The integration of field measurements and satellite observations to determine river solid loads in poorly monitored basins

Raúl Espinoza Villar a,⁎, Jean-Michel Martinez a,b,c, Jean-Loup Guyot b,c, Pascal Fraizy b,c, Elisa Armijos d, Alain Crave e, Hector Bazán d, Philippe Vauchel b,c,f, Waldo Lavado d,f

⁎ Corresponding author. Tel.: +55 61 3307 2433; fax: +55 61 3272 4286.
E-mail addresses: raulev@unb.br (R. Espinoza Villar); jean-michel.martinez@ird.fr (J.-M. Martinez).

Article info

Article history:
Received 14 February 2011
Received in revised form 7 April 2012
Accepted 11 April 2012
Available online xxxx
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Martin Beniston, Associate Editor

Keywords:
Hydrology
Remote sensing
Sediment discharge
Amazon
MODIS

Summary

The use of satellite imagery to assess river sediment discharge is discussed in the context of poorly monitored basins. For more than three decades, the Peruvian hydrological service SENAMHI has been maintaining several gauging stations in the lower part of the Amazon River catchment. This network has been recently supplemented by the Hydro-geodynamics of the Amazon Basin (HYBAM) program, which has a water quality monitoring network distributed over five locations and allows the assessment of river discharge and surface suspended sediment (SSS) concentration. In this paper, the three stations that are located near the confluence of the Marañon and Ucayali Rivers, which form the Amazon River, are reviewed in detail. Two of the stations provide a complete time series of 10-day SSS samples over the studied period. The third station, along the Ucayali River, failed to provide valid estimates of sediment concentration at the river surface. The objective is to use satellite data as a substitute for the missing records in order to assess the Ucayali River sediment discharge, which has never been directly assessed before. An additional goal was to extend the river sediment discharge records for the other two stations. Water reflectance, assessed from the time series of MODIS satellite images, is calibrated using field-sampling campaigns to provide satellite-based SSS estimates. Validation is achieved using an independent dataset consisting of the 10-day SSS samples derived from the HYBAM network. Over a 4-year period between 2004 and 2008, there is greater than 10% agreement between satellite-derived data and network data for the two stations that provided complete field records. Based on satellite-derived SSS estimates assessed from 2000 to 2009, the river sediment balance is shown to be consistent between upstream and downstream stations. The use of satellite data and their integration with field data in the context of poorly monitored basins is discussed, and different cases are proposed.

© 2012 Elsevier B.V. All rights reserved.

1. Introduction

The growing demand for information regarding water resources, either locally or globally, for environmental studies and/or monitoring, necessitates to consider various methods that enable the collection of monitoring parameters. In hydrology, for example, determination of the source, transport and delivery of the constituents in a watershed is based on a network of stations where frequent samples are required to characterize the variations in chemical and sediment concentrations that occur during the hydrological cycle. Hence, the relevance and efficiency of hydrological monitoring is a function of the parameters measured, sampling frequency and spatial distribution of stations within the catchment area (Hooper, 1997).

It is generally accepted that the state of the world’s inland waters should be better understood. Valuable hydrological monitoring should provide both long-term and uninterrupted observations, regardless of political or institutional contingencies that may arise, as may be the case with multinational catchments. However, facilities and maintenance costs tend to discourage the implementation of hydrological monitoring networks. Indeed, it has been estimated that three quarters of the world cannot afford a full-scale water quality monitoring infrastructure and will not be able to construct this infrastructure in the near future (GEMS, 2003). Because
conventional inland water monitoring techniques cannot accommodate the increasing need to monitor the impact of local and global changes, alternative solutions are required.

