



Study of Water Level Variation in the Reservoir at the Ilha Solteira Dam (Brazil) Based on Geodesic Remote Sensing

Estudo da Mudança de Carga Hídrica do Reservatório de Ilha Solteira com Base em Sensoriamento Remoto Geodésico

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Abstract

The construction of water reservoirs for the production of electricity or human consumption is very common in Brazil due to its high availability of water. However, in the last few years, the southeastern region of the country has been undergoing a period of drought that has greatly affected electricity generation, especially in the northwestern region of the state of São Paulo, an area that comprises one of the largest hydroelectric complexes in the world (Ilha Solteira and Jupiá). Ilha Solteira currently has a continuous-monitoring Global Navigation Satellite System (GNSS) station. These data were used in many geoscience studies investigating the Earth's dynamics. This study evaluates the impact of the annual variation in the water level in the reservoir at geodetic altitude provided by the GNSS. Satellite images, GNSS solutions from the Nevada Geodetic Laboratory (NGL), referred to as IGS08, and daily quota and volume estimates from the Reservoir Monitoring System managed by the National Water Agency (ANA) were used. The results indicated a reduction in the reservoir water level and volume, which represented a variation of approximately 3.5 cm at the GNSS altitude.

Keywords: GNSS; Remote sensing; Reduction of water level

Resumo

A construção de reservatórios para armazenar água para produção de energia elétrica ou consumo humano é muito comum no Brasil, devido a sua grande disponibilidade hídrica. Porém, nos últimos anos, a região Sudeste do país vem atravessando um período de estiagem que tem impactado fortemente a geração de energia elétrica, principalmente no noroeste paulista, área onde se encontra um dos maiores complexos hidrelétricos do mundo (Ilha Solteira e Jupiá). Ilha Solteira conta atualmente com uma estação GNSS (Global Navigation Satellite System) de monitoramento contínuo. Estes dados têm possibilitado a realização de diversos estudos em Geociências que buscam compreender a dinâmica terrestre. Neste sentido, este artigo objetiva avaliar o impacto da variação anual de carga hídrica de um reservatório na altitude geodésica fornecida pelo GNSS. Para tanto, foram usadas imagens de satélite, soluções GNSS do Nevada Geodetic Laboratory (NGL), referenciados ao IGS08, e estimativas diárias de Cota e Volume do Sistema de Acompanhamento de Reservatórios gerenciados pela ANA (Agência nacional de Águas). Os resultados indicaram uma redução do nível da água e volume do reservatório que representou uma mudança de aproximadamente 3,5 cm na altitude do GNSS.

Palavras chave: GNSS; Sensoriamento remoto; Redução de carga hídrica



1 Introduction

Brazil is one of the countries in the world with a great potential for energy production by hydroelectric plants due to the high availability of water resources. Hydroelectric plants represent almost 71% of the electricity generated and consumed nowadays in the country. Currently, there are over 640 reservoirs monitored by the National Water Agency, including Itaipu, Furnas, and Ilha Solteira (SAR, 2015).

The Paraná River, the second largest in South America, contains the Jupiá complex, the sixth largest complex of hydroelectric plants in the world. The Hydroelectric Plant of Ilha Solteira, which belongs to this complex, is located between the municipalities of Ilha Solteira (State of São Paulo, SP) and Selvíria (State of Mato Grosso do Sul, MS). With a 5,605 m-long dam and a 1195-km² reservoir, it is the largest plant of the Energy Company of São Paulo (CESP), with an installed capacity of 3,444 MW (CESP, 2015).

The metropolitan region of São Paulo is currently suffering the greatest water crisis since 1930, when the measurement of the levels in its reservoirs and rivers for water supply began. The Cantareira system, responsible for supplying almost half of the population of Great São Paulo (8.8 million people), operated with negative storage levels at the beginning of January in 2016, *i.e.*, the system kept operating with the reservoir's technical level (dead volume). The water crisis also affected energy generation in the southeastern region, especially in the State of São Paulo. For instance, in December 2013, the Hydroelectric Plant of Ilha Solteira produced 2,026 MW (megawatts), and in the same month in 2014, it produced 1,117 MW, representing a 55% reduction (CESP, 2015). The impact of this reduction is observed in the values of the reservoir quota, which reached levels of 318 meters, far from the level of 323 meters, considered ideal by CESP. This reduction is reflected in the water volume stored in the reservoir that, depending on the annual variation, could cause crustal movements. Events of this nature are observed on a global scale as well as a local scale and are associated with the elastic crustal deformation process.

