



HAL
open science

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

► **To cite this version:**

Jean-Michel Martinez, Guyot Jean-Loup, Naziano Filizola, Francis Sondag. Increase in suspended sediment discharge of the Amazon River assessed by monitoring network and satellite data. CATENA, 2009, pp.29. <10.1016/j.catena.2009.05.011>. <ird-00394090>

HAL Id: ird-00394090

<https://ird.hal.science/ird-00394090v1>

Submitted on 10 Jun 2009

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Elsevier Editorial System(tm) for Catena
Manuscript Draft

Manuscript Number: CATENA2220R2

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

Article Type: Special Issue: Sediment Change

Keywords: Hydrology; sediment concentration; Amazon; remote sensing; HYBAM; MODIS

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**

2
3
4 3 This study addresses the quantification of the Amazon River sediment budget which has
5
6
7 4 been assessed by looking at data from a suspended sediment discharge monitoring
8
9
10 5 network and remote sensing estimates derived from MODIS spaceborne sensor. Surface
11
12 6 suspended sediment concentration has been sampled every 10 days since 1995 (390
13
14 7 samples available) by the international HYBAM program at the Óbidos station which
15
16
17 8 happens to be the last gauged station of the Amazon River before the Atlantic Ocean.
18
19 9 Remote sensing reflectance is derived from continuous time series of 554 MODIS
20
21
22 10 images available since 2000 and calibrated with the HYBAM field measurements.
23
24 11 Discharge shows a weak correlation with the suspended sediment concentration during
25
26 12 the annual hydrological cycle, preventing us from computing sediment discharge
27
28
29 13 directly from the water discharge. Accordingly, river sediment discharge is assessed by
30
31
32 14 multiplying daily water discharge measurements by the suspended sediment
33
34 15 concentration averaged on a monthly basis. Comparisons of annual sediment discharge
35
36 16 assessed using both field and satellite datasets show a very good agreement with a mean
37
38
39 17 difference lower than 1%. Both field and satellite-derived estimates of the sediment
40
41
42 18 concentration of the Amazon River are combined to get an uninterrupted monthly
43
44 19 average suspended sediment discharge from 1995 to 2007. Unlike the water discharge
45
46 20 which exhibits a steady trend over the same period at Óbidos, the 12-year suspended
47
48
49 21 sediment discharge increases by about 20% since 1995, significant at the 99% level. In
50
51
52 22 particular, the interannual variability is much more significant in the sediment discharge
53
54 23 than in the river discharge.

55
56 24 **KEYWORDS :** Hydrology, sediment concentration, Amazon, remote sensing,
57
58 25 HYBAM, MODIS.
59
60
61 26

1 INTRODUCTION

2
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
5
6
7 4 discharge estimated at $209\,000 \text{ m}^3/\text{s}$ at the river mouth (Molinier et al., 1996), the
8
9
10 5 Amazon basin is the largest river system in the world. Given its large size, the Amazon
11
12 6 basin experiences significant climate variability (Marengo, 2004). At Óbidos, the most
13
14 7 downstream gauged station on the Amazon River in Brazil offering long term
15
16 8 hydrological monitoring, annual data for the 1903–1999 period indicate a steadily
17
18 9 increasing discharge trend (+9%) over the century, and a recent period of decrease over
19
20 10 the last decade of the past century (Callède et al., 2004). In recent decades, several
21
22 11 suspended sediment discharge budgets have been published for the Amazon (Dunne et
23
24 12 al., 1998; Filizola, 2003; Gibbs, 1967; Meade et al., 1985; Meade et al., 1979), but the
25
26 13 time variability of the sediment concentration, based on 10-day sampling has only been
27
28 14 recently made available thanks to the HYBAM program (<http://www.ore-hybam.org>).
29
30
31
32
33
34
35

36 16 Gibbs (1967) provides the first estimate of the sediment discharge of the Amazon River
37
38 17 at the Óbidos station of about 500 million tons per year using data from only two
39
40 18 sampling campaigns at low and high water levels. Using two additional sampling
41
42 19 campaigns conducted during a high water period, Meade (1979) got a higher sediment
43
44 20 discharge of 900 million tons per year. From the results of eight CAMREX sampling
45
46 21 campaigns, Meade et al. (1985) obtained an even higher sediment discharge value of
47
48 22 1200 million tons per year. More recently, using quarterly data from the Brazilian water
49
50 23 quality network, Bordas et al. (1988) and subsequently Filizola et al. (1999) derived a
51
52 24 new estimate for the annual sedimentary flux at the Óbidos station of 600 million tons
53
54 25 per year, a value close to the first estimate provided by Gibbs. Based on a 10-day
55
56
57
58
59
60
61
62
63
64
65

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) has been furnishing uninterrupted data since 1968. At Óbidos, the
19 watershed covers 4.8×10^6 km² 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 m³/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.

3
4
5
6
7 From March 1995 to December 2007, 390 500-ml SSS samples were collected.
8
9
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 μm 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.

18
19
20
21
22
23
24
25
26
27
28
29
30
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 %.

42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58 *Average suspended sediment concentration*

1
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 μm 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).

