Int J Appl Earth Obs Geoinformation 69 (2018) 27–40

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

journal homepage: www.elsevier.com/locate/jag

Multi-temporal flood mapping and satellite altimetry used to evaluate the flood dynamics of the Bolivian Amazon wetlands

A. Ovando[a,c,*], J.M. Martinez[b], J. Tomasella[a,c], D.A. Rodriguez[d], C. von Randow[c]

[a] Centro Nacional de Monitoramento e Alerta de Desastres Naturais (CEMADEN), São Jose dos Campos, São Paulo,Brazil
[b] Institut de Recherche pour le Développement (IRD), France
[c] Centro de Ciência do Sistema Terrestre/Instituto Nacional de Pesquisas Espaciais (CCST INPE), São Jose dos Campos, São Paulo, Brazil
[d] Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia (COPPE) - Universidade Federal do Rio de Janeiro (UFRJ)

ARTICLE INFO

Keywords:
Llanos de Moxos
Satellite altimetry
Hydrology
Flood dynamics

ABSTRACT

The Bolivian Amazon wetlands are extensive floodplains distributed over the Mamore, Beni, Madre de Dios and Guapore Rivers. Located within the upper Madeira River Basin, the wetlands play important roles in regulating the biogeochemical processes and hydrological cycle of the region. In addition, they have major ecological and hydrological relevance for the entire Amazon Basin. These wetlands are characterized by the occurrence of episodic floods that result from contrasting hydro-meteorological processes in the Andean Mountain region, the piedmont area and the Amazon lowlands. In this study, we characterized the flood dynamics of the region using multi-temporal flood mapping based on optical altimetry (MODIS – Moderate Resolution Imaging Spectroradiometer – M*D09A1) and satellite altimetry (ENVISAT RA-2 and SARAL AltiKa altimeters). This study provides new insights regarding the frequency, magnitude and spatial distribution of exogenous floods, which are created by flood waves from the Andes; and endogenous floods, which result from runoff originating in the lowlands. The maximum extent of flooding during 2001–2014 was 43144 km^2 in the Mamore Basin and 34852 km^2 in the Guapore Basin, and the total surface water storage in these floodplains reached 94 km3. The regionalization of flood regimes based on water stage time series signatures allowed those regions that are exposed to frequent floods, which are generally located along rivers without a direct connection with the Andes, to be distinguished from floodplains that are more dependent on flood waves originating in the Andes and its piedmonts. This information is of great importance for understanding the roles of these wetlands in the provision of ecosystem services.

1. Introduction

The Amazon floodplains are characterized by complex hydrological, geomorphological and biological processes and provide multiple functions and ecological services, which explains their long and ongoing history of human occupation (Sioli, 1984). Among the major Amazonian wetlands, the "Llanos de Moxos" (LM) is a vast savanna floodplain located in the fluvial system of the Mamoré-Beni-Guaporé (Iténez) river system in Bolivia, which lies within the eastern Andes, the adjacent Amazon alluvial fans and the Precambrian Brazilian shield. The LM is considered a vital contributor to the overall ecological health of the entire Amazon, and it has recently been designated by the Ramsar Convention as a wetland of global importance (WWF, 2013). In addition to having rich natural diversity, the LM was the setting for many complex pre-Columbian societies; thus, it has an archaeological heritage and is an important example of the complex human-environmental interactions that occur in large wetlands.

Despite the multiple ecosystem services provided by the LM, it has not been adequately characterized with respect to its hydrology. Therefore, environmental changes that impact the hydrological cycle and have the potential to compromise the functions and services of the LM ecosystem are poorly understood. Thus, it is important to develop suitable methods and tools to obtain an understanding of the complex functioning of the wetlands in this region, and quantitative and qualitative information must be provided to support their conservation.