Satellite imagery can provide the synoptic, continuous and long-term global observation that is needed. The optical qualities of water have been shown to be closely linked to certain quality parameters of interest, such as turbidity (Dekker, 2002; Mertes et al., 1993), algal pigment (Gohin et al., 2002; Schalles et al., 1998) and organic matter (Vodacek et al., 1995). Similarly, satellite images provide invaluable information for the detection of oil spills (Lennon et al., 2006). However, such observations have usually been limited to one-shot studies due to the unavailability of space-borne platforms that offer adequate spatial resolution and revisit frequency for most continental water. In a recent study, global monitoring space-borne sensors, such as MODIS, have been used to complete a monitoring network and assess the SSS at the Amazon River surface in Brazil over the course of several years (Martínez et al., 2009). This approach opens up new prospects for monitoring surface water quality because MODIS sensors provide daily global coverage, which in turn, enables water reflectance to be estimated anywhere in the world.

Monitoring sediment transport in river systems is a good way of assessing the erosional and sedimentation processes that take place in river catchments. The Intergovernmental Council of the International Hydrological Programme (IHP) emphasized the significant socio-economic and environmental impacts of these processes in river basin management and the fact that they are still poorly understood for practical use. A more complete knowledge of sediment transport is critical in areas where monitoring remains inadequate, such as the largest watersheds of the world in boreal and tropical areas. In the present study, MODIS data are used to complete a monitoring network covering the Amazon River in Peru. In that region, the Peruvian water agency (SENAMHI) has been monitoring the main river water level for more than 20 years, but no information was available for basic water quality parameters. Using ground measurements, satellite data are calibrated and used to assess the Marañon, Ucayali and Amazon River sediment discharge. The accuracy of the method will be discussed as well as the integration of conventional ground measurements with spatial techniques.

2. Site and methods

2.1. Hydrology

The Amazonian Basin drains 76% of the Peruvian territory (IIAP, 1998) (977,900 km²) and accounts for 98% of all Peruvian water resources (DGAS, 1995). At the confluence of the Ucayali and Marañon Rivers, the Amazon River is formed. The Marañon River drains 350,000 km², of which 189,000 km² are mountainous areas in the Andes. The Ucayali River drains 360,000 km², of which 198,000 km² are mountainous areas in the Andes. The Marañon River drains the northern and central parts of the Peruvian Andean Cordillera, and the Ucayali River drains the southern part. The Amazon plain is scarcely populated, preventing the establishment of a dense hydrological station network.

Fig. 1 shows the locations of the three gauging stations discussed in this study: San Regis (SRG) (4.51°S, 73.91°W), along the Marañon River; Requena (REQ) (5.03°S, 73.83°W), along the Ucayali River; and Tamshiyacu (TAM) (4.00°S, 73.16°W), along the Amazon River. The Peruvian service of Meteorology and Hydrology (SENAMHI) has been recording river water levels twice a day at these three stations since the 1980s. Since 2004, as part of the HYBAM program (http://www.ore-hybam.org), discharge has also been measured by acoustic Doppler current profilers (ADCPs) (Filizola and Guyot, 2004) during field campaigns conducted three times a year, thereby greatly improving the quality of the rating curves at each station. Fig. 2 shows the discharge time series for the three stations. The hydrological cycle is very similar between the SRC and REQ stations, with a flood peak between March and May and a low-water period between August and October. The mean annual discharge of the Marañon River is approximately 16,200 m³/s at SRC, whereas the mean annual discharge of the

![Fig. 1. The locations of the three hydrological stations in Peru: San Regis (SRG) along the Marañon River and Requena (REQ) along the Ucayali River, which join to form the Amazon River, and Tamshiyacu (TAM), 80 km downstream from the river confluence.](image-url)
Ucayali River is approximately 11,200 m$^3$/s at REQ. Because there are no significant tributaries between the three stations, the river discharge at TAM is simply the sum of the REQ and SRG discharges, excluding any measurement errors.