3
4
5
6
7 4 *Remote sensing images*
8
9

10
11
12 6 Numerous papers deal with the sensitivity of remote sensing reflectance to the
13
14 7 suspended sediment concentration in oceanic and inland waters. A significant number
15
16 8 of researchers have reported a strong positive correlation between surface suspended
17
18 9 concentrations and spectral radiance (Bhargava and Mariam, 1990; Bhargava and
19
20 10 Mariam, 1991; Doxaran et al., 2002; Hinton, 1991; Martinez et al., 2004; Mertes et al.,
21
22 11 1993; Novo et al., 1989a; Novo et al., 1989b; Ritchie and Cooper, 1988; Ritchie et al.,
23
24 12 1987) and have noted that the relation may depend on the range of concentration, water
25
26 13 types and suspended matter origin. Most studies agree that the best correlation between
27
28 14 reflectance and SSC is between 700 and 800 nm in turbid inland waters. In this study
29
30 15 we propose to use data from the latest generation of spaceborne sensors such as MODIS
31
32 16 that are promising in terms of inland water monitoring because they offer the spatial
33
34 17 resolution and spatial coverage that are compatible with the dimensions of river systems
35
36 18 while allowing for fine temporal resolution.
37
38
39
40
41
42
43
44

45
46 20 The Collection 5 atmospherically-corrected surface reflectance products from the Terra
47
48 21 and Aqua MODIS spaceborne sensors are utilized in this study. The MODIS data
49
50 22 product MOD09Q1 (Terra on-board sensor) and MYD09Q1 (Aqua on-board sensor)
51
52 23 provides calibrated reflectance for two radiometric bands measured at a 250 m pixel
53
54 24 resolution while offering near-daily time coverage over tropical areas
55
56 25 (<http://modis.gsfc.nasa.gov>). Band 1 is centered at 645 nm and band 2 at 858.5 nm
57
58
59
60
61
62
63
64
65

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).

3
4
5
6
7 We calibrate the reflectance – surface suspended sediment concentration by comparing
8
9
10 MODIS images and SSS measurements assessed every 10 days between 2000 and 2007.
11
12 Strong cloud cover typical of tropical areas makes it difficult to have the MODIS
13
14 acquisition date matching the field sampling date which likely introduces a significant
15
16 bias in the comparison between both datasets. To reduce this bias, monthly average
17
18 estimates of the SSS concentration (3 samples each month) and 8-day composites
19
20 (between 3 and 4 reflectance estimates each month) are used. Because MODIS images
21
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
25
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
29
30 have not been stratified in relation to the season of the year in order to assess the
31
32 robustness of the relationship.
33
34
35
36
37
38
39
40

41 Figure 5 shows the relationship between the water endmember reflectance extracted
42
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
46
47 reflectance as a function of SSS concentration with no saturation up to 200 mg/l. A
48
49 reflectance / SSS concentration linear model has been calibrated using bootstrap
50
51 resampling techniques and York least square regression (York et al., 2004) that
52
53 accounts for uncertainties in both variables.
54
55
56
57
58
59
60
61
62
63
64
65

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 δ and the objects omitted from the resampled set to compute the
7 RMSE ε . 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

2
3
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 m³/s
23 with a coefficient of variation of 6.2 %. Between 1996 and 2007, the annual mean
24 sediment discharge is about 754.10⁶ 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 m³/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 15 **CONCLUSION**

16
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
17 This work has been supported by CNPq and MCT (Ministry of Science and
18 Technologies) in Brazil, IRD and French Space Agency (CNES) in France. Our thanks
19 also go to all the HYBAM program partners in Brazil : the Brazilian Water Agency
20 (ANA), the National University of Brasilia (UnB), the Amazonas State University
21 (UEA) and the Mineral Resources Research Company (CPRM). The authors wish to
22 thank the anonymous reviewers for their comments and suggestions.

23 24 **BIBLIOGRAPHY**

25

- 1 Bhargava, D.S. and Mariam, D.W., 1990. Spectral reflectance relationships to turbidity
2 generated by different clay materials. *Photogrammetric Engineering Remote*
3 *Sensing*, 56: 225-229.
- 4 Bhargava, D.S. and Mariam, D.W., 1991. Effects of suspended particle size and
5 concentration on reflectance measurements. *Photogrammetric Engineering*
6 *Remote Sensing*, 57: 519-529.
- 7 Bordas, M.P., Lanna, A.E. and Semmelmann, F.R., 1988. Evaluation des risques
8 d'érosion et de sédimentation au Brésil à partir de bilans sédimentologiques
9 rudimentaires. In: M.P. Bordas and D.E. Walling (Editors). *Sediment Budgets*.
10 IAHS, Porto Alegre, pp. 359-368.
- 11 Callède, J. et al., 2004. Evolution du débit de l'Amazonie à Obidos de 1903 à 1999.
12 *Hydrological Sciences Journal*, 49(1): 85-97.
- 13 Calède, J., Guyot, J.L., Ronchail, J., Molinier, M. and De Oliveira, E., 2002.
14 L'Amazonie à Óbidos (Brésil) : étude statistique des débits et bilan hydrologique.
15 *Hydrological Sciences Journal*, 47(2): 321-333.
- 16 Callède, J., Kosuth, P. and De Oliveira, E., 2001. Etablissement de la relation hauteur-
17 débit de l'Amazonie à Obidos : méthode de la dénivelée normale à géométrie
18 variable. *Hydrological Sciences Journal*, 46(3): 451-463.
- 19 Calède, J., Ronchail, J., Guyot, J.L. and De Oliveira, E., 2008. Amazonian
20 deforestation : its influence on the Amazon discharge at Óbidos (Brazil) *Revue*
21 *des sciences de l'Eau*, 21(1): 59-72.
- 22 Doxaran, D., Froidefond, J.M., Lavender, S. and Castaing, P., 2002. Spectral signature
23 of highly turbid waters. Application with SPOT data to quantify suspended
24 particulate matter concentrations. *Remote Sensing of Environment*, 81: 149-161.
- 25 Dunne, T., Mertes, L.A.K., Meade, R., Richey, J.E. and Forsberg, B.R., 1998.
26 Exchanges of sediment between the floodplain and channel of the Amazon river
27 in Brazil. *Geological Society of America Bulletin*, 110(4): 450-467.
- 28 Efron, B. and Tibshirani, R.J., 1993. An introduction to the bootstrap. *Monographs on*
29 *Statistics and Applied Probability*, Vol. 57. Chapman & Hall, New York.
- 30 Espinoza Villar, J.C. et al., Submitted. Contrasting regional discharge evolutions in the
31 Amazon basin (1974 – 2004). *Journal of Hydrology*.
- 32 Espinoza Villar, J.C. et al., 2008. Spatio-temporal rainfall variability in the Amazon
33 basin countries (Brazil, Peru, Bolivia, Colombia and Ecuador), *International*
34 *journal of climatology*. DOI: 10.1002/joc.1791.
- 35 Filizola, N., 2003. Transfert sédimentaire actuel par les fleuves amazoniens. Ph.D.
36 Thesis, Paul Sabatier University, Toulouse, 292 pp.
- 37 Filizola, N. and Guyot, J.L., 2004. The use of Doppler technology for suspended
38 sediment discharge determination in the River Amazon. *Hydrological Sciences*
39 *Journal*, 49(1): 143-153.
- 40 Gibbs, R.J., 1967. Amazon rivers: Environmental factors that control its dissolved and
41 suspended load. *Science*, 156: 1734-1737.
- 42 Goulding, M., Barthem, R. and Ferreira, E., 2003. *The Smithsonian Atlas of the*
43 *Amazon*. Smithsonian Institution press, Washington and London.
- 44 Guyot, J.L., Filizola, N. and Laraque, A., 2005. Régime et bilan du flux sédimentaire de
45 l'Amazonie à Óbidos (Pará, Brésil) de 1995 à 2003, *Proceedings of Sediment*
46 *Budget symposium held during the Seventh IAHS Scientific Assembly*. IAHS
47 *Publication vol. 291, Foz do Iguaçu*, pp. 347-354.
- 48 Guyot, J.L., Filizola, N., Laraque, A. and Seyler, P., 1999. La variabilité saisonnière des
49 flux sédimentaires dans le bassin de l'Amazonie, *Conference on hydrological and*
50 *geochemical processes in large-scale river basins*, Manaus, Brazil.