Elósegui *et al.* (2003) considered that surface loads, locally induced by lakes and glaciers, could be a significant source for the crustal deformation and could promote substantial crustal displacements. Davis *et al.* (2004) argued that the water redistribution at the Earth's surface also has a role in the load or weight changes in the Earth's crust. In addition, because it is supported by the sublithospheric mantle below, the crust will respond by deforming elastically in annual time scales.

Although the use of a Global Navigation Satellite System (GNSS) is widely employed for navigation, topography, and engineering, its use is not as pronounced in studies of the Earth's dynamics. Studies have demonstrated the potential of GNSS for measuring the Earth's elastic response due to surface loading (Blewitt, 2003; Bevis, 2005; Tregoning, 2009; Han *et al.*, 2016).

By analyzing a geodetic station in Antuco (Chile), Bevis *et al.* (2003) verified non-constant vertical movements of approximately 50 mm caused by volume variations in a lake located 20 km away from the station. The same authors, by analyzing the geodesic data from the station at Manaus, identified a vertical displacement cycle with variations ranging from 50 to 75 mm caused by the annual variation of the Amazon River.

Borsa *et al.* (2014) studied the west coast of the United States, which, since 2013, has undergone a severe drought. With the use of precipitation data and GNSS stations, it was possible to observe the average elevation change of 5 mm reaching 15 mm in the mountains of California.

Prol *et al.* (2015) observed a strong anticorrelation between the increase in the water level of the Aquidauana River and the reduction of the geodesic altitude. The results showed that the GNSS could assist in the monitoring of the Pantanal flooding level.

This study presents the effects of the annual variation in the water level of a reservoir using the geodesic altitude provided by the GNSS. The selected area was Ilha Solteira, which, in addition to representing the largest hydroelectric plant in the State of São Paulo and the third largest in the coun-

try, is located in a region that has a geodesic station of the Brazilian Network for Continuous Monitoring (RBMC), providing ideal conditions for conducting this study.

2 Material and Methods

The Municipality of Ilha Solteira is located in the northwestern region of the State of São Paulo and is part of the Mesoregion of Araçatuba (Figure 1). With coordinates $20^{\circ} 25' 58''$ S of latitude and $51^{\circ} 20' 33''$ W of longitude, it has an average altitude of approximately 335 meters. Geomorphologically, Ilha Solteira is part of the Western Plains of São Paulo. The reservoir of the Hydroelectric Plant of Ilha Solteira, with a water surface of $1,195 \text{ km}^2$, crosses four state borders, those of São Paulo, Minas Gerais, Goiás, and Mato Grosso do Sul (CESP, 2015).

To perform the study, Landsat 5 sensor TM, and Landsat 8 sensor OLI satellite images were used. The images were used as the basis for classification of the area of the water surface in the reservoir at Ilha Solteira, where it was possible to verify the variation that occurred in the last several years.

The Landsat 5 scenes were obtained free of charge from the website of the National Institute of Space Studies. In turn, the Landsat 8 scenes were

obtained from the website for Earth Explorer. To cover the entire reservoir, three images were used, with the following orbits/point: 222-073, 222-074 and 223-074. The years 2009, 2013, and 2014 were studied, requiring a total of nine scenes. All were from the month of September to reduce or eliminate cloud cover.

To exemplify the changes that took place in the area of the reservoir, a multi temporal composition was generated with the mid-infrared band, which corresponds to band number seven in Landsat 5 and 8.

The digital image processing (DIP) step was performed in different Geographic Information Systems platforms. For the georeferentiation, the PCI Geomatica software (PCI, 2003) was used. The Landsat 5 scenes were corrected based on the Landsat 8 scenes, which have high positional acuity (Stoerrey *et al.*, 2014; Roy *et al.*, 2014).