2.2. Monitoring Network for surface suspended sediment concentration

From August 2004 to July 2006, 65, 72 and 72 500-ml SSS samples were collected from the REQ, SRG and TAM stations, respectively. The SSS concentration at the river surface was sampled every 10 days at a fixed point by a local operator in a small boat. The bottles were stored and sent for filtering approximately every 3 months to the UNALM (University National Agraria La Molina, Lima) laboratory. The samples were filtered using 0.45-μm cellulose acetate filters, dried for 24 h at 50°C and weighed. The weight difference before and after filtration allows the amount of suspended matter to be determined per unit of liquid.

Fig. 3 shows the temporal series of SSS concentrations at the TAM, SRG and REQ stations. At the TAM station, the mean SSS concentration is 317 mg/l, with a maximum of 846 mg/l and a minimum of 36 mg/l over the studied period. At the SRG station, the mean SSS concentration is 169 mg/l, with a maximum of 596 mg/l and a minimum of 31 mg/l. At the REQ station, SSS samples yield a much lower value, with a mean concentration of 77 mg/l. After crosschecking the SSS data from the three stations, it became apparent that measurements at the REQ station were incorrectly sampled. Misplacement of the measurement point within the plume of a local tributary draining the local forest, the Tapiche River, is likely to have caused the error. Due to the remoteness of the Ucayali River, sampling was abandoned, and as a result, 10-day SSS data was not available for that location.

2.3. The average concentration of suspended sediments

For each station, sampling campaigns were conducted between 2005 and 2008 (8 in TAM, 10 in SRG, 9 in REQ) to compare the 10-day surface samples to the average suspended sediment (ASS) concentration across the whole river reach. The measurements were defined to collect the hydrological samples at least twice during the following periods: rising water, flood peak and low-water stage. During these campaigns, the river discharge was measured with ADCP. ASS was estimated using nine 500-ml water samples collected at three verticals and three different depths from the...
surface to the bottom of the water column. Each sample was processed using the same protocol used for the 10-day HYBAM measurement network.

Fig. 4 shows the SSS concentration as a function of the ASS concentration for all campaigns. The ASS concentration is strongly correlated with the SSS concentration, which confirms that the surface estimate is a robust predictor of the average concentration in the river reach. Although one unique relation can be used for all three stations together, we segment the dataset by river for better accuracy, and we make use of the following relationship between ASS and SSS concentrations for the TAM, SRG and REQ stations:

\[
\begin{align*}
\text{ASS}_{\text{TAM}} &= 1.12 \times \text{SSS}_{\text{TAM}} + 34.3 \\
\text{ASS}_{\text{SRG}} &= 1.00 \times \text{SSS}_{\text{SRG}} + 72.5 \\
\text{ASS}_{\text{REQ}} &= 1.18 \times \text{SSS}_{\text{REQ}} + 67.6
\end{align*}
\]

The same equations are used to derive ASS concentrations from SSS concentrations over the whole period using either the measurement network (2004–2006) or the satellite data (2000–2008).

2.4. Satellite images

The collection five atmospherically corrected surface reflectance products from the Terra and Aqua MODIS space-borne sensors are utilized in this study. The MODIS data products MOD09Q1 (Terra on-board sensor) and MYD09Q1 (Aqua on-board sensor) provide calibrated reflectance for two radiometric bands measured at a 250-m 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 is at 858.5 nm (infrared). Eight-day MODIS surface reflectance composite data were acquired between March 2000 and October 2009 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) the use of these images reduces the amount of data to be analyzed because a large number of daily images cannot be used in view of the persistent cloud coverage; and (iii) these composite images significantly reduce 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.

The retrieval of river stream reflectance using MODIS data is hampered by the low spatial resolution, which may result in few pure (non-mixed) water pixels, depending on the river width and image acquisition geometry. Spectral mixing has been described extensively in the literature and occurs when different materials are present in the same pixel. In the context of this study, spectral mixing may occur between water, vegetation or sandbanks. Accordingly, a specific algorithm has been developed to derive the water endmember reflectance in each image. First, river pixels are partitioned into homogenous clusters using the K-means algorithm (Martinez et al., submitted for publication, 2009). Then, 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 for publication).