- 1 Hinton, J.C., 1991. Application of eigenvector analysis to remote sensing of coastal
2 water quality. *International Journal of Remote Sensing*, 12: 1441-1460.
- 3 Marengo, J.A., 2004. Interdecadal variability and trends of rainfall across the Amazon
4 basin. *Theoretical and Applied Meteorology*, 78: 79-96.
- 5 Martinez, J.M. et al., Submitted. Surface water quality monitoring of rivers with
6 MODIS data - Application to the Amazon River. *Remote Sensing of*
7 *Environment*.
- 8 Martinez, J.M. et al., 2007. Surface water quality monitoring in large rivers with
9 MODIS data - Application to the Amazon basin, *International Geosciences and*
10 *Remote Sensing Symposium*, Barcelona.
- 11 Martinez, J.M., Maurice-Bourgoin, L., Kosuth, P., Seyler, F. and Guyot, J.L., 2003.
12 Analysis of multitemporal MODIS and Landsat 7 images acquired over
13 Amazonian floodplain lakes for suspended sediment concentration retrieval,
14 IGARSS, Toulouse, France.
- 15 Martinez, J.M., Maurice-Bourgoin, L., Moreira-Turcq, P., Seyler, F. and Guyot, J.L.,
16 2004. Amazon floodplain water quality monitoring using MERIS and MODIS
17 data, *ENVISAR and ERS Symposium*. ESA Publication, Salzburg, pp. 10.
- 18 Meade, R.H., Dunne, T., Richey, J.E., Santos, U.M. and Salati, E., 1985. Storage and
19 remobilization of suspended sediment in the lower Amazon river of Brazil.
20 *Science*, 228: 488-490.
- 21 Meade, R.H. et al., 1979. Sediment loads in the Amazon River. *Nature*, 278: 161-163.
- 22 Mertes, L.A.K., Smith, C.T. and Adams, J.B., 1993. Estimating Suspended Sediment
23 Concentrations in Surface Waters of the Amazon River Wetlands from Landsat
24 Images. *Remote Sens. Environ.*, 43: 281-301.
- 25 Molinier, M., Guyot, J.L., Oliveira, E. and Guimaraes, V., 1996. Les regimes
26 hydrologiques de l'Amazonie et de ses affluents. In: P. Chevallier and B.
27 Pouyaud (Editors). *L'hydrologie tropicale: geoscience et outil pour le*
28 *developpement*. AIHS, Paris, pp. 209-222.
- 29 Novo, E.M.L.M., Hamsom, J.D. and Curran, P.J., 1989a. The effect of sediment type on
30 the relationship between reflectance and suspended sediment concentrations.
31 *International journal of remote sensing*, 10: 1283-1289.
- 32 Novo, E.M.L.M., Hamsom, J.D. and Curran, P.J., 1989b. The effect of viewing
33 geometry and wavelength on the relationship between reflectance and suspended
34 sediment concentration. *International journal of remote sensing*, 10: 1357-1372.
- 35 Ritchie, J.C. and Cooper, C.M., 1988. Comparison of measured suspended sediment
36 concentrations with suspended sediment concentrations estimated from Landsat
37 MSS data. *International journal of remote sensing*, 9: 379-387.
- 38 Ritchie, J.C., Cooper, C.M. and Yongqing, J., 1987. Using Landsat Multispectral
39 Scanner data to estimate suspended sediments in Moon Lake, Mississippi.
40 *Remote Sensing of Environment*, 23: 65-81.
- 41 Strasser, M.A., Vinzon, S.B. and Kosuth, P., 2002. Bottom structures geometry of the
42 Amazon river, *International Conference on Fluvial Hydraulics*, Louvain-la-
43 Neuve, pp. 1185-1193.
- 44 Wehrens, R., Putter, H. and Buydens, L.M.C., 2000. The bootstrap: a tutorial.
45 *Chemometrics and Intelligent Laboratory Systems*, 54: 35-52.
- 46 York, D., Evensen, N.M., López Martínez, M. and De Basabe Delgado, J., 2004.
47 Unified equations for the slope, intercept, and standard errors of the best straight
48 line. *American Journal of Physics*, 72(3): 367-375.

