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

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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.

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

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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.

KEYWORDS : Hydrology, sediment concentration, Amazon, remote sensing, HYBAM, MODIS.

INTRODUCTION

With a drainage basin area of 6.1 10^6 km^2 (Goulding et al., 2003) and a mean annual discharge estimated at 209 000 m^3/s at the river mouth (Molinier et al., 1996), the Amazon basin is the largest river system in the world. Given its large size, the Amazon basin experiences significant climate variability (Marengo, 2004). At Óbidos, the most downstream gauged station on the Amazon River in Brazil offering long term hydrological monitoring, annual data for the 1903–1999 period indicate a steadily increasing discharge trend (+9%) over the century, and a recent period of decrease over the last decade of the past century (Callède et al., 2004). In recent decades, several suspended sediment discharge budgets have been published for the Amazon (Dunne et al., 1998; Filizola, 2003; Gibbs, 1967; Meade et al., 1985; Meade et al., 1979), but the time variability of the sediment concentration, based on 10-day sampling has only been recently made available thanks to the HYBAM program (http://www.ore-hybam.org).

Gibbs (1967) provides the first estimate of the sediment discharge of the Amazon River at the Óbidos station of about 500 million tons per year using data from only two sampling campaigns at low and high water levels. Using two additional sampling campaigns conducted during a high water period, Meade (1979) got a higher sediment discharge of 900 million tons per year. From the results of eight CAMREX sampling campaigns, Meade et al. (1985) obtained an even higher sediment discharge value of 1200 million tons per year. More recently, using quarterly data from the Brazilian water quality network, Bordas et al. (1988) and subsequently Filizola et al. (1999) derived a new estimate for the annual sedimentary flux at the Óbidos station of 600 million tons per year, a value close to the first estimate provided by Gibbs. Based on a 10-day sampling from the HYBAM program, Guyot et al. (2005) suggest an increasing sediment discharge from 2000 to 2003 and also noted that the trend in suspended sediment concentration is not correlated with discharge. In other words, it is not possible to derive a simple relationship between river flow and suspended sediment concentration. It is therefore not possible to derive sediment discharge from the daily measurement of river water flow alone but instead, simultaneous monitoring of sediment concentration and of water discharge is required. In the current study, based on an updated HYBAM dataset (1995-2007) and surface suspended sediment concentrations calculated by MODIS reflectance inversion (Martinez et al., 2004) for the 2000-2007 period, new results are presented highlighting improved monitoring of suspended sediment. To quantify the Amazon River mean annual sediment discharge as well as the inter and intra-annual variability, various datasets from the Óbidos station have been used, namely :

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

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

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

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

DATA AND METHODS

Surface-Suspended Sediment Estimates

The Óbidos hydrological station managed by the Brazilian water agency (www.ana.gov.br) has been furnishing uninterrupted data since 1968. At Óbidos, the watershed covers 4.8×10^6 km² and the river mouth is located 900 kilometers downstream (Figure 1). Discharge has been derived from the rating curve established within the HYBAM project (Callede et al., 2002; Callède et al., 2001). Figure 2 shows the monthly average Amazon River discharge from 1968 to 2007. The Amazon River average annual discharge is 173,000 m^3/s, with, during the last decade, a noteworthy dry year (-15%) in 1997/1998 marked by a strong El Niño episode. The river discharge shows a very stable value over the period considered for the study of sediment discharge : 1995-2007.

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

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

Average suspended sediment concentration

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

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

$$ASS = 1.24 \; . \; SSS + 43.5 \qquad (1)$$

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

Remote sensing images

Numerous papers deal with the sensitivity of remote sensing reflectance to the suspended sediment concentration in oceanic and inland waters. A significant number of researchers have reported a strong positive correlation between surface suspended concentrations and spectral radiance (Bhargava and Mariam, 1990; Bhargava and Mariam, 1991; Doxaran et al., 2002; Hinton, 1991; Martinez et al., 2004; Mertes et al., 1993; Novo et al., 1989a; Novo et al., 1989b; Ritchie and Cooper, 1988; Ritchie et al., 1987) and have noted that the relation may depend on the range of concentration, water types and suspended matter origin. Most studies agree that the best correlation between reflectance and SSC is between 700 and 800 nm in turbid inland waters. In this study we propose to use data from the latest generation of spaceborne sensors such as MODIS that are promising in terms of inland water monitoring because they offer the spatial resolution and spatial coverage that are compatible with the dimensions of river systems while allowing for fine temporal resolution.

The Collection 5 atmospherically-corrected surface reflectance products from the Terra and Aqua MODIS spaceborne sensors are utilized in this study. The MODIS data product MOD09Q1 (Terra on-board sensor) and MYD09Q1 (Aqua on-board sensor) provides calibrated reflectance for two radiometric bands measured at a 250 m pixel resolution while offering near-daily time coverage over tropical areas (http://modis.gsfc.nasa.gov). Band 1 is centered at 645 nm and band 2 at 858.5 nm (infrared). MODIS surface reflectance 8-day composite data were acquired between March 2000 and October 2007 from the NASA Earth Observing System (EOS) data gateway. We chose composite images because i) the 8-day composite is compatible with the 10-day field measurement sampling frequency; ii) it reduces the amount of data to be analyzed as a large number of daily images cannot be used in view of the persistent cloud cover and iii) it significantly reduces the directional reflectance effects and atmospheric artifacts. For each date, the composites from Terra and Aqua are automatically scanned and the image with the lowest cloud coverage is selected. When both composites exhibit low cloud coverage, the composite acquired with the lowest satellite viewing angle is preferred.

