Inferring floodplain bathymetry using inundation frequency

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Abstract

This study proposes a new method to retrieve the bathymetry of turbid-water floodplains from the inundation frequency (IF) data derived from over 32 years of composite optical remote sensing data. The new method was tested and validated over the Curuai floodplain in the lower Amazon River, where the entire bathymetry was surveyed in 2004, and water level gauge data has been available since 1960. The depth was estimated based on the relationship derived from IF and surveyed depth data, and the results were compared to those retrieved from bare-Earth DEM. We further assessed the sensitivity of the approach by analyzing the deepest part of the lake (i.e., permanent water body ~ 8m) with high IF, as well as the effect of gradual sedimentation in the lake over time. The results showed that the model is highly accurate and sensitive to IF changes even in the permanent water body areas, suggesting that this model can be used in other seasonal lakes worldwide with turbid-waters, where large-scale bathymetry surveys are not feasible due to high operation costs.

Highlights

- A new method is proposed to generate bathymetry from Inundation frequency
- Inundation frequency and lake depth showed a statistically robust relationship
- We validated the estimated bathymetry map and conducted a sensitivity analysis
- The proposed method can be used for bathymetry of other seasonal lakes with turbid water

Keywords

Bathymetry; Inundation frequency; Remote sensing; Hydrology; Ecology

1. Introduction

Large seasonal lakes are critical for controlling river flooding by storing water temporarily, acting as important sediment and nutrient sinks, and serve as crucial natural habitats for aquatic and avian species (Dunne, et al. 1998, Mertes 1997; Junk, 1989 and 1997). They
are important global carbon and nutrient sinks (Curtarelli et al. 2016, Downing, 2006, Kalinin et al., 2016), as well as critical resources to humans at the local to regional scales because they provide valuable water for drinking and industrial consumption, food sources, transportation, and recreation (Postel, 2000). The bathymetry of a seasonal lake is a variable of utmost importance in limnology, ecohydrology and fluvial geomorphology because it controls the water quality, macrophyte distribution, water column mixing and stratification, sediment deposition, while sustaining the terrestrial and benthic ecosystems in the floodplain by controlling nutrient fluxes (Alcântara, et al. 2010a; Melack and Bruce, 2001, Zhang et al. 2019). It also provides clues on the history of the floodplain landscape and underlying geomorphic processes by preserving the sedimentologic records (Irion et al. 1995).

Bathymetry is also an essential input for hydrodynamic modeling and can be used to determine water resource availability for humans (e.g., Rudorff et al. 2014; Park et al. 2020).

However, traditional bathymetric survey methods pose several challenges (Agrafiotis et al., 2020, Dietrich 2017, Kasvi et al., 2019, Kinzel et al., 2013, Mandlburger et al., 2020, Shintani and Fonstad, 2017, Tomsett and Leyland, 2019). For example, vessel-based acoustic echo-sounding or total station surveys, although relatively accurate, are oftentimes restricted by high operating costs, lack of manpower, and weather conditions. In addition, these techniques require physical contact with the riverbed during the surveying, which may disturb the original topography as well as habitat features, such as fish spawning locations (Kasvi et al., 2019). Moreover, their usage involves a trade-off between spatial extent and spatial resolution, which could lead to a discontinuous collection of topography from the river bed and an incorrect interpretation of phenomena such as erosion and deposition volumes (Lane et al., 1994; Westaway et al., 2001). Furthermore, bathymetric measuring devices such as echosounders were developed mainly for water bodies with relatively deeper depth (>0.2m), resulting in poor spatial resolution and precision when used in shallow zones with depth <0.2 m (Kasvi et al. 2019, Dietrich 2017, Yorke and Oberg 2002). Therefore, mapping bathymetry via conventional methods is challenging and even more difficult at a large spatial
scale. Given these numerous difficulties, it comes as no surprise that bathymetric data is scarcely available in remote places such as in the world's large rivers and lakes where access is limited, and navigation is difficult, even for the rivers of global importance such as the Mekong or Amazon (Bangen et al. 2014, Schaperow et al., 2019).

