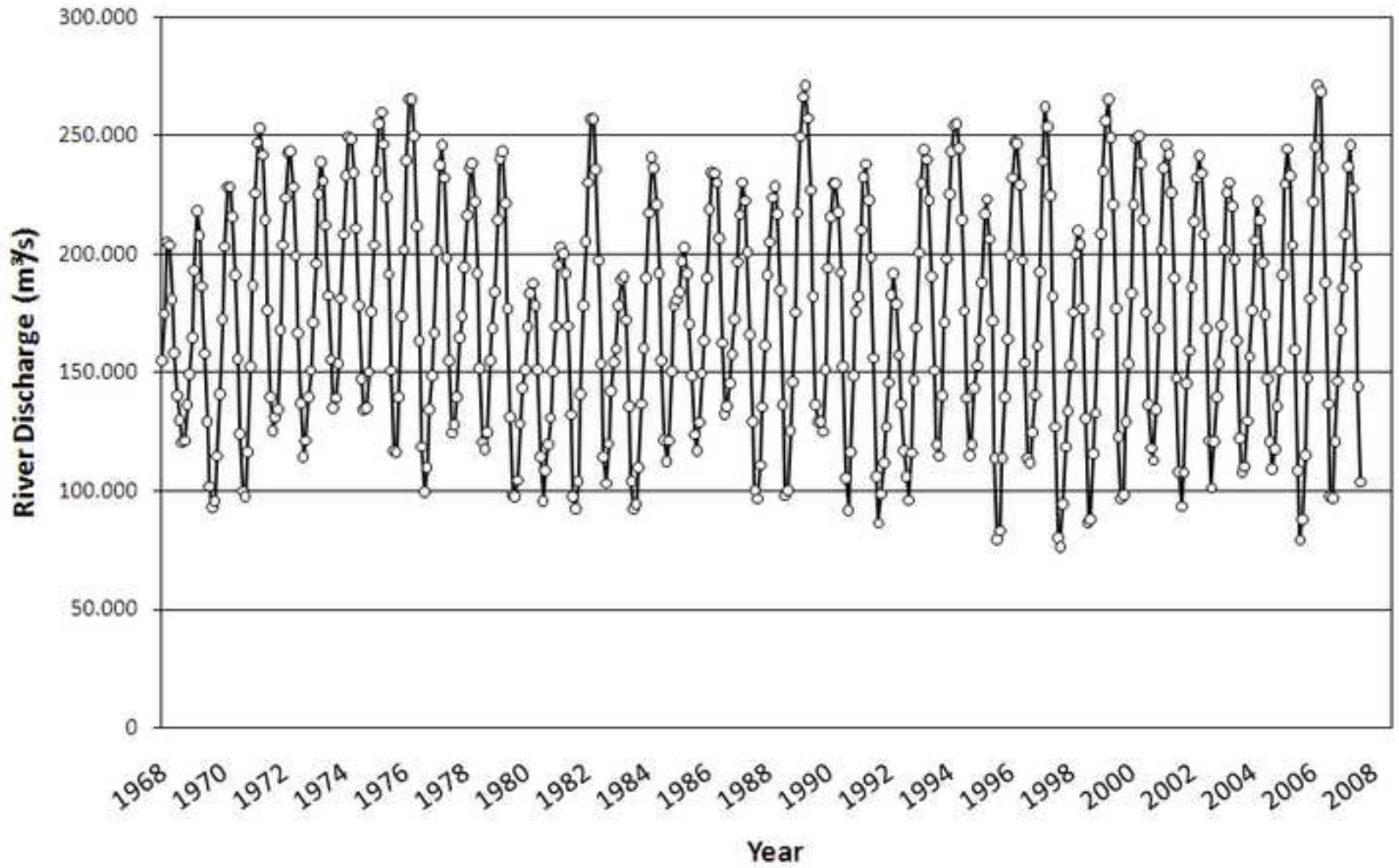




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