In recent decades, remote sensing and numerical modeling have had great relevance for understanding the hydrological functioning of the Bolivian Amazon wetlands. Much of the knowledge on this subject is the result of the application of remote sensing techniques along with in situ observational information. At the end of the 1990s, a description of the flood dynamics of the Bolivian Amazon based in both radar (RADARSAT) and Landsat ERS images was provided via a research

* Corresponding author at: Centro Nacional de Monitoramento e Alerta de Desastres Naturais (CEMADEN), São Jose dos Campos, São Paulo, Brazil. Tel.: +55 12 3205 0130.
E-mail addresses: alex.ovando@cemaden.gov.br (A. Ovando), daniel.andres@coc.ufrj.br (D.A. Rodriguez).

https://doi.org/10.1016/j.jag.2018.02.013
Received 10 August 2017; Received in revised form 17 January 2018; Accepted 21 February 2018

initiative entitled BIOBAB (Aquatic BIOdiversity of the Bolivian Amazon Basin) (Bourrel et al., 2009). Later, at the beginning of the 2000s, flood extents for the LM were assessed using the Scanning Multichannel Microwave Radiometer (Nimbus-7 satellite) (Hamilton et al., 2004, 2002). More recently, fluvial dynamics using Landsat TM and Google Earth images were assessed by Plotzki et al. (2012). Near real-time flood estimations from NASA's Global Flood Mapping project and the Flood Observatory are also available for this area. Studies encompassing the whole Amazon have also provided relevant information regarding wetland extension, vegetation and other characteristics (e.g., Hess et al. (2003, 2015), who estimated the extension and vegetation cover of the floodplains using dual-season mosaics (JERS-1 Mosaics). The use of remote sensing to assess vegetation cover or land use change has wide applications, and many studies of the Bolivian Amazon and its wetlands have been performed using remote sensing technology. Examples of the use of remote sensing techniques to assess flood characteristics based on floristic and vegetation composition rather than on direct water detection include Crespo and Van Damme (2011) and Junk and Furch (1993). Remote sensing techniques have also been used in combination with scarce in situ hydrologic data (Hamilton et al., 2004; Bourrel et al., 2009; Ovando et al., 2016).

Despite the limitations of hydrometeorologic, topographic, pedologic and thematic information for hydrological-hydrodynamical modeling, several model applications have been performed since the 2010s. Escurra et al. (2014) implemented the Soil Water Assessment Tool (SWAT) to simulate the monthly water balance from 1997 to 2008 and scenarios for 2050, although no specific routines were used for the simulation of floodplains. Later, Villazon and Inturias, (2015), employed a distributed WFLOW model (www.openstreams.nl) for a portion of the central Mamoré Basin, which included specific analyses for flood forecasting. Other models implemented for the whole Amazon and the Madeira basin have included specific routines for the floodplains in Moxos (e.g., Siqueira-Júnior et al., 2015) including the assimilation of radar altimetry data (Paiva et al., 2013).

The large extent and remoteness of the Amazon wetlands limit the establishment of a dense network of in situ hydrometric and pluviometric measuring stations that could provide complementary information for remote sensing studies and/or inputs for hydrological or hydrodynamic models (Fig. 1). Therefore, satellite altimetry is widely used to complement local observations of water levels in ungauged rivers and wetlands (DaSilva et al., 2012). Satellite altimetry data are extremely important as the main source of information for observational studies and can be used to improve hydrological-hydrodynamic models (Garambois et al., 2016; Getirana, 2010; Paiva et al., 2013; Paris et al., 2016)

Recently, the HYBAM-OS project and the Brazilian National Water Agency (ANA) have integrated satellite altimetry estimates from virtual stations (Martinez et al., 2015) with the Amazon River network to retrieve historical records and perform real-time monitoring of rivers and floodplains (www.hidrosat.ana.gov.br). Although a large number of virtual water stage stations occur along the Amazon and within the LM, hydrological information for areas within the wetlands remains limited.