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

We calibrate the reflectance – surface suspended sediment concentration by comparing MODIS images and SSS measurements assessed every 10 days between 2000 and 2007. Strong cloud cover typical of tropical areas makes it difficult to have the MODIS acquisition date matching the field sampling date which likely introduces a significant bias in the comparison between both datasets. To reduce this bias, monthly average estimates of the SSS concentration (3 samples each month) and 8-day composites (between 3 and 4 reflectance estimates each month) are used. Because MODIS images have only been available since March 2000, a total of 93 months can be theoretically used for comparison purposes. Nevertheless, because the 10-day measurement dataset has suffered various interruptions, a total of 77 out of 93 months was selected for calibration and validation of the reflectance – SSS concentration relationship. Samples have not been stratified in relation to the season of the year in order to assess the robustness of the relationship.

Figure 5 shows the relationship between the water endmember reflectance extracted from the MODIS infrared band and the monthly average SSS concentration measurements derived from the 10-day samples. The reflectance shows an increasing reflectance as a function of SSS concentration with no saturation up to 200 mg/l. A reflectance / SSS concentration linear model has been calibrated using bootstrap resampling techniques and York least square regression (York et al., 2004) that accounts for uncertainties in both variables.

The general bootstrap approach involves resampling of the dataset with repeated replacements (Wehrens et al., 2000) to generate an empirical estimate of the sampling distribution. Accordingly, a large number of 'bootstrap samples' is generated, each with the same size as the original dataset. For each bootstrap sample, a linear model using York regression is built and tested against those objects present in the sample to compute the RMSE δ and the objects omitted from the resampled set to compute the RMSE ε. To achieve a better estimate of the prediction error, we use the *0.632 bootstrap* b_{632}. Practical and theoretical evidence suggests that this is a very reliable estimator (Efron and Tibshirani, 1993). The final bootstrap estimate is the average value of b_{632} over N iterations of the procedure :

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

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

RESULTS

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

Figure 7 shows the monthly average sediment discharge at the Óbidos station computed with field measurements and satellite images. Monthly average sediment discharge is calculated multiplying monthly average discharge records times monthly average ASS concentration. Monthly average discharge is calculated by averaging the daily discharge records. ASS concentration data are assessed from SSS concentration estimates using equation (1). Monthly average ASS concentration is calculated by averaging either the HYBAM 10-day estimates or the MODIS-derived 8-day estimates. Direct comparison of both sediment discharge budgets can be carried out on 2 cycles (2001 and 2005) for which complete records are available for both field measurements and satellite images. The relative difference is -3.0 % (sediment discharge of 788.10^6 tons with field measurements and of 811.10^6 tons using satellite images) for the hydrological cycles of 2001 (November 2000 – October 2001) and +1.8 % for 2005 (sediment discharge of 797.10^6 tons with field measurements and of 782.10^6 tons using satellite images). Field-derived and satellite-derived SSS estimates complement each other for monitoring the suspended sediment discharge. On the one hand, the field measurements provide estimates at fixed and regular dates but fail to provide an assessment of the sediment concentration heterogeneity across the river surface. Additionally, the monitoring network is prone to many potential sources of failure including variable sampling location, operator reliability or loss of samples. When a problem occurs, it may take a few weeks or even months before it can be fixed, resulting in a significant loss of data. On the other hand, satellite measurements must first be calibrated using field measurements and availability depends primarily on the weather. Furthermore, during the rainy season, a clear sky is a remote possibility which may lead to interruptions in the monitoring service. Nonetheless, MODIS images were constantly available for 93 consecutive months. This shows that the daily coverage offered by the MODIS sensor is a prerequisite for long term monitoring of tropical areas by remote sensing means. Finally, satellite imagery provides unprecedented knowledge of the surface heterogeneity for much larger areas than a monitoring network would allow.