Remote sensing of bathymetry in coastal research has been practiced since the 1980s (Lyzenga 1981, Gould et al., 1997, Sandidge and Holyer, 1998) and have been more recently applied to rivers and streams (Winterbottom and Gilvear 1997, Bryant and Gilvear, 1999). Remote sensing of bathymetry is a rapidly growing field in fluvial geomorphology, considering the recent advancements in the availability of quality satellite images (e.g., resolution and pixel sensitivity) and processing methods that offers a more flexible alternative to the conventional mapping methods and may enable larger-scale depth measurements over a multi-temporal scale (Chernyshov et al. 2020, Hilldale and Raff, 2008, Kinzel et al., 2007, Marcus and Fonstad, 2010, Tomsett and Leyland, 2019).

Remote sensing of bathymetry can be broadly divided into none-imaging (Light Detection and Ranging, LIDAR) and imaging or optical methods (Feurer et al., 2008, Gao 2009, Woodget et al. 2015). Depth retrieval in rivers by non-imaging methods relies on detecting the distance between the sensor, water surface, and riverbed using near-infrared (NIR) laser pulses (e.g., Lague et al., 2020, Schwarz et al., 2019, Saylam et al., 2018). In contrast, imaging methods (airborne and spaceborne imaging techniques) estimate the water depth based on the image pixel values (e.g., Dierssen and Zimmerman, 2003, Legleiter 2016, Legleiter and Fosness, 2019). These techniques have their own strengths and limitations. For example, none-imaging LIDAR bathymetry requires low-altitude aircraft (a plane or helicopter), which is expensive and reduces user control over survey timing and frequency (Kasvi et al., 2019). In addition, various environmental conditions may affect the transmission of the laser pulse through water, making it more difficult to separate the reflections from the water surface, water column and the bed (Kinzel et al., 2013, Lague and Feldmann, 2020, Pan et al., 2015, Schwarz et al., 2019, Su et al., 2019, Xing et al., 2019, Yang, et al., 2020,
Zhao et al., 2018). The availability of the Unmanned Aerial Vehicles (UAVs), along with the cheap and accessible application of structure-from-motion (SFM) photogrammetric techniques have increased the usage of imaging methods by fluvial geomorphologists (Shintani and Fonstad, 2017, Javernick et al., 2014). Satellite imaging, while often obstructed by cloud, can be used to obtain shallow water bathymetry over a relatively larger extent (Fonstad and Marcus 2005, Legleiter et al. 2009, Moramarco et al. 2019). However, the accuracy of both imaging and non-imaging methods is largely influenced by a variety of instrumental and environmental factors such as the image resolution, signal-to-noise ratio (SNR), cloud cover and local weather condition, and the capability of the signal penetrating the water due to its optical properties, floating and submerged vegetation, turbulent flows, and the amount of suspended sediments in the water among many other factors (Agrafiotis et al. 2020, Eren et al. 2019, Flener et al., 2012; Kasvi et al. 2019, Legleiter et al. 2018, Li et al. 2019, Mandlburger et al., 2020, Overstreet and Legleiter, 2017, Saylam et al., 2018, Tomsett and Leyland, 2019).

Among the listed factors above, suspended sediment, together with the suspended organic matter (e.g., chlorophyll-a) and Colored Dissolved Organic Matter (CDOM), is usually the predominant factors controlling the lake water turbidity. The applicability and accuracy of both imaging and non-imaging remote sensing techniques are largely constrained by water turbidity as it obstructs the path of electromagnetic radiation, and light reflectance by suspended sediments will be interrupted with the river bed reflections (Gao 2009, Legleiter et al. 2018 and 2019, Saylam et al. 2018). Since most studies to-date have relied on spectral characteristics of the bedforms based on optically imaging methods, the performance of their optical approaches is limited to relatively less turbid, shallow water bodies as the light energy reduce exponentially through the water column (Feurer et al., 2008, Polcyn et al., 1970, Lyzenga, 1978).