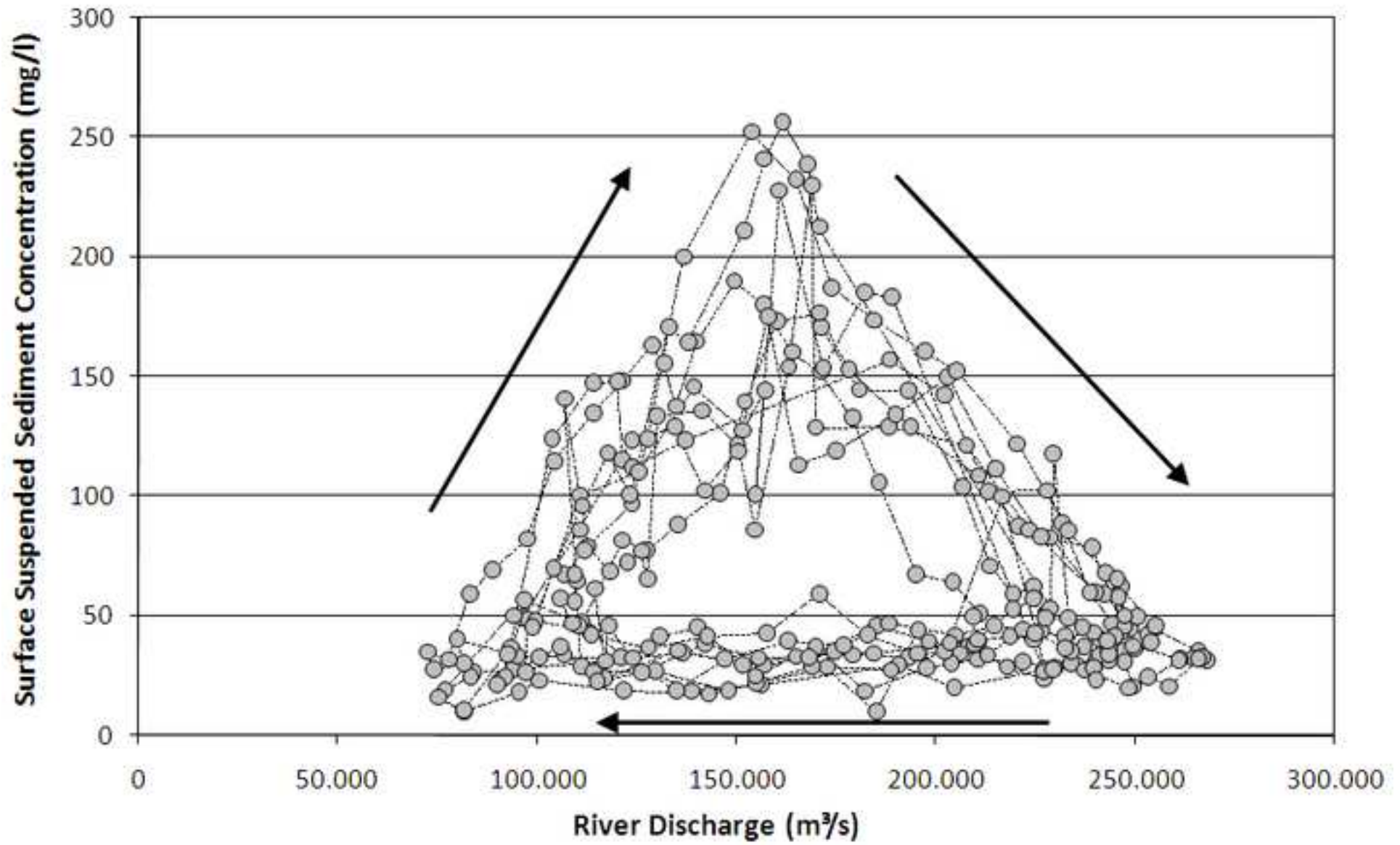


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