Yearly averaged field and satellite-derived suspended sediment discharges were merged to produce a continuous assessment of the inter-annual variability of the sediment discharge of the Amazon River. When available and complete, field-based data records were considered while the remote sensing data was used for the period without complete field measurements (2002, 2003, 2004, 2006 and 2007 cycles). Thus, a complete and continuous assessment of the sediment discharge of the Amazon River was obtained from 1995 to 2007, representing twelve consecutive hydrological cycles (with the beginning of a hydrological cycle in November). Yearly average discharge and yearly average sediment discharge were calculated summing the monthly estimates for each variables. Over this period, the mean river discharge has been 173,000 m^3/s with a coefficient of variation of 6.2 %. Between 1996 and 2007, the annual mean sediment discharge is about 754.10^6 tons / year with a coefficient of variation of 8.6 %. This value is consistent with previous studies by Bordas et al. (1988), Filizola (2003) and Guyot et al. (2005) and much higher than the river bed transport, assessed to be of about 4.7 10^6 tons / year at this station (Strasser et al., 2002). The 1997/1998 hydrological cycle shows a very low discharge (-15 % relative to the rest of the time series). If we remove this particular hydrological cycle from the statistics, the mean river discharge remains almost constant at 175,000 m^3/s but the coefficient of variation falls to 4.1 %. Clearly, the sediment discharge exhibits a much greater variation over time than the discharge. Finally, the intra-annual variation in sediment discharge is much more regular than inter-annual variation. For example, half the annual sediment budget (51 % on average) is discharged between January and April for every year considered.

Over the 1996-2007 period, an increasing trend of sediment discharge significant at the 99% level can be noticed. More specifically, the Amazon River sediment discharge time series exhibits two contrasting periods, that is, before and after the 2001 hydrological cycle. Before 2001, the annual mean sediment discharge was approximately 688.10^6 tons / year (coefficient of variation of 4.4 %). Then the annual mean sediment discharge increased to 801.10^6 tons / year (coefficient of variation of 4.0 %) accounting for an increase of 16 % in terms of absolute sediment discharge between both periods. These observations suggest a significant change in the sediment transport regime of the Amazon River even though the river discharge fails to exhibit a specific trend and the time series is not long enough to reach a definitive conclusion on this topic.

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

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

CONCLUSION

This study contributes to the quantification of erosion processes in one of the main surviving natural ecosystems. Although our work only covers the last 12 years, it demonstrates the interest of new techniques such as remote sensing for long term monitoring of inland waters. The surface reflectance data appears to be robustly linked with the suspended sediment concentration at the river surface over a large range of concentration and for several consecutive hydrological cycles. By combining an excellent temporal resolution and a fine calibration quality, MODIS data may be used operationally along field observations to provide more observations in poorly gauged basins, such as the large-scale river basins. However, the quest for a universal algorithm for suspended sediments retrieval from satellite data is never likely to succeed because the scattering efficiency of suspended particles is very much a function of average particle size that is quite variable from one catchment to another. Thus, local calibration of satellite data would have to be developed and tested for each river basin.

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

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FIGURE CAPTIONS

Figure 1 : Location of Óbidos on the Amazon River, 900-km upstream from the river mouth. At Óbidos, the Amazon River has received most of its tributaries including the Madeira River (the main tributary in terms of suspended sediment concentration) and the Negro river (volumetrically the main tributary). At Óbidos, the drainage area is 4.8 10^6 km².

Figure 2: Monthly average river discharge of the Amazon River at Óbidos. Over the period considered in this study (1968-2007), the average discharge is 173,000 m³/s.

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

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

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

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

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

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

Figure 1
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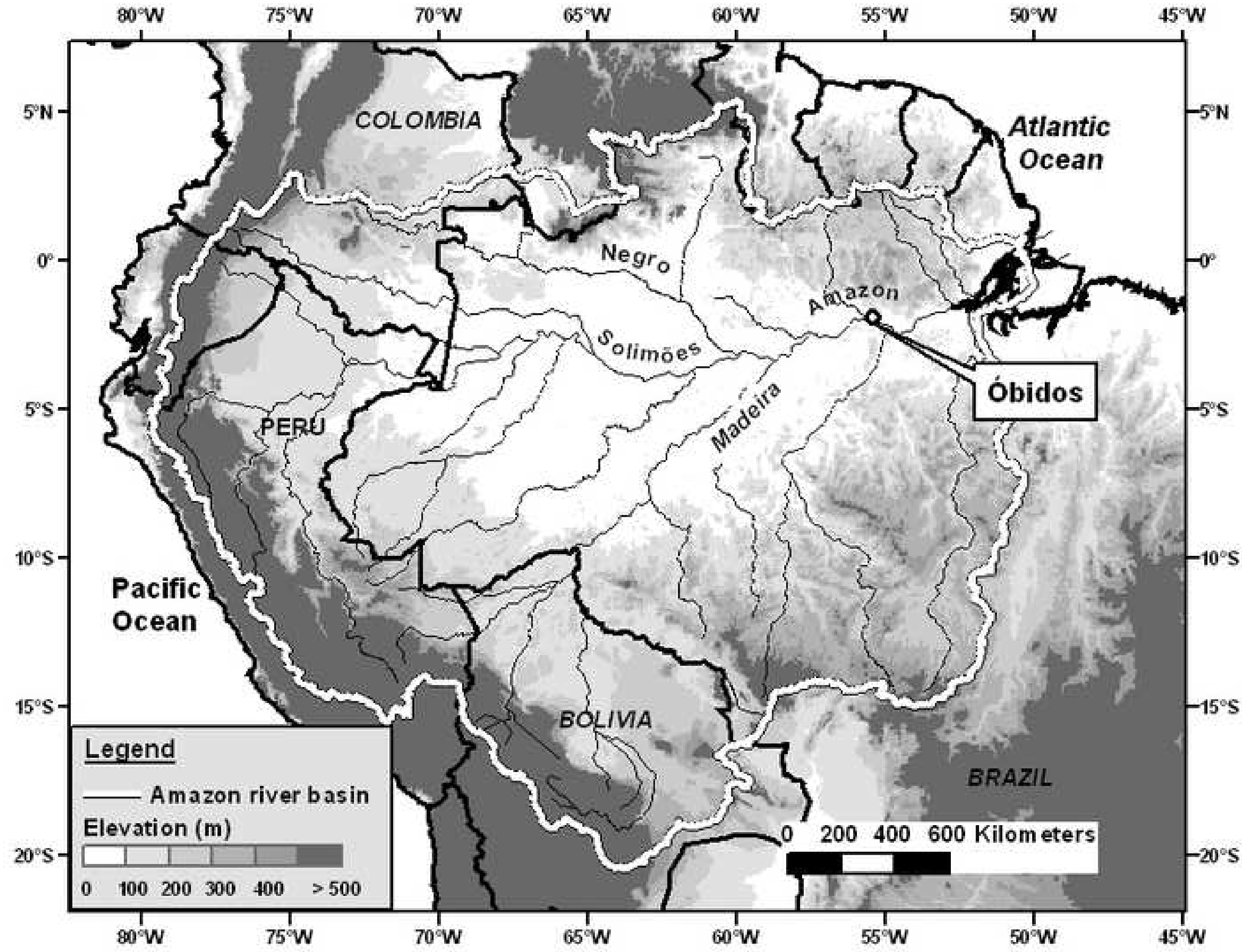