3. Results

We calibrate the satellite reflectance with the SSS concentration by comparing the water endmember reflectance retrieved from the 8-day MODIS composites and SSS measurements assessed during the sampling campaigns between 2005 and 2008. Fig. 5a and b shows the 8-day composite surface reflectance as a function of the average SSS concentration for the Amazon River (TAM) and the Marañon River (SRG), respectively, collected during the sampling campaigns. The average river SSS concentration is assessed for each sampling campaign by averaging the three surface samples collected across the river reach. The number of matchups at each station is a function of cloud coverage during field sampling campaigns. Fig. 5a shows the reflectance to be strongly correlated \( r^2 = 0.99, N = 7 \) with SSS measurements over a large range of concentrations (142–500 mg/l) at the TAM station. Fig. 5b displays the reflectance as a function of the SSS concentration at the SRG station, showing mild dispersion \( r^2 = 0.87, N = 6 \) for a more limited range of concentrations (88–430 mg/l). Fig. 5c shows the 8-day
composite surface reflectance as a function of the SSS samples for the REQ station. A close correlation is found ($r^2 = 0.80$, $N = 6$) for a large range of concentrations in the range of 116–864 mg/l.

The calibration curves for each station show the ability of the MODIS sensors to monitor SSS concentrations over the three rivers studied. Furthermore, the relationship between reflectance and SSS concentration varies slightly from one river to another but can also remain stable over time. These differences may be related to different sediment types between the river catchments. As expressed by Krik (1994), the quest for a universal algorithm may be unsuccessful because the sediment–reflectance relation is a function of the mineralogy, concentration and average particle size of sediments, which in turn, is dependent on the catchment characteristics. It has been shown that the Marañon River contains a dominant illite+chlorite clay assemblage (53%) and significant smectite content (17%). The Ucayali River exhibits a different clay composition, which is dominated by smectite (Guyot et al., 2007).

To validate the satellite-derived SSS estimates, we make use of an independent field dataset, i.e., the HYBAM sampling network database. However, the accuracy of matchups between in situ and satellite data may be hampered by the strong cloud cover typical of tropical areas, which makes it difficult to match the MODIS acquisition date with the field sampling date, especially during the rainy season. An analysis of the variability of the SSS samples within a short time scale shows significant variation between samples. At the TAM and SRG stations, two consecutive 10-day samples show a mean variation of 35% and 60%, respectively, considering all samples collected at each station between 2004 and 2006. Accordingly, to reduce the bias introduced by the time delay in the matchups between the 8-day reflectance and the 10-day SSS estimates, monthly averages are considered.

Figs. 6 and 7 show the monthly average sediment discharge at the TAM and SRG stations computed from the HYBAM/SENHAMI network and from satellite images. In every case, the monthly average discharge is calculated by multiplying the monthly average discharge records with the monthly average ASS concentration. The monthly average discharge is computed by averaging the daily discharge records. The ASS concentration data are assessed from the SSS concentration estimated using the equations at (1) TAM, (2) SRG and (3) REQ. The monthly average ASS concentration is calculated by averaging either the 10-day estimates or the MODIS-derived 8-day estimates.