In this study, we present a new method to derive the bathymetry of a large seasonal lake solely using remote sensing data. The performance of this method is independent of turbidity
conditions. The Inundation Frequency (IF) map based on more than 32 years of composite optical remote sensing data by Pekel et al. (2016) was used to calibrate the surveyed depth information to retrieve a mathematical relation between the two variables. This method was tested (calibrated/validated) on the Curuai floodplain lake in the lower Amazon River. The Curuai floodplain lake is one of the largest lakes in the Amazon, where the lake area seasonally fluctuates between 600-2,300 km² every year, storing ~6 km³ and 25 million tons of water and sediment during the rising phase, respectively (Alsdorf et al. 2010, Alcântara et al. 2010b, Park and Latrubesse, 2019). This floodplain was chosen as a testing site because it is the only floodplain in the basin where the bathymetry has been surveyed (Barbosa et al. 2006), and it is operated by a gauge station. The possible effect of gradual sedimentation in the lake over time, on the model’s performance, is discussed in-depth and accounted for.

The innovative aspect of our proposed approach lies in the usage of IF maps, which are built upon binary information (water or non-water pixels) to estimate the lake depth. This would overcome most of the conventional bathymetric imaging limitations caused by the environmental factors listed above. For instance, the two most limiting obstacles, i.e. turbidity and depth, are efficiently controlled since this method does not use the water-leaving reflectance, but it infers the spatial distribution of depth based on IF values. Moreover, the usage of IF data is not spatially limited. Therefore, the proposed method can be used to derive bathymetry by solely using remote sensing data for any seasonal lake, whether turbid or deep, around the world. Finally, given that IF data has been recently made public at a global scale by Pekel et al. (2016), the proposed method may become an attractive option for environmental managers with little expertise in remote sensing, since deriving IF from several decades of images can be a challenging task for them. On the other hand, multiplying the calibration model (IF-depth) to IF maps is a relatively simple GIS task that can be readily done by any open-source software. This method has the potential to be applied in numerous types of environmental studies where bathymetry information is
indispensable, such as flood mapping, nutrient and sediment storage, and human impacts on water supply, from local to regional scales.

2. Data and methods

The developed approach was tested at the Curuai floodplain, which is located 850 km from the Atlantic Ocean, near the city of Óbidos, Pará State, Brazil (2°16′4.8″S, 55°28′7.1″W). The bathymetry survey data of Curuai floodplain was acquired from Barbosa et al. (2006). The survey was conducted with the Lowrance-480M single-beam echosounder in June 2004, which is typically when peak discharge occurs in the Amazon river (Figure 1A). The bathymetry data interpolated based on depth across a length of 4,600 km survey transect, has a sufficiently high resolution (15 m horizontal and 1 cm vertical), which can be used for grid-based hydrologic modeling or storage volume calculations.

IF data of Curuai floodplain over the Amazon river was extracted from the publicly available Global Surface Water database (Pekel et al., 2016) (Figure 1B) in which the authors used a 32-year (1984-2015) Landsat imagery archive to extract open-water bodies and determine IF at a global scale at 30-m resolution. IF in their database is scaled from 0-100%, indicating no inundation (dry surface) and permanent water body, respectively. The 32-year duration of the IF data was long enough that even the deepest part of the lake experienced completely dry conditions several times, and the maximum IF was 95% at the southeast part of the Curuai floodplain, which is the deepest.

Firstly, within the extents of Curuai floodplain, a fishnet (200m x 200m) was generated, which resulted in 46,400 grids (Figure 1C). The attribute table of this fishnet contains values of IF (%) and depth (m) from bathymetry rasters based on their intersection. The small rounded-lakes with areas less than one square kilometer (<1 km²) within the floodplain are those that are not hydrologically connected to the river during the wet season; meaning that
their IF is not in phase with the river hydrograph (Park and Latrubesse, 2017), and therefore these lakes were filtered out from the further analysis.