The water surface area classification was performed in the Ecognition software (Definiens, 2013) which works with the object-oriented classification mode. Only two classes were defined: water and anthropic. After initial tests, the values that adjusted best to the segmentation and subsequent classification were: *Scale parameter 50*, *Shape 0.1*, and

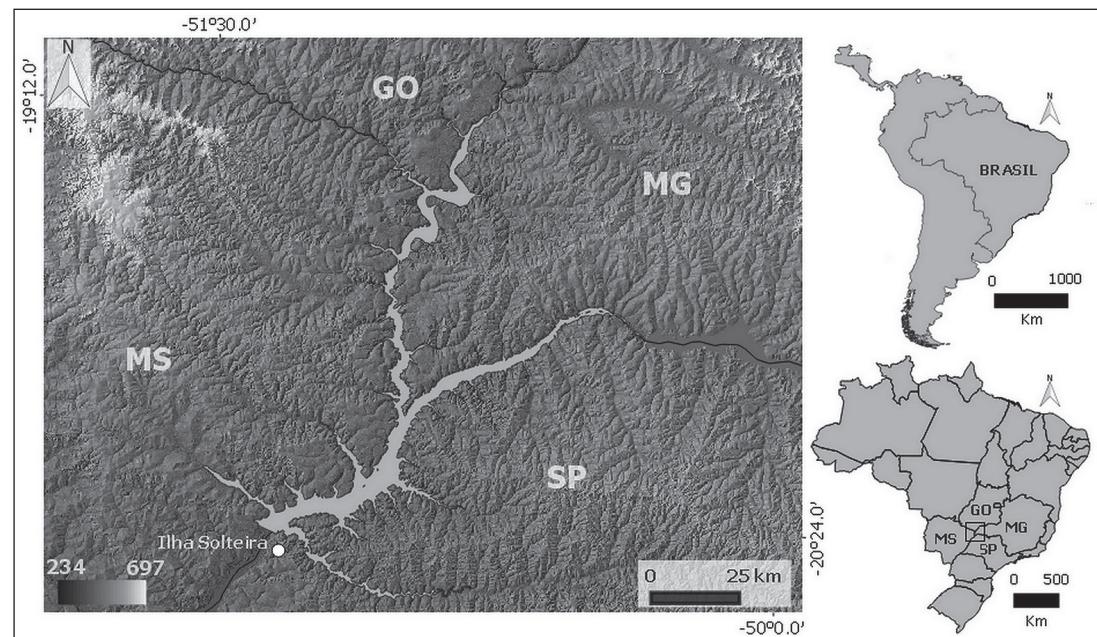


Figure 1 Location of the Municipality of Ilha Solteira, located in the northwest region of the State of São Paulo, with the altimetry map in the background.

Compactness 1.0. The result of the classification was exported in the Shapefile format for use in the QGIS 2.8.1 Wien software (Sherman *et al.*, 2015), where the values for the reservoir's surface area were obtained. This software also generated the multi temporal composition, as well as the maps presented in the study.

The data from the GNSS station of Ilha Solteira were obtained from the Nevada Geodetic Laboratory (NGL) website, in a text file format (*.txt) referred to as IGS08, derived from the latest version of the International Terrestrial Reference Frame (ITRF), ITRF2008.

Data from the Reservoir Monitoring System managed by the National Water Agency were also used, which provides daily readings of parameters, such as quota and effective volume as percentages. The available data covered September 2010 to June 2015. The use of these data required their conversion to volume in cubic meters and then liters, where 1 L = 1 kg. This procedure was necessary to quantify the minimum weight exerted by the mass of water in the reservoir. This study did not consider the influence of bottom sediments and underground water, it has considered only the water line as an adjustment factor for the local topography.

Finally, data smoothing was performed. This required the fitting of the quota data with the altitudes provided by the GNSS (Up) by using a mobile mean in Microsoft Excel software. In addition, correlation graphs were generated and presented as the results of this study.

3 Results and Discussion

From the remote sensing data, it was possible to obtain the water surface area for 2009, 2013, and 2014. The object-oriented classification method allowed the separation of the areas where retreat occurred. In 2009, the reservoir area was 1,183,201 km². In 2013, the area did not change significantly, covering 1,163,123 km². However, in 2014, the area was 893,700 km², showing a significant area reduction in a period of one year.

By analyzing the multi temporal composition image (Figure 2), the water surface retreat is evident.