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 km².
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 m³/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
[Click here to download high resolution image](#)

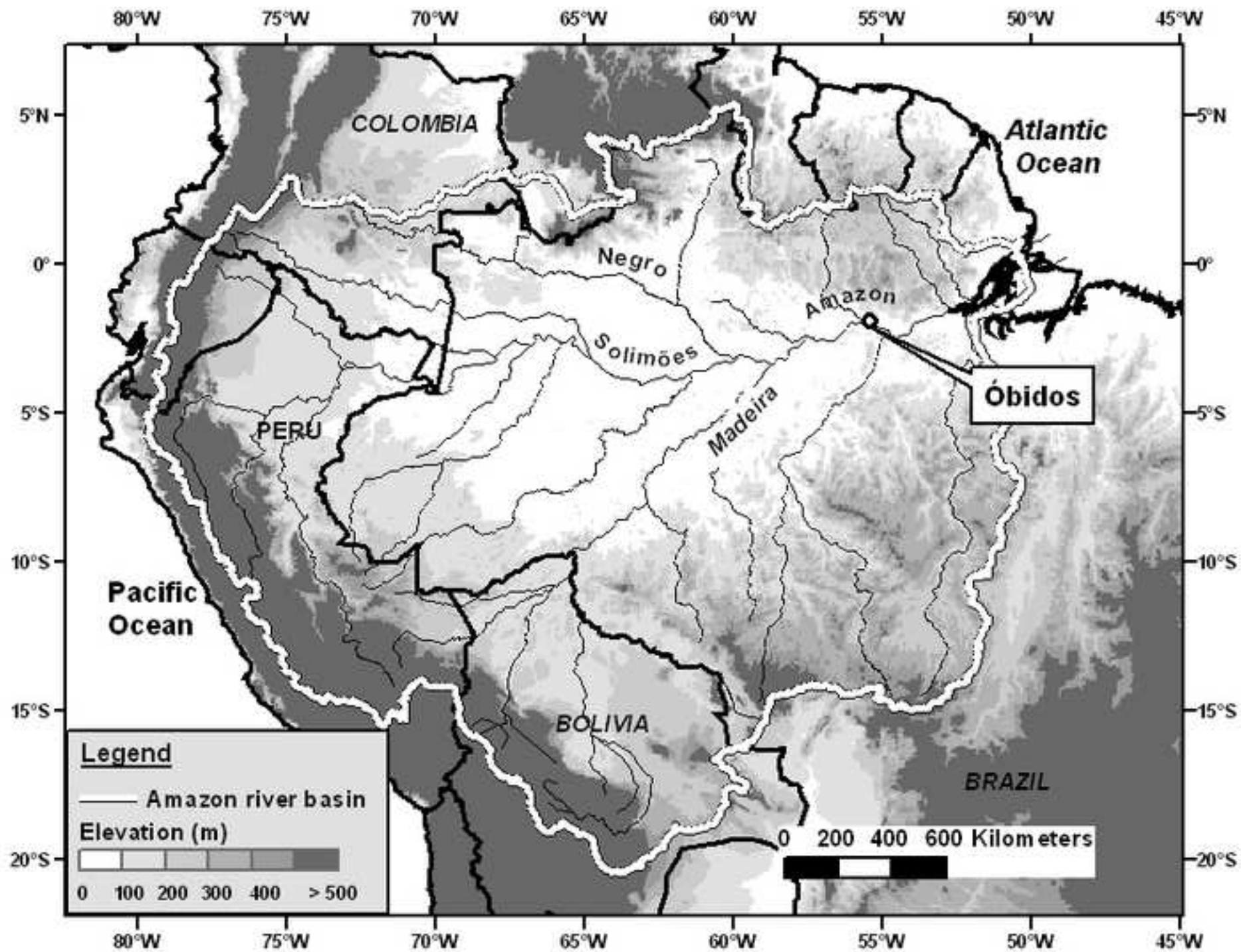


Figure 2
[Click here to download high resolution image](#)