In the next step, IF and depth values were plotted against each other (Figure 1D), showing a robust relationship between the variables, with a statistically significant slope at 95% confidence level ($p$-value<0.001 and $R^2=0.58$). Although the two variables are highly correlated over the complete IF range (0-100%), we noticed that the correlation was much stronger over the range above IF=50%. Indeed, the available data point distribution below IF=50% is sparse, with only 404 points out of 45,700 points in the fishnet grid (i.e. approximately 0.8%). When we used the Analysis of variance (ANOVA) test using only these 404 points, the slope between the two variables was not statistically significant ($p$-value=0.45).

Figure 2 shows the cumulative distribution of the lake areas plotted against the IF, showing the insignificant extent of the area covered by points with IF<50% and their geographical distribution in the area of study. These points are mostly located at the peripheral lake boundaries, levees, and floodplain channel ridges, which are positive landforms where the depth is shallow even during the peak flood season. These landforms are rarely inundated and are not in strong phase with the river seasonality (hence IF is less sensitive to it), and therefore were filtered out in the analysis.

The refined empirically driven relationship was applied to the IF layer to generate a bathymetry map of the Curuai floodplain. We assessed the accuracy of the resulting floodplain bathymetry using two sources. First, we performed residual analysis through leave-one-out cross-validation using the identical echosounder-driven bathymetry data that was used to derive the empirical relationship. Then, it was further validated using the most recent vegetation-removed Digital Elevation Model at 90m spatial resolution (MERIT-DEM) (Yamazaki, 2017) over the floodplain. Although the vertical resolution of MERIT-DEM could be considered relatively coarse (1m) to validate the flat topography of bathymetry, this is
presently the most accurate depth measurement (compared to other DEMs) that can enable us to validate our results in the remote floodplains in the Amazon.

Figure 1. Curuai floodplain in the Amazon river (extent delimited by white dashed line). A: Bathymetry survey data in June 2004 collected by Barbosa et al. (2006). B: Inundation frequency (IF) data from Pekel et al. (2016). C: Generated fishnet grid (200m x 200m) intersecting IF and bathymetry rasters (Attribute table of the point file consisting of three fields is shown as an example). The Inset map shows the Amazon Basin and the major hydrographic networks. The three important large major tributaries are labelled: Madeira (MA), Negro (NE), and Tapajos (TA). D: statistical relationship (raw correlation) between the depth and the inundation frequency.
**Figure 2.** A: Cumulative distribution of lake areas (%) showing an insignificant area of water bodies with IF<50% at Curuai floodplain. B: Geographical distribution of points with IF<50 % at Curuai floodplain (N=404) and selected regions magnified. The background is the Landsat true color image (30 m) during flood season showing representative geomorphic features in the impeded floodplain (floodplain channel, rounded lakes, and levee complex) and distribution of points.

### 3. Results

#### 3.1. The relation between inundation frequency and lake depth, and cross-validation

Using the remaining data points (over a range of IF>50% and Area <1 km²), a linear regression model was fitted to the depth-IF data. Figure 3A presents this linear relationship where the slope between the two variables is statistically significant at a 95% confidence level ($p<0.0001$). The coefficient of determination ($R^2$) of the regression model is 0.62, an increase from 0.58 when points with IF<50% are filtered out. Figure 3B presents the cross-validation results with the residual at the vertical axis over different IF range (50-100%), showing that the distribution of the residual is inconsistent. For that, we analyze the residual over three separated IF zones: 50-63%, 63-93%, and 93-100%, which are separated by lines intersecting RMSE=0 (Figure 3B). Each IF zone presents a distinct error pattern, whether over- or underestimation, with different levels of RMSEs.