It is possible to observe some islands (highlighted in red) that formed in the reservoir. For spectral targets, such as the water, the mid-infrared tends to absorb the electromagnetic radiation to a greater extent. In turn, for vegetation areas and exposed soil, the mid-infrared is mostly reflected.

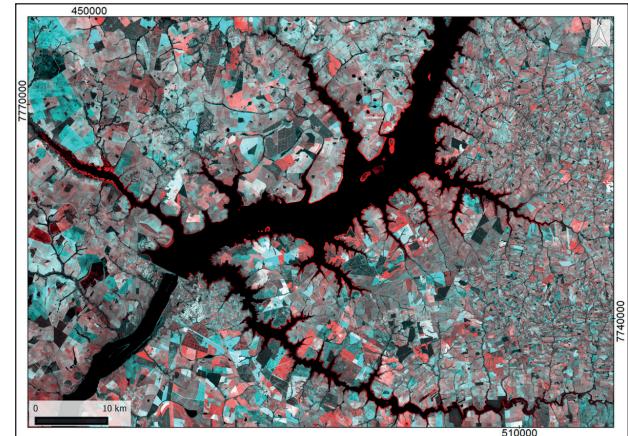


Figure 2 Multitemporal composition of the study area (R: Landsat 8 of 2014, G: Landsat 5 of 2009, B: Landsat 5 of 2009). Medium infrared scenes were used in this processing. The intense red indicates where there was retreat in the water mirror between 2009 and 2014.

The analysis of the daily readings of the Reservoir Monitoring System showed the changes in the classification process of the reservoir area and the multi temporal composition. One of the analyzed parameters was the variation in volume. Initially, a correlation test was performed between the quota data and the volume converted to cubic meters, obtaining a correlation of 99 %. According to the official data of CESP, the total volume of the Ilha Solteira reservoir is 21,060 million m³. Figure 3 shows the annual variation in the volume of the reservoir. This occurs due to the loss of water by annual evaporation, which is approximately 10% of the storage volume (Hernandes, 2005).

In terms of volume in cubic meters, the levels remained similar between the years 2011 and 2013 because the Ilha Solteira reservoir has a system of flow control that, depending on the time of the year, could be reduced to maintain its operational levels.

With the annual variation of the volume and quota automatic control, there is an up and down movement in the water level when the data of the

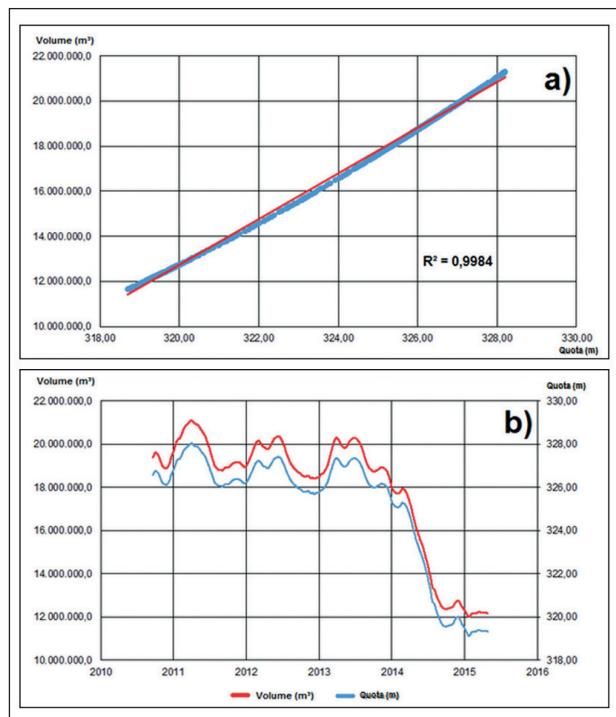


Figure 3 a. Correlation graph with the volume data converted to cubic meters; b. annual variation of the volume, behavior that is also verified in the quota data.

altimetry component (Up) are analyzed. Figure 4 presents the graphs with the quota and Up data. In Figure 4A, the values do not present the mobile mean and have a correlation of 66%. After the curve fitting process (Figure 4B), the observed correlation was 88%, which, in addition to improving the visual aspect of the curves, facilitates the interpretation of the data.