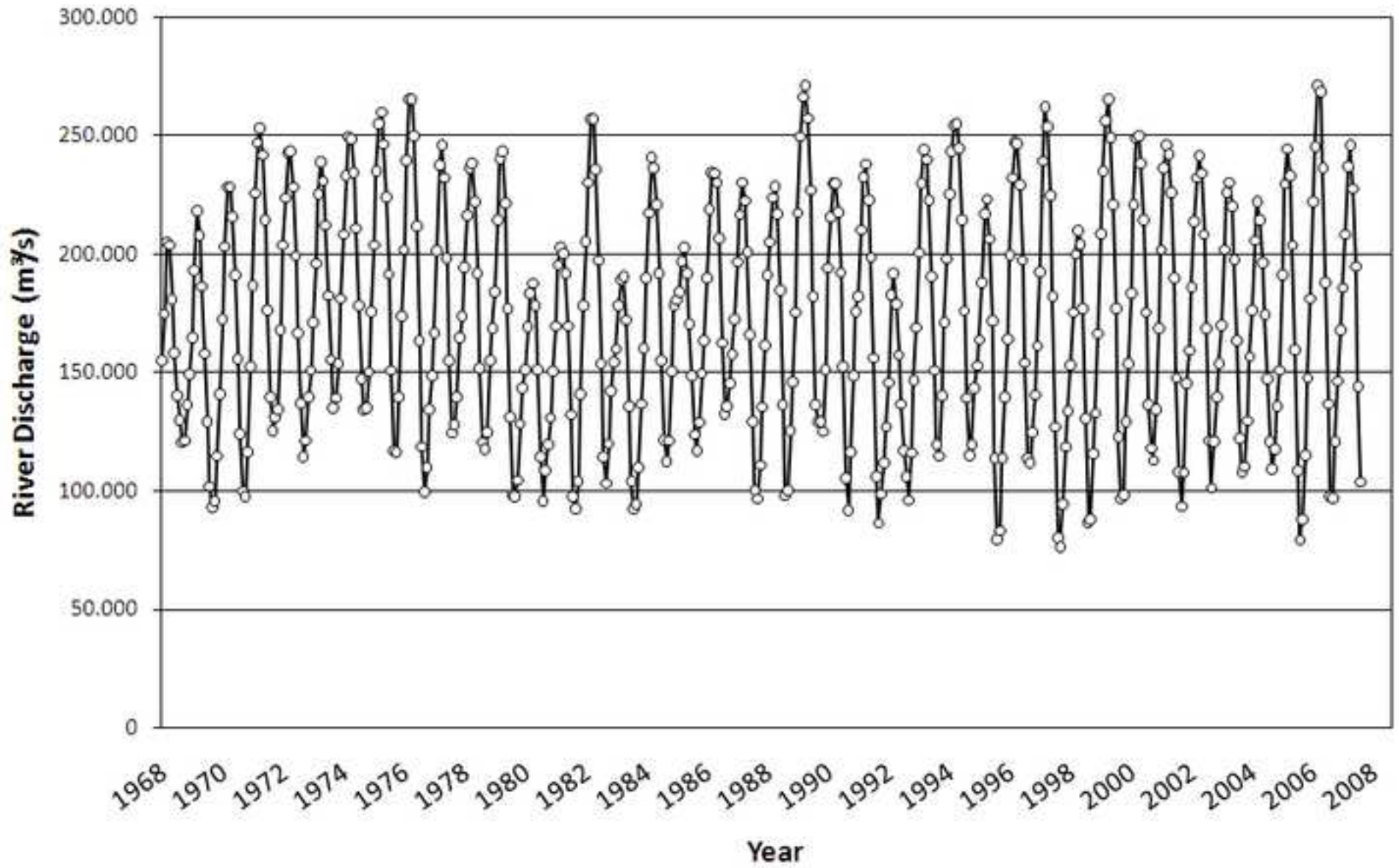


Figure 3
[Click here to download high resolution image](#)