Figure 2
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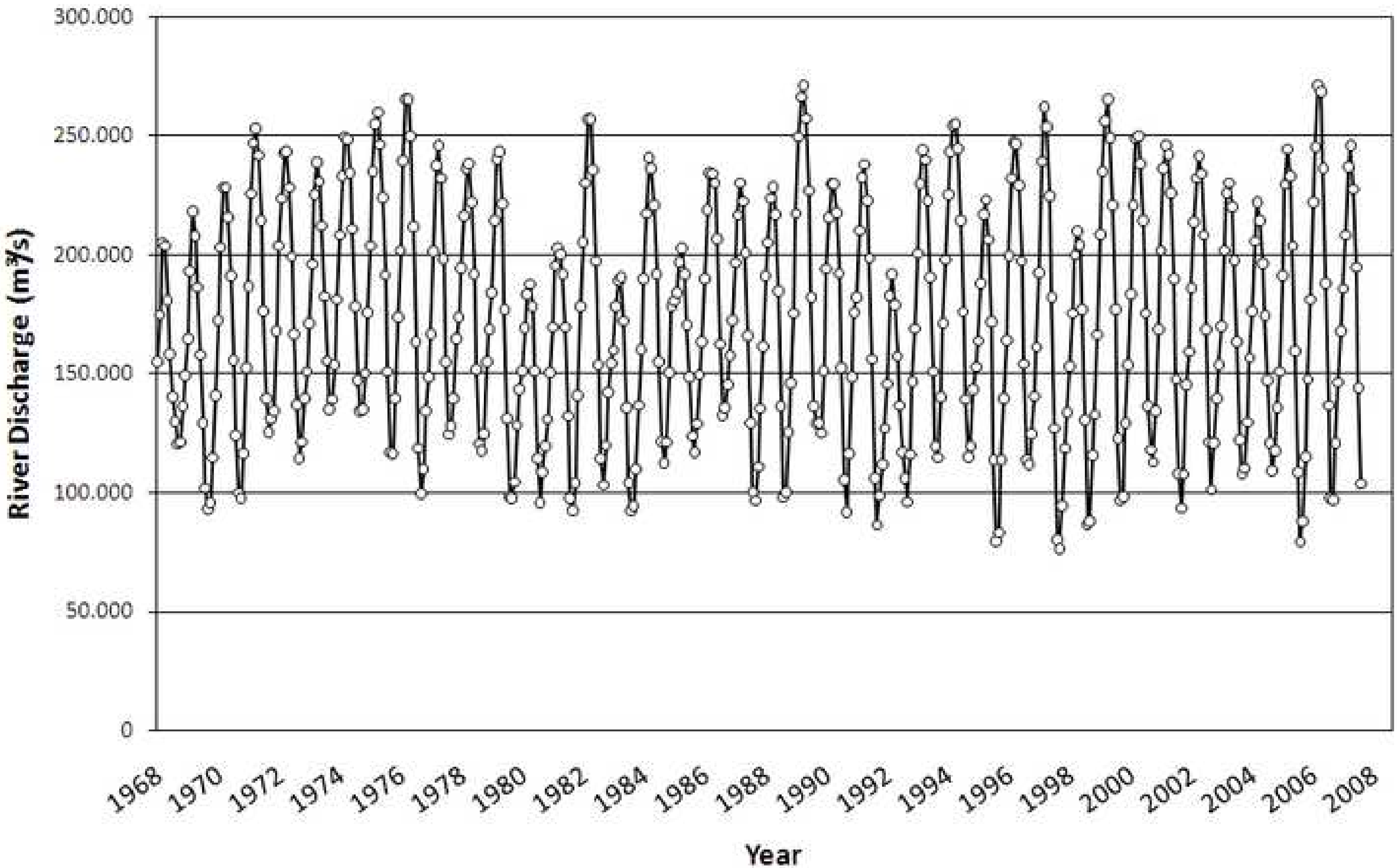