In this study, multi-temporal flood maps (from MODIS–Moderate Resolution Imaging Spectroradiometer data) were combined with floodplain water level time series data derived from satellite altimetry (ENVISAT & SARAL) to investigate key issues regarding the hydrological functioning of the LM. These issues include the spatial and temporal distribution of flooding; the relative contributions of exogenous floods created by flood waves from the Andes and of endogenous floods originating in the lowlands; and estimations of temporary water storage in the floodplains during floods.

The findings of this study provide information on the dynamics of the floods in the region and provide a valuable example of addressing water ecosystem services in remote areas by combining the use of flood mapping and satellite altimetry.

2. Study area (Bolivian Amazon wetlands)

The Bolivian wetlands are composed of a vast savanna floodplain of approximately 150000 km^2 (Hamilton et al., 2004). The mean altitude of the wetlands is approximately 150 m above sea level (masl), and the mean slope is less than 10 cm per km (Guyot, 1993). These wetlands are located in the fluvial system of the Mamoré-Beni-Guaporé (Iténez) Rivers and lie within the eastern Andes, the adjacent Amazon alluvial fans and the Precambrian Brazilian shield (Fig. 1).

Interannual variability in streamflow can influence the flood intensity and extent in the region depending on the meteorological conditions in the Andean slopes and piedmont area and within the lowlands (Espinoza Villar et al., 2009; Roche et al., 1992). Thus, variable sources of floodwaters, including distinct upland watersheds and local precipitation, result in high variability in the magnitude of both flooding and droughts (Hamilton et al., 2004; Hanagarth, 1993).

Flood estimates in the LM vary depending on the methods used, the area under study and the period of study. Radar estimates range from 80000 km^2 to 90000 km^2 of floodable savannas and from 45000 km^2 to 60000 km^2 of floodable forest as reported by Hess et al. (2015) (for the 1995–1996 flood season) and Ovando et al. (2016) (during 2007–2008), respectively. Hamilton et al. (2004), using passive microwave radiometry, estimated 78 000 km^2 for the 1997 flood. Using optical and SAR high-resolution images (approximately 30 m pixel size), Bourrel et al. (2009) estimated a flooded area of 30000 km^2 for the 1997 flood. Other maximum flood estimates for the area, such as 150000 km^2 reported by Junk (1993), 100000 km^2 estimated by Hanagarth (1993) and 215171 km^2 estimated by Crespo and Van Damme (2011), are based mainly on vegetational and floristic approaches.

3. Methods

3.1. Multi-temporal flood maps

In this study, a set of multi-temporal maps of flooded areas for the period 2001–2014 were used (632 maps in total), which were derived using both active and optical systems: the MODIS M*D09A1 product, the PALSAR L1.5 product, and ScanSar HH images (Ovando et al., 2016). These maps were based on an object-based image analysis (OBIA) approach (Blaschke, 2010) using segments or cluster-based mapping algorithms rather than pixel-based schemes. Thus, the minimum mapping unit consisted of a small polygon or cluster obtained by image segmentation.

For every mapping unit (polygon), the following equation was applied to obtain the frequency of flooded days:

$$FFp = \frac{NFD}{Ns} \tag{1}$$

where *FFp* represents the frequency of flooded days, *NFD* represents the number of flood days, and *Ns* represents the total number of days in the multi-temporal flood map series.

A previous comparison of MODIS and SAR-derived flood maps for March 2007, June 2007, December 2007, March 2008 and March 2009 (Ovando et al., 2016), revealed that the two sensors show good agreement in flood detection for savanna schemes ($r^2 = 0.91$). However, a systematic underestimation of the flooded area by MODIS is observed, with a mean relative difference of 33%. When assessing the extent of the flooded areas beneath dense vegetation, the authors reported that in the case of Flooded Sparse Forest, the relative difference between MODIS and PALSAR-derived estimates is 39%. Furthermore, as expected, the MODIS estimates for Flooded Dense Forest are almost null, with a difference of 96% between the MODIS and SAR estimates. This bias is likely due to the different physics involved in the light/microwave interaction with the landscape and the influence of clouds in the optical system. Thus, it is important to highlight that the multi-