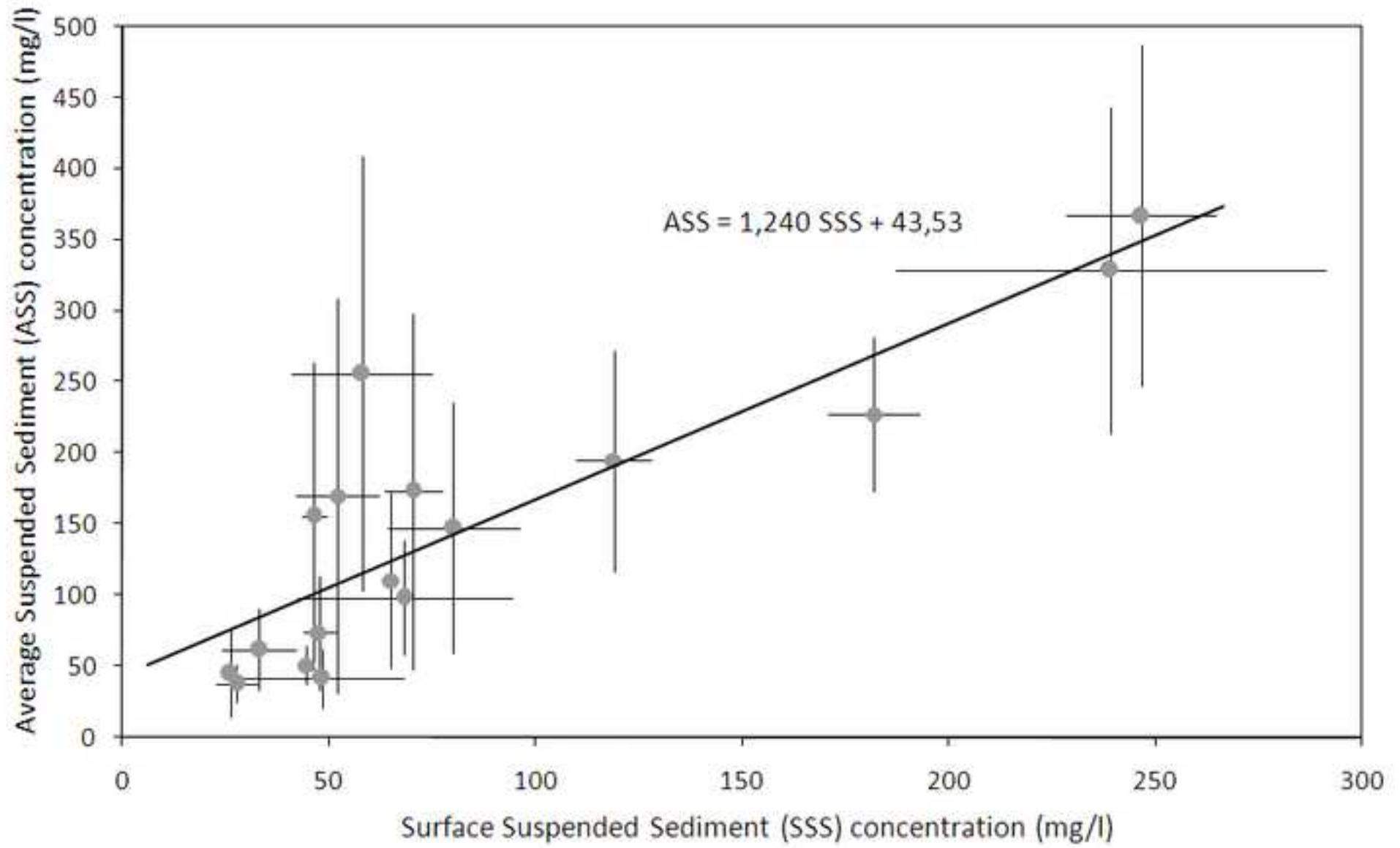


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