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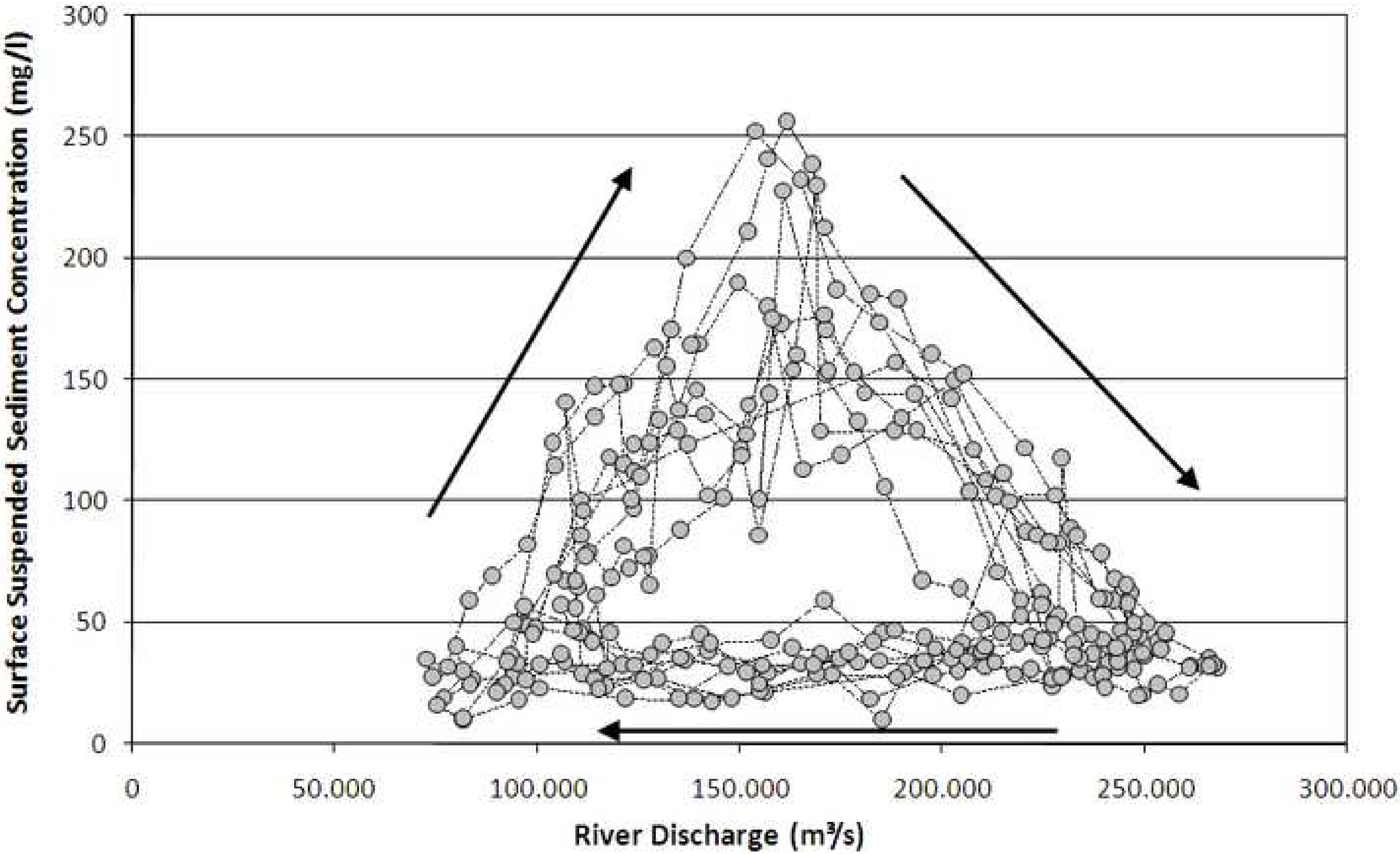