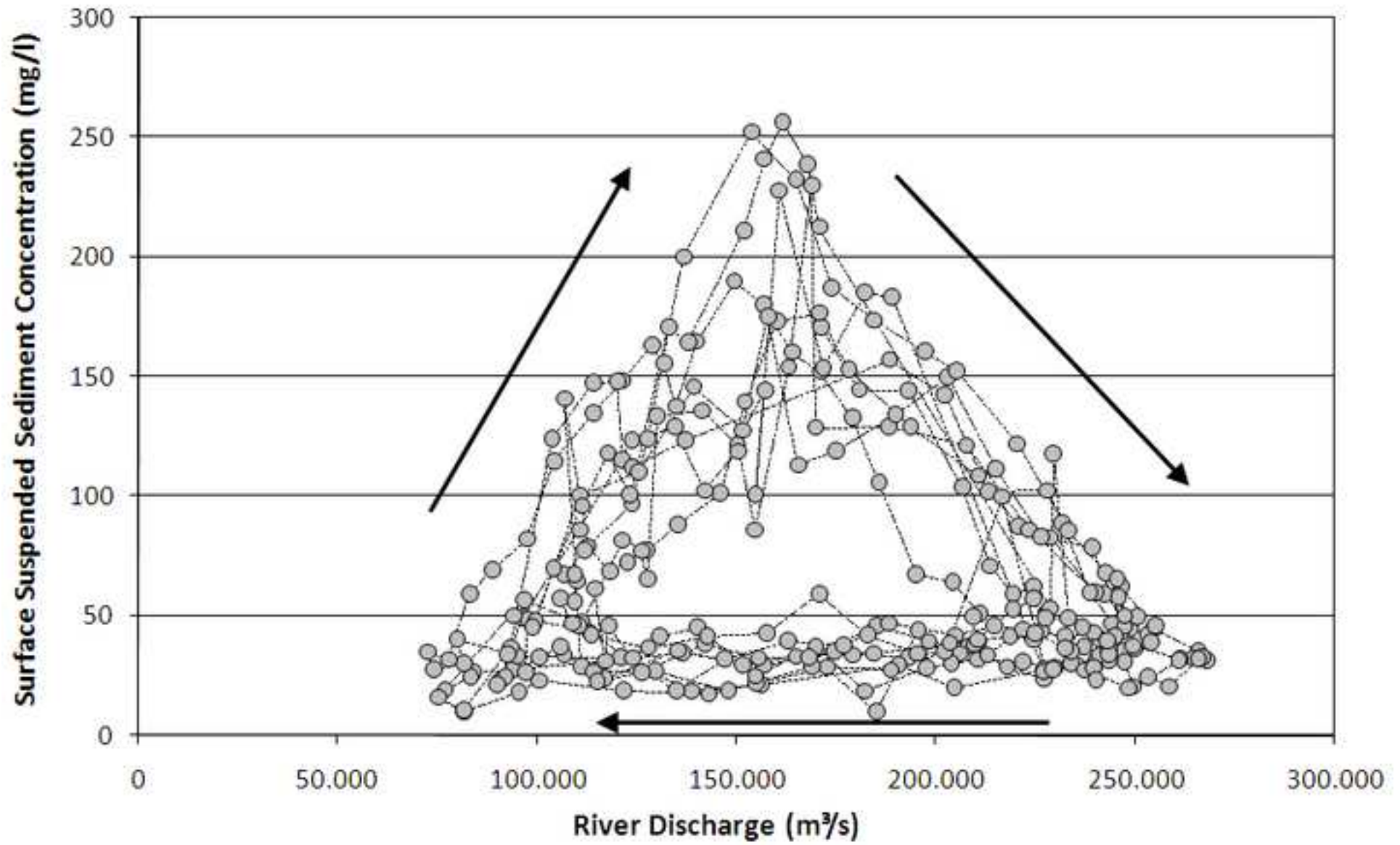


Figure 4
[Click here to download high resolution image](#)

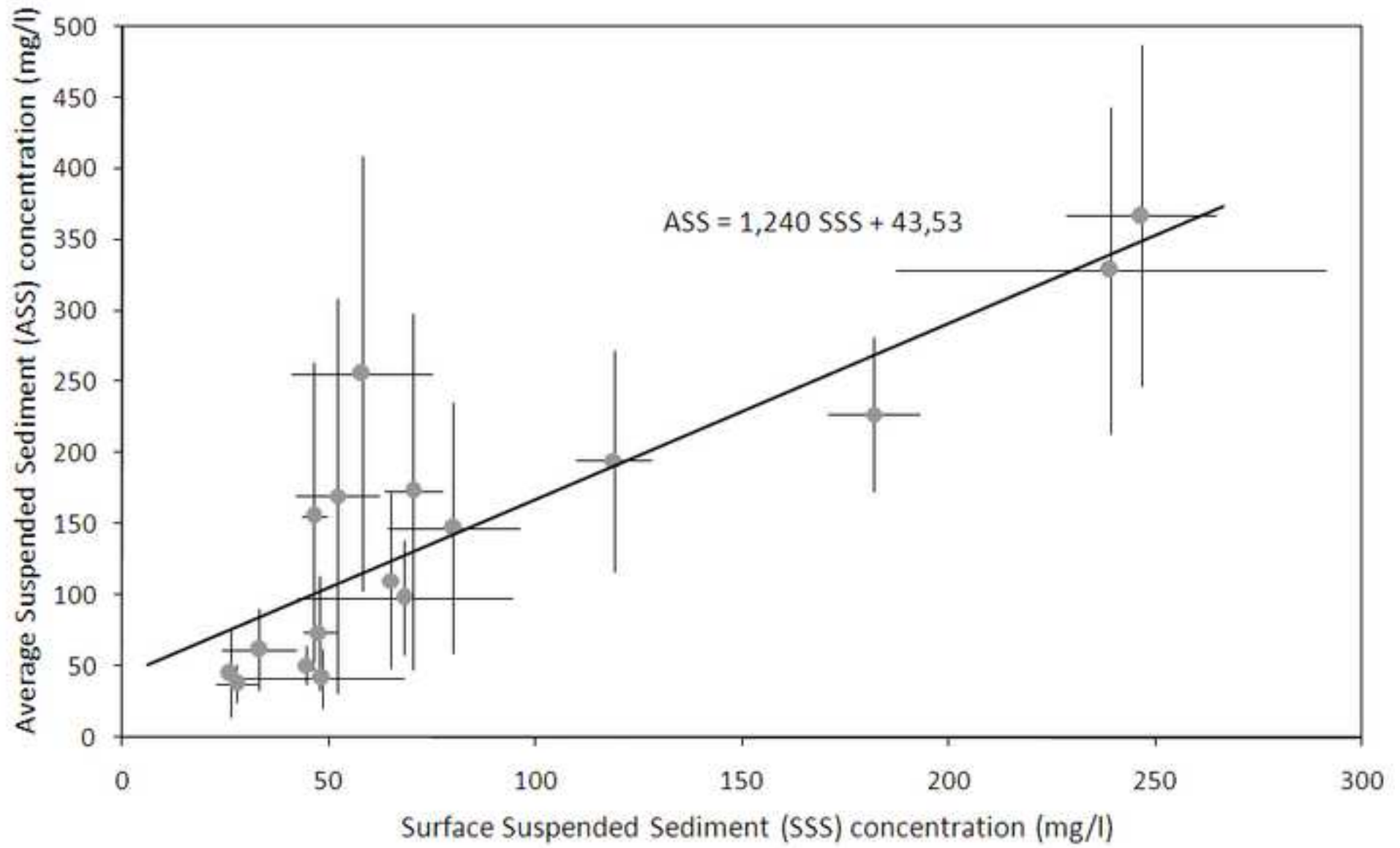


Figure 5
[Click here to download high resolution image](#)