It is evident from the graph that, when the reservoir quota levels are high, the water volume in the system is consequently higher. This causes the altitudes observed by the GNSS to have an inverse behavior (anticorrelation). The process of adding load to the surface causes the crust to be pushed down, while an upward movement is observed when there is a decrease in the load.

During the study years, there is an inversion in the curves of the graph between the end of 2013 and the beginning of 2014. Table 1 shows the annual mean (September 2010 to June 2015) of the water volume in the reservoir in cubic meters, of the volume in liters, and of the weight (gigatonnes) of the

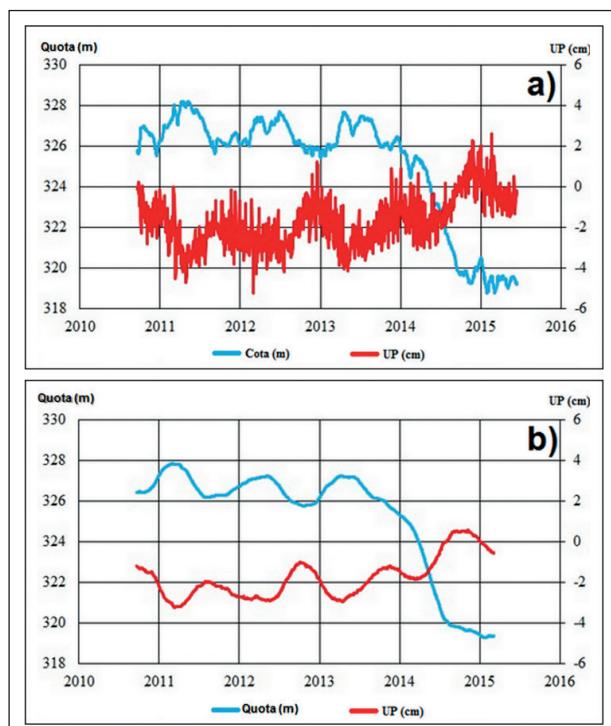


Figure 4 Adjustments made with the altimetric component (Up) and dimension data.

mass of water, in order to define the minimum necessary weight to cause variations in the water levels of the Ilha Solteira reservoir observed by the GNSS.

Year	Volume (m³)	Liters	Gigatonnes
2010	19173479,8	19173479802	19,173
2011	19843313,47	19843313471	19,843
2012	19400215,9	19400215900	19,4
2013	19393926,96	19393926965	19,394
2014	15439871,12	15439871118	15,44
2015	12212979,53	12212979533	12,213

Table 1 Annual averages for volume in cubic meters and liters for the Ilha Solteira reservoir. The mass weight of water in Gigatonnes was calculated considering that one liter of water equals one kilogram.

In general, the reservoir volume remained stable until the year 2013. However, between 2013 and 2014, there was a deficit of approximately 4 gigatonne, which, when compared to 2015, increases to 7 gigatonnes.

The effect of this deficit in the altimetry component (Up) can be observed in Fig 5b, where the in-

crease reached approximately 3.5 cm. When the quota value is considered, the reduction reaches approximately 4 m. In comparison to similar studies performed on the west coast of the United States (Borsa *et al.*, 2014) estimated a deficit of approximately 240 gigatonnes. However, according to Prol *et al.* (2015), the altitude variations caused by the decrease in the load did not occur instantaneously, and they associated this with an event called “Temporal Translation.”

4 Conclusions

The results obtained in this study indicate the potential of the GNSS application, when combined with other data sources, to study reservoir level variation and hydrology.

Additionally, with the reduction in the water level and, consequently, the volume of the reservoir, especially between 2013 and 2015, the Up response was an increase of approximately 3.5 cm in the GNSS altitude, in response to the decrease in the reservoir level. This suggests that the local topography can undergo vertical variations within a year.

These variations are most likely caused by crustal elastic deformation. In some cases, the over-load produced by the reservoir could alter the local stresses and cause induced seismic activity, as reported in other locations of Brazil, such as near the Hydroelectric Plant of Capivari Cachoeira, NE of Curitiba-PR. Special attention is drawn to the increase in the water pressure in the pores and fractures of the rock massif contributing to a decrease in the rock and soil resistance to shear strain.

Therefore, the presence of GNSS stations near reservoirs of hydroelectric plants or large natural water storage systems, such as the Pantanal, would help in understanding the Earth's dynamic compression.

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