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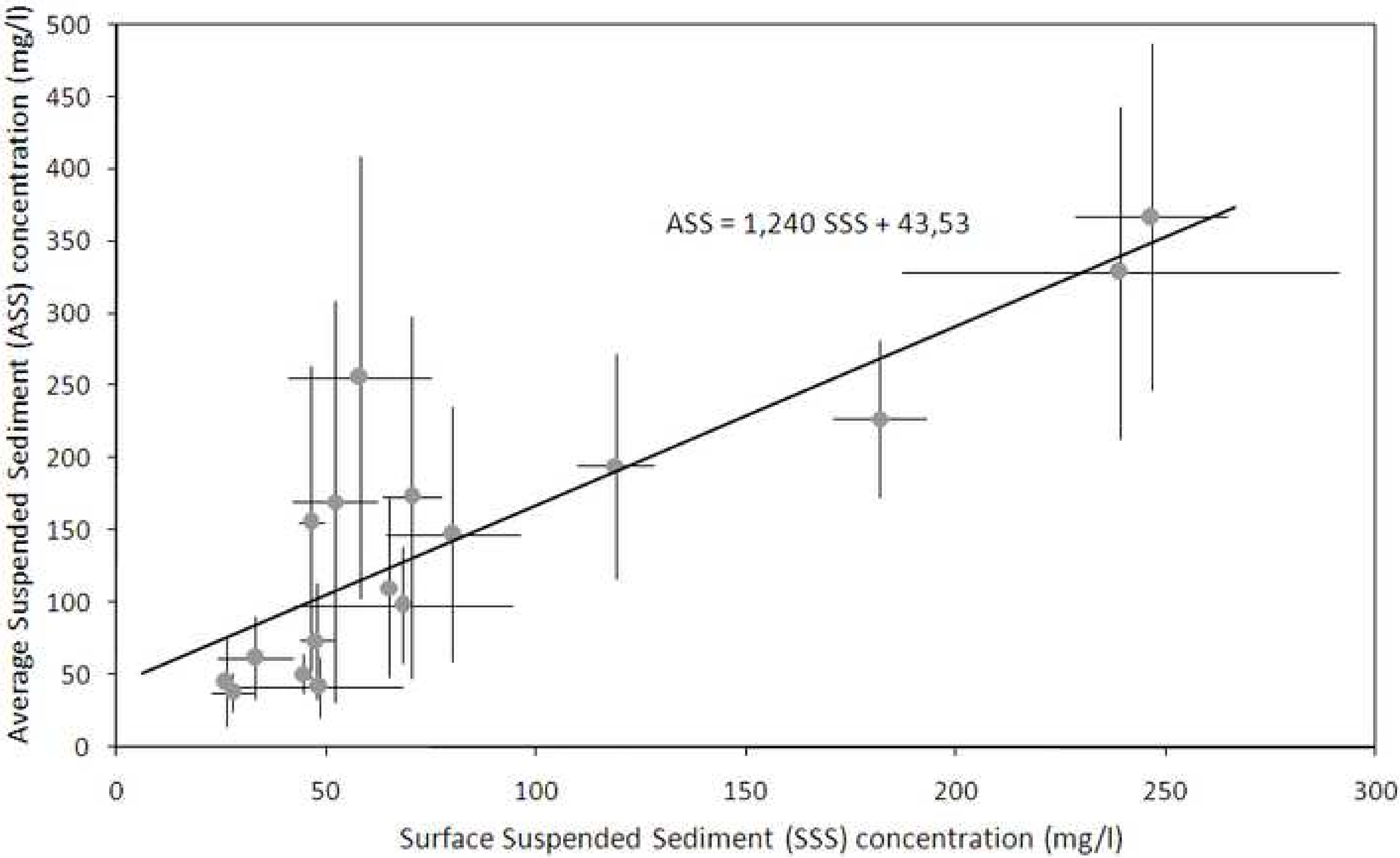