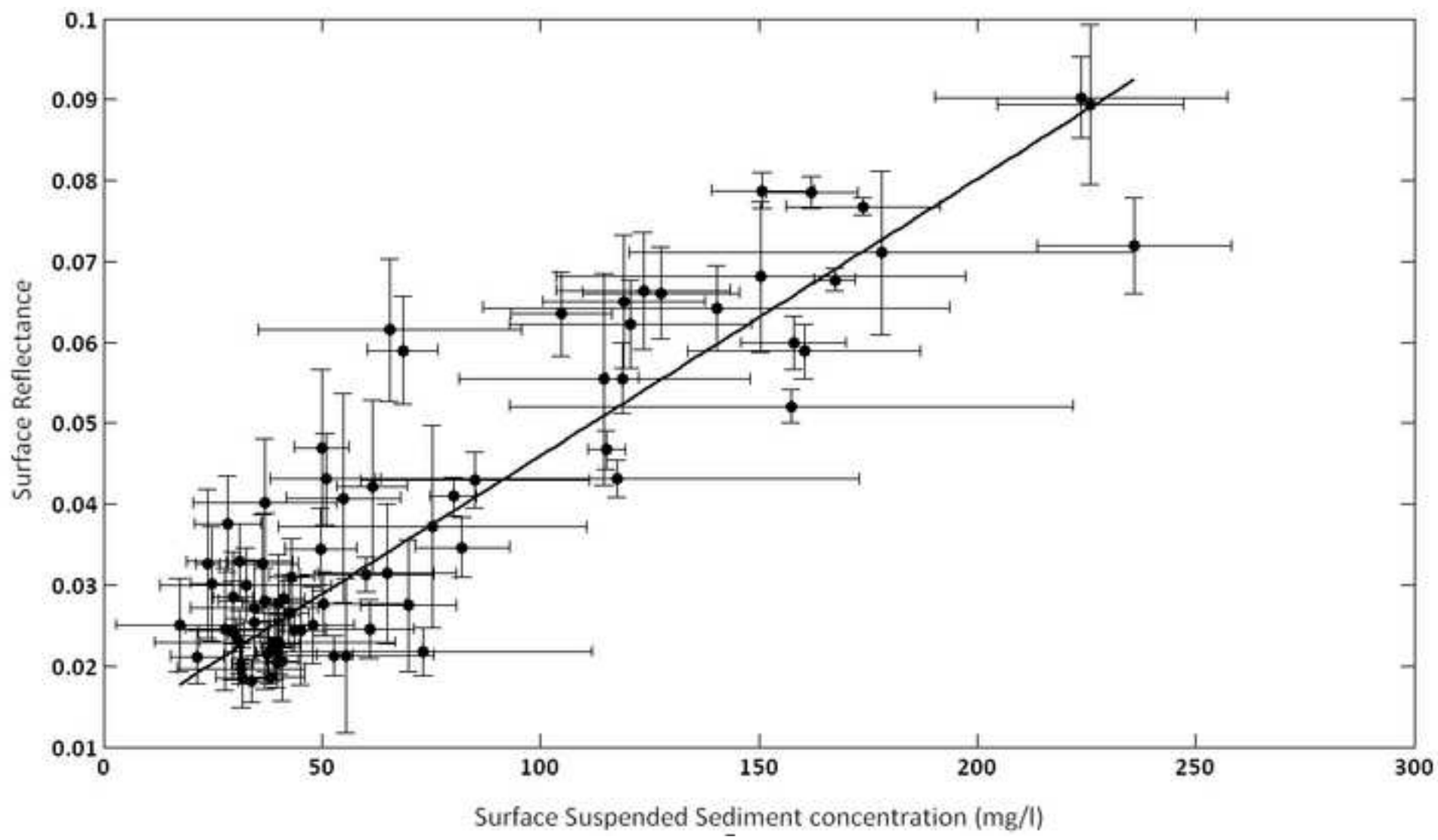


Figure 6
[Click here to download high resolution image](#)