For the IF ranging between 50-63%, the regression model tends to underestimate the depth with an average RMSE of 0.45 m (Figure 3A red dashed circle). This underestimation may be explained by the morphological complexities of the floodplain that develops into a patchy hydrological network of several rounded lakes (Alsdorf, 2003). In the lower Amazon River, there are two flooding mechanisms: channelized flow and overbank dispersion (Dunne and Aalto, 2013). Channelized flow can be initiated through the breached levee, and floodplain channels are developed to hydrologically connect the rounded lakes in the floodplain. It has been recently observed that, however, this channelized connectivity does not necessarily
relate to the proximity of the lake to the river (Park and Latrubesse 2017). Because some rounded lakes are not hydrologically linked to the river via floodplain channels, instead they are connected at a relatively later stage due to locally elevated topography. Nevertheless, most of these rounded lakes located close to the river are susceptible to overbank flooding during the high water period (rather than channelized flows), and they receive a good part of the annual water and sediment budgets through this process (Park 2020, Rudorff et al. 2018). Therefore, the rounded lakes adjacent to the river could have relatively lower IF but have deeper depth during the high-water season. We visually confirmed that most of these data points within and close to the red dashed circle in Figure 3A are small rounded lakes close to the river. They are hydrologically connected mostly by overbank flows, or connected to the river at a very late stage during the high-water season. This was verified using the weekly time-series of Surface Suspended Sediment Concentration (SSSC) maps developed along the lower Amazon River by Park and Latrubesse (2014).

The other two zones with IF ranges 63-93%, and 93-100% presented small RMSEs of 0.16 and 0.27m, respectively. The small degree of overestimation for the latter zone (93-100%) is also related to the seasonal connectivity of the lakes with the channel over the deeper part of the floodplain, where most of the channels are permanent water bodies (Hess et al. 2003). These permanent water bodies present IF=95% (although they are disconnected to the river during the dry season), thereby ramping up the overall IF value and limiting the sensitivity of the depth-IF model. This sensitivity issue was further analyzed and discussed in detail in the next section.

Analysis of our model showed different residual patterns along with the different levels of IF, which is mainly related to the floodplain’s hydrogeomorphic control. The presented RMSEs of the model is small (0.16-0.45m), being less than 5% of the annual water stage variability of the Curuai floodplain lake (~8m on average). Compared to the other studies that estimated riverine bathymetry from remote sensing, the RMSEs from our model are much smaller. For example, Yuan et al. (2020) mapped a portion of a floodplain topography of the
Congo river by combining Interferometric Synthetic Aperture Radar (InSAR) and satellite altimetry with an RMSE around 2.71m; Kasvi et al. (2019) used optical modeling to map bathymetry in a small river (width ~20m) with errors ranging between -0.05 m to -0.12m. In fact, a few cm-scale accuracies could be achieved mostly in much smaller scale bathymetric studies where high-resolution images and detailed reference data are acquired through a field survey (Curtarelli et al. 2015). Upon validation of the inferential statistics of the IF-depth model, the bathymetry of the Curuai floodplain was estimated, as illustrated in Figure 3C.

**Figure 3.** A: Linear regression relationship between the depth and inundation frequency, which is statistically significant at a 95% confidence level. B: Depth residuals of the regression model and Root mean square error (RMSE) over different IF ranges. C: Estimated bathymetry over the Curuai floodplain.

3.2. Validation of the result

The most accurate data for validation of our relationship is perhaps the field survey bathymetry, which was used in the previous section to establish the linear regression and to cross-validate the estimated depth. In order to further validate our results, the MERIT-Digital
Elevation Model (MERIT-DEM) (Yamazaki et al. 2017) was used over the Curuai floodplain. Although a global-scale DEM such as the MERIT-DEM, may not be sufficiently accurate at a local-scale, this is currently the best topography data available for validation of results.