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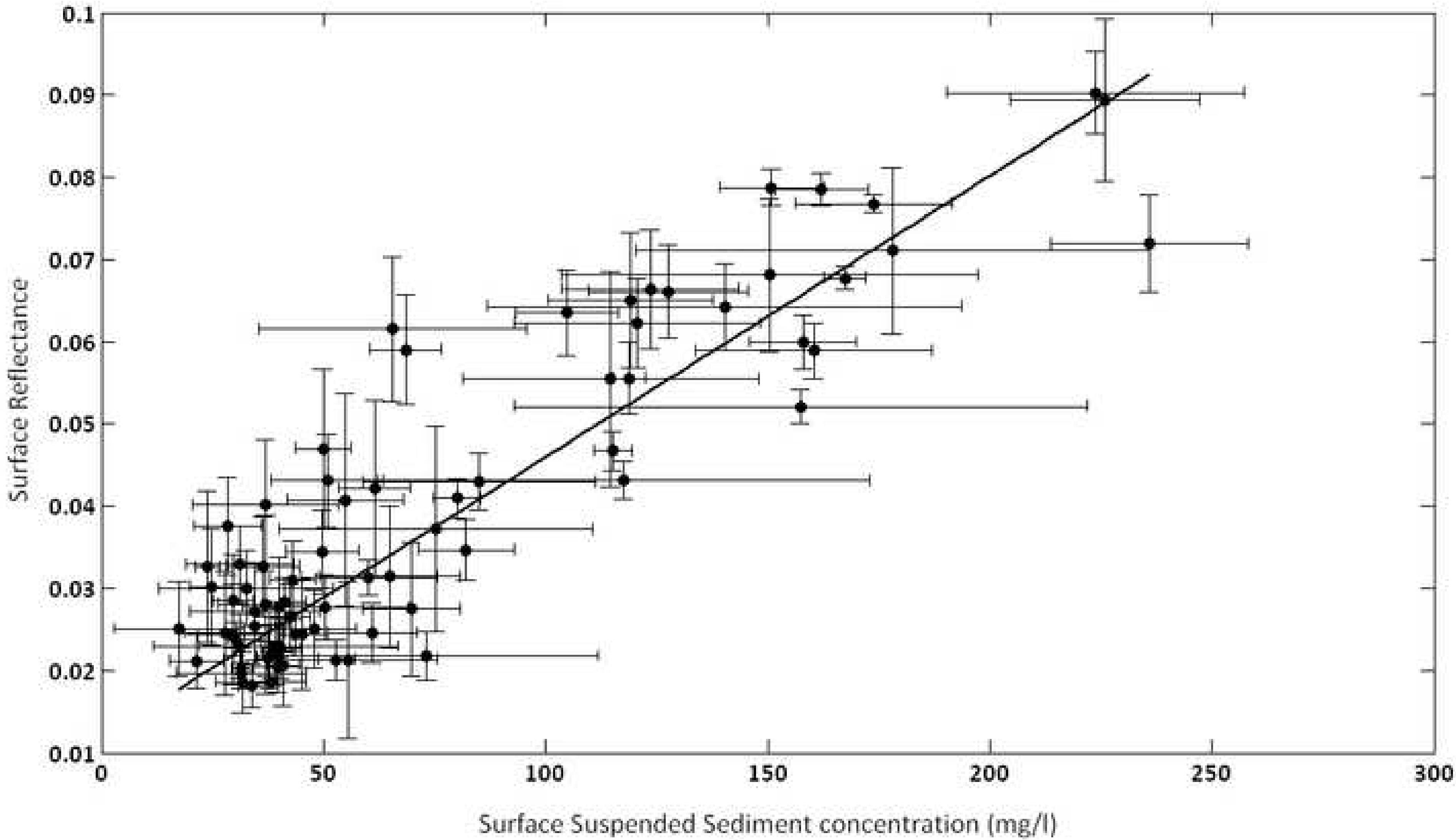

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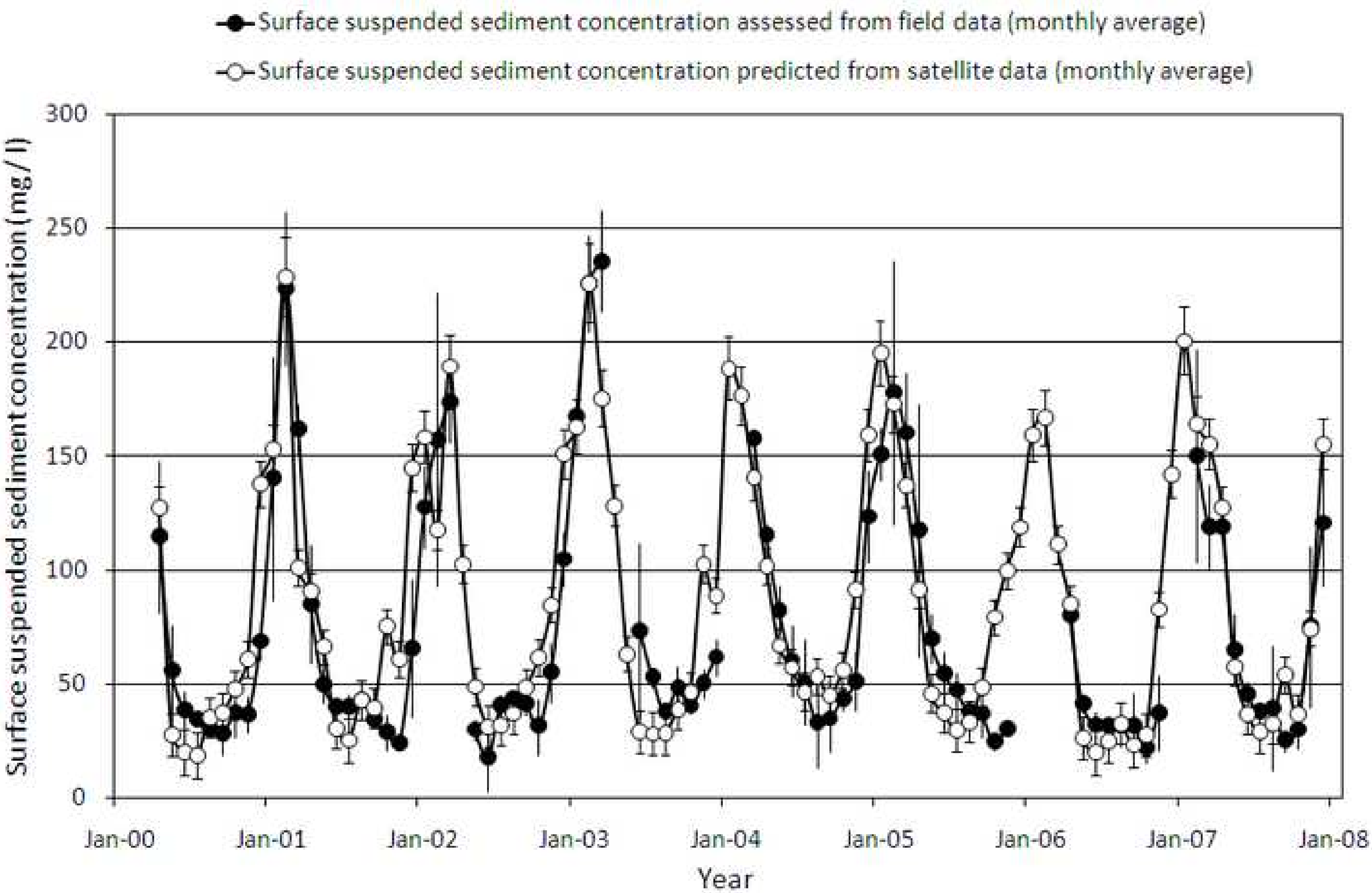