The sediment discharge estimate is compared during the two hydrological cycles (from August 2004 to July 2005 and August 2005 to July 2006) whose complete records are available for both network-derived and satellite-derived SSS concentrations. The Root Mean Square Difference (RMSD), which calculates the mean distance between the satellite-derived and the HIBAM SSS samples, is approximately 75 mg/l (27% relative difference) at TAM station and 72 mg/l (45% relative difference) at SRG station. These values agree with a previous study (Martinez et al., 2009) that found a 36% relative difference when comparing MODIS-derived estimates and HIBAM samples at one station in Brazil. However, the sampling campaign data show that there is a significant SSS concentration heterogeneity across the river reach at each station (Fig. 5) that may account for a large part of the differences between network-derived and satellite-derived SSS estimates. The network-derived and satellite-derived estimates of the river sediment discharge closely agree in time and in quantity. At the TAM station, the relative difference between the annual solid discharge estimates is −9% (sediment discharge of 496 × 10^6 tons using network measurements and 546 × 10^6 tons using satellite data) for the 2004–2005 hydrological cycle. At the same station, the relative difference decreases to −2.7% for the 2005–2006 hydrological cycle (sediment discharge of 438 × 10^6 tons using field measurements and 450 × 10^6 tons using satellite images). At the SRG station, the relative difference is −1.58% (sediment discharge of 190 × 10^6 tons using field measurements and 193 × 10^6 tons using satellite images) for the 2004–2005 hydrological cycle and +1.43% for the 2005–2006 hydrological cycle (sediment discharge of 173 × 10^6 tons using field measurements and 170 × 10^6 tons using satellite images). In both cases, the solid discharge minimum and maximum are correctly captured by the satellite, although some discrepancies can be found during the flood peak at SRG. The much higher variability in time of the SSS at the SRG station (60%) likely introduces some bias in the matchups.

We compare the river sediment discharge at each station, calculated from the ASS concentration assessed by satellite and from the discharge at each gauging station. Because there is no significant tributary between the SRG, REQ and TAM stations, the sediment discharge at the TAM station should simply be the sum of the sediment discharge assessed at the SRG and REQ stations. Fig. 8 shows the monthly average sediment discharge at the TAM station as a function of SRG and REQ estimates for the corresponding months during the 2000–2009 hydrological cycles, representing 104 months. The root mean square error (RMSE), which is the sum of the residuals, is approximately 6 × 10^6 tons/month (18% relative to the sample average). The dispersion appears to increase as a function of sediment discharge, causing a slight underestimation of downstream sediment discharge by approximately 3%.

4. Discussion

These results demonstrate that, in the context of a poorly monitored basin with a reduced set of network monitoring stations and...
sampling campaigns, satellite data can be used to provide long-
term observations of suspended sediment discharge. Thus, this 
study demonstrates that satellite information can be used to (1) supplemen
ting missing records, (2) crosscheck the data quality when 
field records are available, (3) extend the time series before or after 
a station has been installed or discontinued, and (4) provide esti-
mates where installation and/or maintenance costs prevent the 
set up of a water quality monitoring station. The case of the REQ 
station along the Ucayali River falls under applications #2 and 
#4 because that station failed to provide robust data and thus 
was closed. Application #3 may apply to both the SRG and TAM 
stations, which have a short time series that began in 2004, 
whereas MODIS data are available beginning in March 2000. 

Finally, application #2 may apply to any monitoring station in 
the context of checking for consistency between stations along 
the same river from upstream to downstream.

The analysis of our dataset demonstrates that satellite data can 
be efficiently used to complement a monitoring network when one 
or more stations fail. In poorly gauged basins, it may take a few 
weeks or even months to identify and fix a problem, resulting in 
a significant loss of data. Once calibrated, we show that satellite 
data are able to provide a constant quality estimate at any station 
and for several years. MODIS sensors offer global coverage and fre-
quently observations, which means that the same method/sensor 
can be used simultaneously over different locations separated by 
hundreds of kilometers. Thus, one of the best applications in the field

Fig. 6. Comparisons of the monthly average river discharge with suspended sediment discharge derived from field measurements (triangles) and MODIS images (black dots) at the TAM station (Amazon River).