The baseline of the DEM’s elevation values was corrected based on the mean monthly water level of June 2004 when a bathymetric field survey was conducted by Barbosa et al. (2006) for comparison with our estimated bathymetry. Figure 4A shows a linear relationship between the estimated depth and the elevation extracted from the corrected DEM data. The correlation coefficient is high (R=0.73), with relatively constant residuals across different depths. Given the coarse resolution of the DEM, which may lead to omitting subpixel topographic variation, the validation result is satisfying.

The model’s sensitivity was further tested over the deepest part of the lake (known to be a permanent water body, according to Hess et al. 2003) where the highest IF was 95%. In order to test the model’s sensitivity to IF, and therefore its ability to accurately estimate depths over permanent water bodies, we modelled the deepest part of the lake using a 10 km transect (A-A’) of the floodplain within the Curai Lake (Figure 4B). Figure 4C shows the surveyed depth and the inundation frequency used in this study across the AA’ transect, which clearly shows that the depth and IF have a negative relationship with a high correlation coefficient (R=0.81) in the deepest part of the lake. Therefore, even in the deepest part of the lake, the estimated depth can be considered sufficiently sensitive to the IF.

Figure 4C shows that even at the deepest part of the lake, the average inundation frequency over a 32-year period does not reach 100% (i.e., 95%). This implies that the lake must have been completely dry at some points over this long period. We plot the daily water level data measured over 32 years (1982-2013) at the Curuai gauge station obtained from the Hydro-Geodynamics of the Amazon (HYBAM), which is close to the deepest part of the lake (Figure 4C). Also, we acquired a Landsat image on December 31st in 2010 over the transect when
the lake was relatively dry (Figure 4E), and the water level at the station was low (456 cm). This image showed that vegetation in the floodplain bed was exposed; these were a mixture of shrubs, bare land, or grasslands, but not flooded forests (Hess et al. 2003, Martinez, 2007). Although the lake was not completely dried on the date of this image, as shown in water level records from the Curuai station, the annual minimum water level fell below 456 cm in a total of 10 times (Figure 4D). In other words, the Curuai lake had experienced episodes of even drier conditions than what is reflected in the Landsat image presented in Figure 4E. This observation corroborates with the fact that the IF over the floodplain computed by Pekel et al. (2016) derived using all the available images from the Landsat archive since 1985, did not reach 100% over the floodplain. In the whole Curuai floodplain, the highest IF is ~95%, and this is because the relatively deeper part of the lake also experienced several dry conditions over the past few decades. Therefore, in this study, IF constructed using long-term data (in this case > 30 years) is sufficiently sensitive to map the floodplain bathymetry, including the permanent water bodies.
4. Discussion: Applicability and possible limitations

In this study, we demonstrated the application of our proposed method using a case-study in the Curuai floodplain in the Amazon. The proposed method has foreseeable potential applicability to other large seasonal floodplain lakes on a global scale. Curuai floodplain has a patch network of large irregular shaped rounded lakes, often referred to as impeded floodplains, divided by ridges formed by the progradation of floodplain channels (Alsdorf 2003; Park and Latrubesse 2017). This hydro-geomorphic characteristic of the Curuai represents the lower Amazon floodplain geomorphology. It is also an important characteristic of many large anabranching rivers worldwide (Dunne and Aalto, 2013; Latrubesse, 2008). Therefore, when the proposed model has been validated in Curuai, we may consider its applicability in other lower Amazon floodplains and also on a global scale over floodplains presenting similar geomorphic styles. Moreover, generating IF maps is usually a computationally intensive work which requires some expert knowledge in remote sensing, the publicly-available global-scale IF maps produced by Pekel et al. (2016) would facilitate the derivation of bathymetric maps of seasonal lakes by a wide variety of environmental managers and scientists.