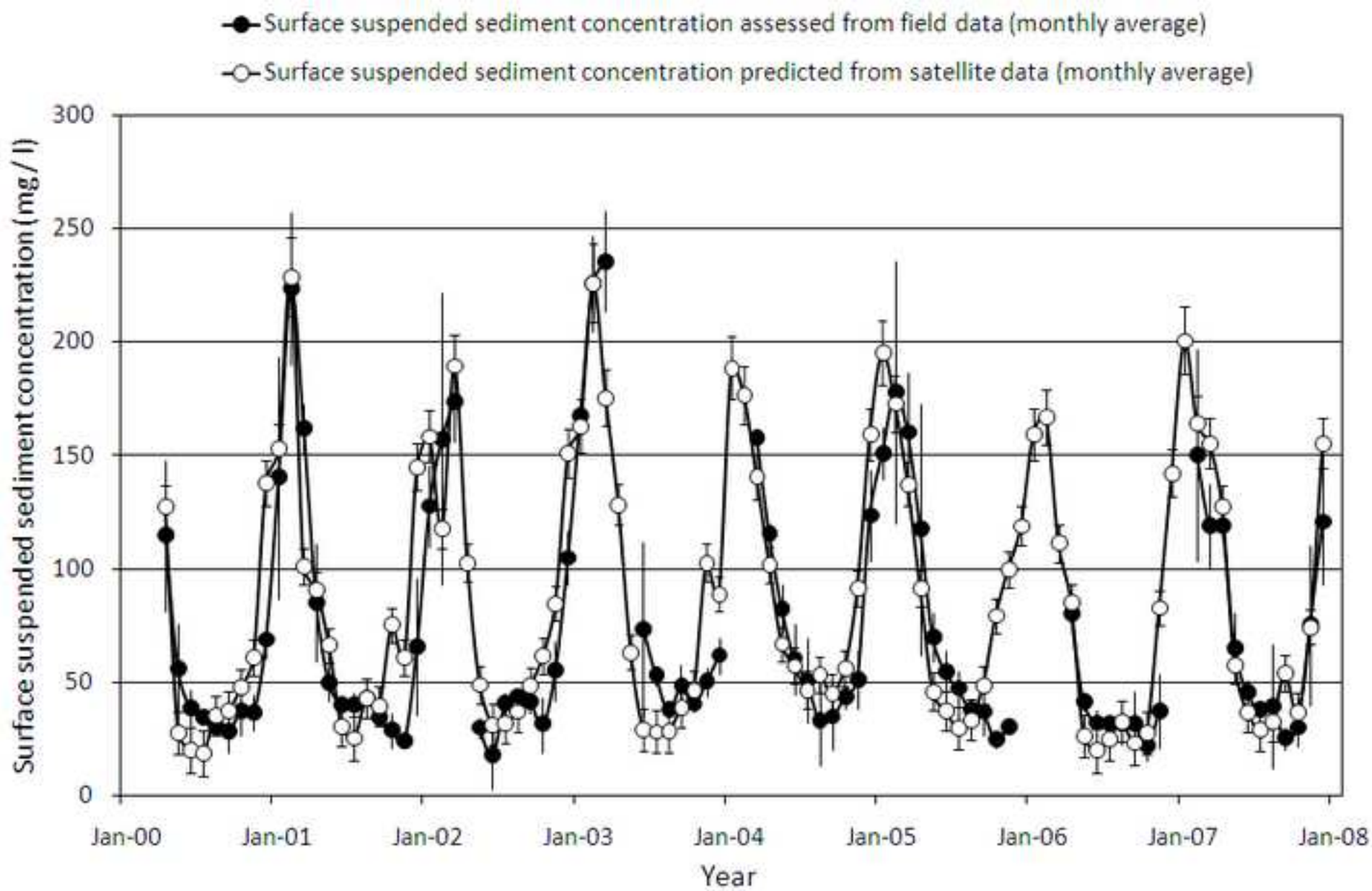


Figure 7
[Click here to download high resolution image](#)

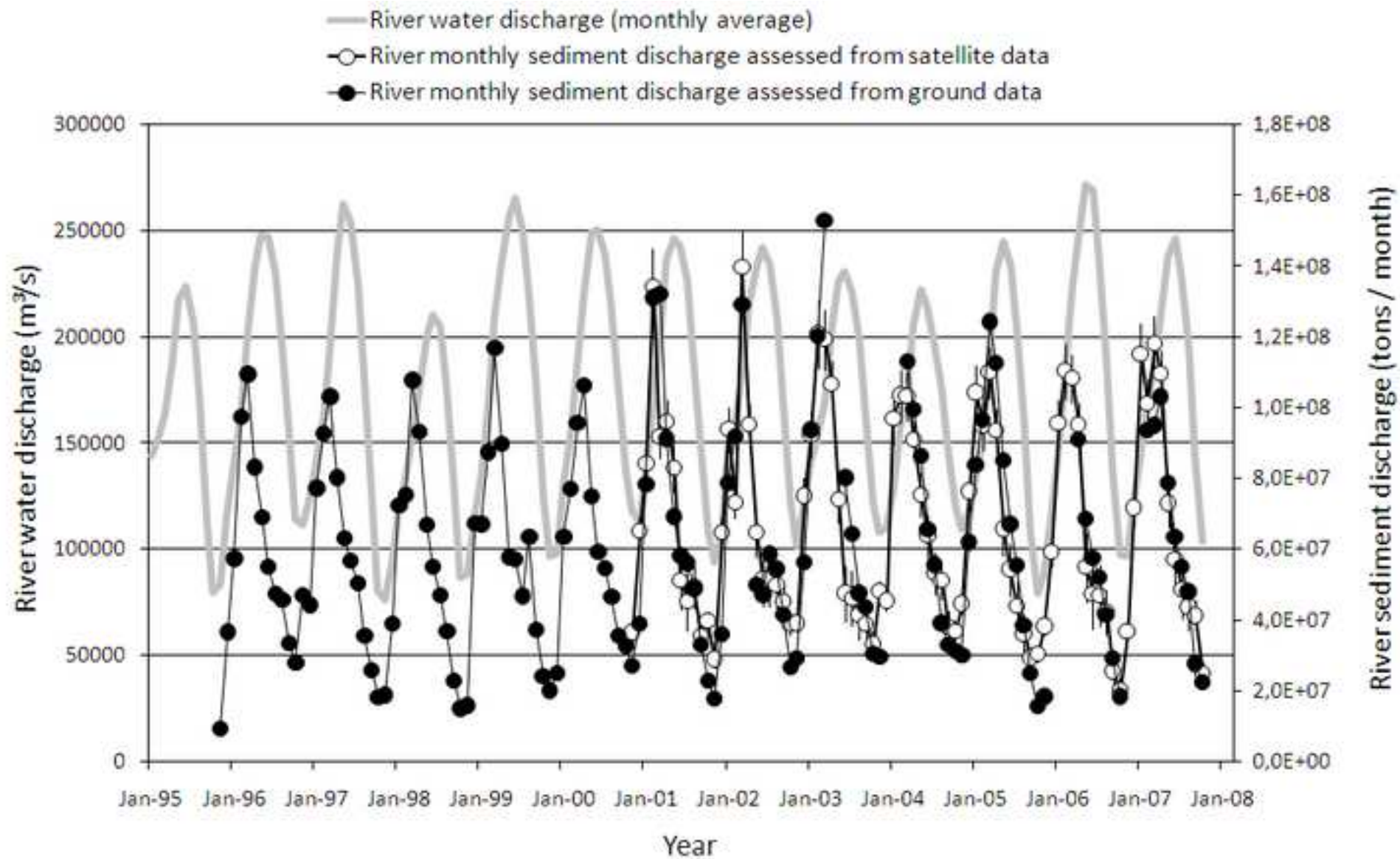


Figure 8
[Click here to download high resolution image](#)