Fig. 7. Comparisons of the monthly average river discharge with suspended sediment discharge derived from field measurements (triangles) and MODIS images (black dots) at the SRG station (Marañon River).
of hydrology for satellite data may be the assessment of both spatial and temporal heterogeneities at different scales. One limitation may be the fact that satellite data can only provide estimates for the superficial water layer (less than one meter, in our case, due to very strong water turbidity). It is well known that the SSS concentration can be a good predictor of the ASS concentration for the whole river reach for fine sediments but may be much less robust for coarser sediments such as sand. The spatial resolution of MODIS data limits the use of such data over small- and medium-sized rivers, but it is hoped that earth-observation satellites will offer better spatial resolution and an adequate revisit frequency in a few years.

We have processed MODIS images from 2000 to 2009 to assess the river sediment balance over the last decade. During that time, the mean annual sediment discharge of the Marañon River is estimated by satellite data to be $150 \times 10^6$ tons/year, showing low inter-annual variability, with a $12\%$ coefficient of variation. A very close agreement is found with the measurement network that assessed $168 \times 10^6$ tons/year over the 2004–2006 period (Guyot et al., 2007a). Intra-annual variability remains moderate with a range of variation of $4–24 \times 10^6$ tons/month. Between 2000 and 2009, the mean annual sediment discharge of the Ucayali River is estimated by satellite data to be $270 \times 10^6$ tons/year, with a $9\%$ coefficient of variation. The monthly sediment discharge shows strong variability from $2 \times 10^6$ tons/month during the lowest recorded water flow in August 2005 up to $56 \times 10^6$ tons/month.

Over the 2000–2009 period, the mean Amazon River sediment discharge at the TAM station was $392 \times 10^6$ tons/year with an $8\%$ coefficient of variation. The maximum sediment discharge is recorded during the 2004 hydrological cycle with $430 \times 10^6$ tons, whereas the minimum sediment discharge was $339 \times 10^6$ tons/year the following year. The intra-annual sediment discharge shows a significant variability from a maximum of $61 \times 10^6$ tons/month to a minimum of $8 \times 10^6$ tons/month. Sediment discharge exhibits a slightly higher variability over time than river discharge. For example, at the TAM station, the annual sediment discharge and the annual river discharge had $8\%$ and $6\%$ coefficients of variation, respectively. For the Marañon River, the annual sediment discharge and the annual river discharge had approximately $12\%$ and $7\%$ coefficients of variation, respectively. The Ucayali River contributes approximately two-thirds ($65\%$) of the Amazon River at the TAM station. Compared to recent results (Martinez et al., 2009) from the Amazon River near to the basin outlet (Obidos station, Brazil), we observe that the sediment discharge of the Amazon River downstream of the Marañon/Ucayali confluence accounts for nearly half of all sediment discharge into the Atlantic Ocean.

5. Conclusion

Large river basins, such as those in the tropics or boreal areas, may be the first to display the impacts of climate change and other anthropogenic-induced alterations because these basins are major components of the global water cycle. However, these areas are often the least monitored due to the cost of infrastructure. The use of alternative solutions to monitor basic water quality parameters, such as sediment concentration, should be considered, at least to complement and double-check the accuracy of existing records. This study demonstrates that existing sensors, such as MODIS, can be considered for the operational monitoring of river sediment discharge in large river catchments. Our method is based on a calibration of satellite images using a reduced number of field sampling campaigns to cover the complete range of SSS concentrations at each station. From the satellite-derived SSS estimates, we compute an average concentration over the river reach, which is combined with the river discharge to assess the river sediment discharge. The accuracy of the method is checked in two ways. First, the river sediment discharge assessed from the satellite is checked against another independent estimate, assessed from the HYBAM 10-day samples between 2004 and 2006. For stations where both field data and satellite data are available, it is shown that the derived sediment discharge estimates are in close agreement (better than $10\%$). Second, it appears that using satellite-derived measurements, the river sediment budget is closed between the upstream and downstream stations.

References


Please cite this article in press as: Espinoza Villar, R., et al. The integration of field measurements and satellite observations to determine river solid loads in poorly monitored basins. J. Hydrol. (2012), http://dx.doi.org/10.1016/j.jhydrol.2012.04.024