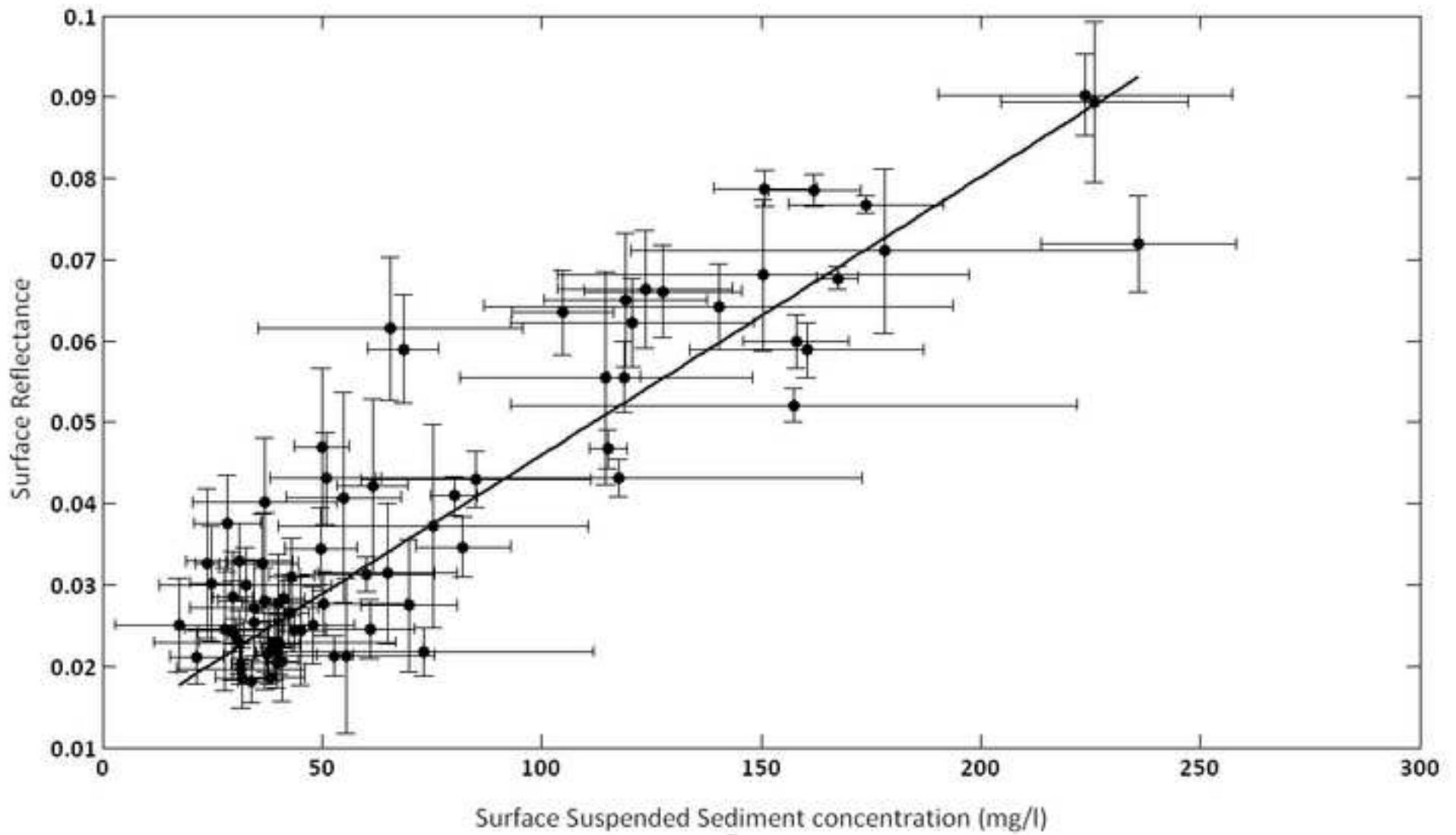


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