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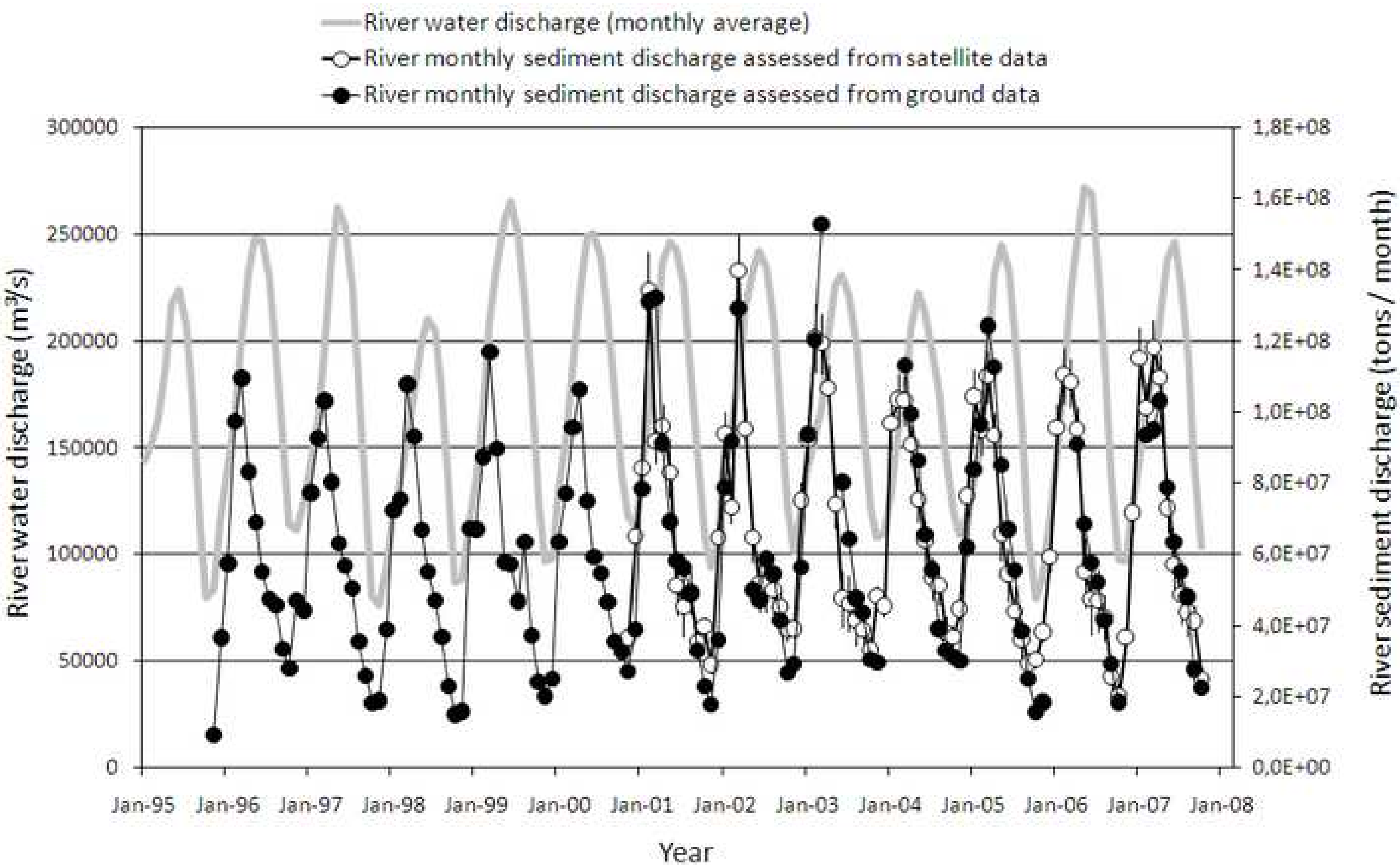

Figure 8
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