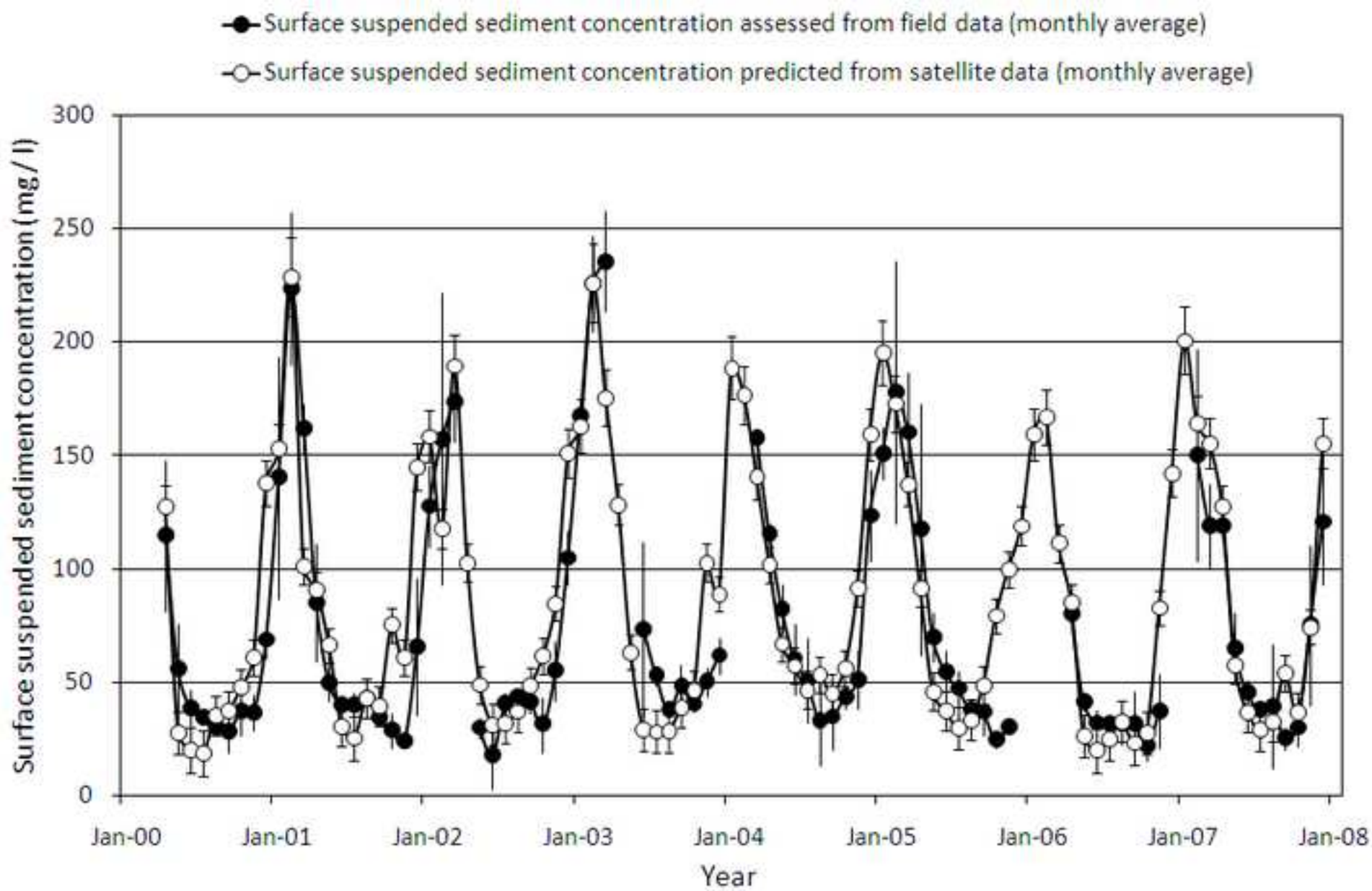


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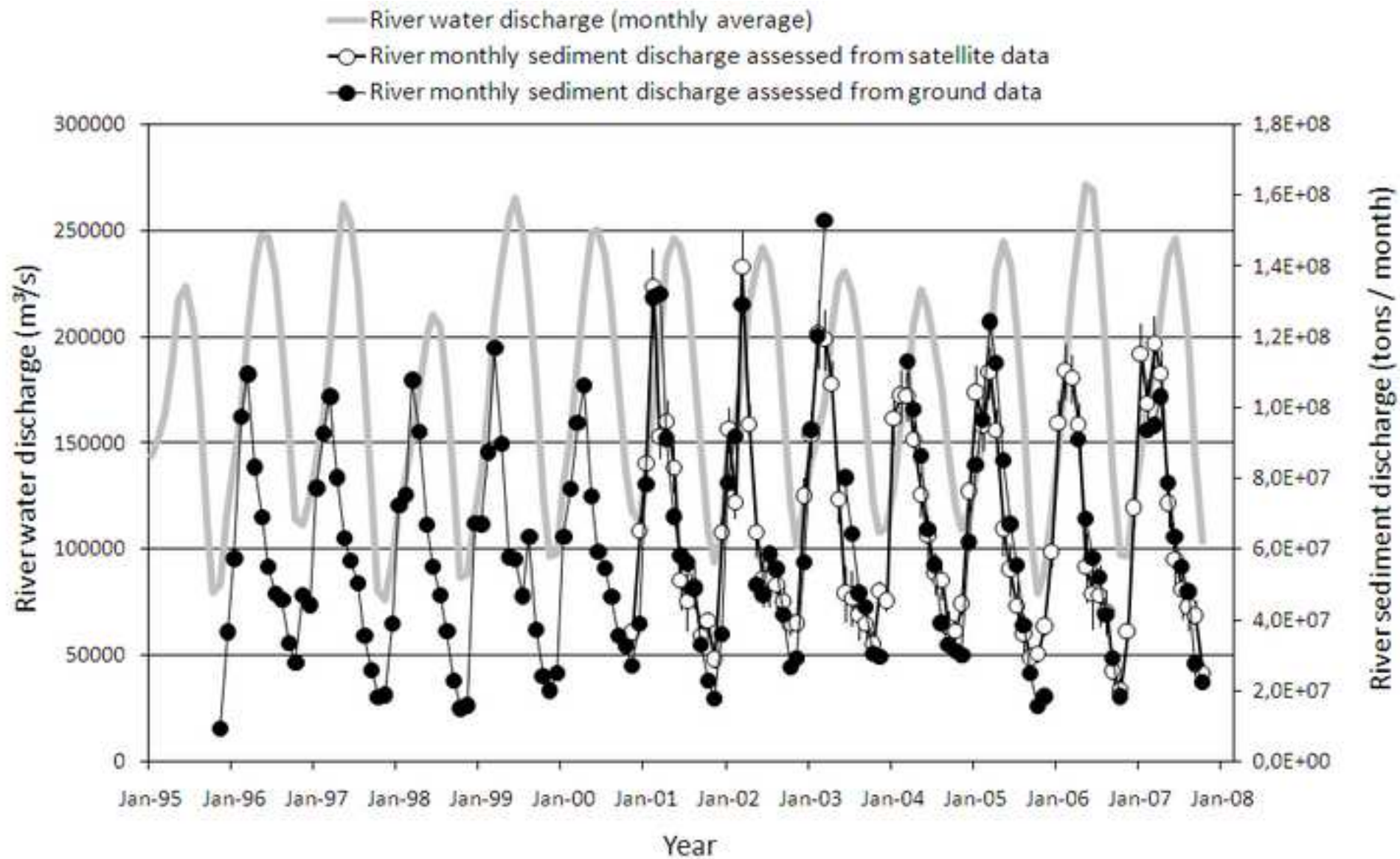


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