The proposed method is not limited to only floodplains (regions) where bathymetry data is available a priori. Available DEMs at a global scale, such as the SRTM (Farr et al. 2007) and its derived products which were used to validate results in this study, can be used to estimate the bathymetry. On the other hand, bathymetry data is becoming increasingly
available with advances in surveying techniques and UVAs (Lewis and Park, 2018). For smaller scale bathymetry mapping where depth has not been surveyed, and the coarse resolution of the global DEM is not feasible, our proposed method still would provide qualitative results of depth (i.e., relative depth), even when IF data is not calibrated with the depth data. That will provide the general topography of the floodplain, which can still be considered a valuable source of data for researchers in the field of riverine environments. Nevertheless, an efficient alternative would be to survey the bathymetry of a part of the lake (given that surveying the bathymetry of the entire lake will be time-consuming and logistically difficult), to generate a minimal number of depth samples to calibrate IF.

As illustrated, the accuracy and sensitivity of depth estimation based on IF may be lower for the deeper part of the lakes where IF is ~95%, and the lake is almost permanently underwater (Figure 4). The sensitivity tests in the current study, however, showed that the model is still considered sensitive when the deepest cross-section of the lake was analyzed due to the long span of observations. However, this would depend both on the lake morphology and hydroclimatic regime, considering that the inter-annual climatic variability can be significant in the large river basin (Darby et al. 2016, Marengo et al. 2018). We believe that the use of a long time series of IF data will, to some extent, ensure that even the deepest parts of the lake and permanent bodies are accounted for.

Large river floodplains such as the tropical Amazon are large sediment depositional systems (Park & Latrubesse 2019), and therefore their bathymetries are susceptible to continuous aggradation. However, the trapping efficiency of sediment is low when averaged over a large area. For example, it has been reported by several authors that the Curuai floodplain stores around 2-40 Mt/yr (Park & Latrubesse 2019; Dunne et al. 1998; Rudorff et al. 2018), and when divided by the total floodable area during the flood peak, the average sedimentation rate is around 1 cm/yr. Another study showed a similar rate (~1 cm/year, although not spatially distributed information) based on the $^{210}$Pb chronology of sediment cores obtained from the floodplain (Moreira-Turcq et al. 2004). Since the IF used in this study was based on
32-year Landsat images (1984-2015), IF might have been affected by effect of floodplain aggradation during this period. Approximately 30 cm of aggradation of floodplain topography can be expected based on these published sedimentation rates of the floodplain. However, we argue that this effect is still negligible because it represents less than 4% of the annual water level variability of Curuai lake (i.e. ~8m). Moreover, the gradual sedimentation over a long-time period on the lake has been accounted for in the IF, because IF represents an “average” pattern over the composite image period. That means, when elevated landforms due to sedimentation change the depth of the lake, the altered water residence time subsequently adjusts the IF.

5. Summary

A new method for retrieving bathymetry from Inundation frequency data was proposed and tested over the Curuai floodplain in the Amazon. Integrating publicly available global IF maps produced by Pekel et al. (2016) over a 32-year span with measured field bathymetry by Barbosa et al. (2006), we established a linear relationship between the two variables and presented statistically significant slope with a high coefficient of determination ($R^2=0.62$). Based on this, the bathymetry was estimated over the whole floodplain. The accuracy of the bathymetry was tested against the MERIT-DEM model, and its sensitivity was assessed in the deepest part of the lake where IF is ~95%. The accuracy and sensitivity analyses both showed that model to be robust and can be applied to estimate bathymetry in other seasonal lakes and floodplains around the world.

Bathymetry of large seasonal lakes can be easily retrieved using the newly proposed approach and the publicly available global-scale IF maps produced by Pekel et al. (2016). The retrieved bathymetry can be further verified and calibrated either using available DEMs at a global scale, such as the publicly available SRTM or UVAs surveying. While we acknowledge that both accuracy and sensitivity of the proposed method are reduced at the
deepest part of the lakes where IF values are ~95%, our proposed approach can still yield valuable data of the general topography of the floodplain bed since long durations of IF data (32 years) and inter-annual climatic variability, specifically at large river basins, can enhance the sensitivity and accuracy of the proposed approach (as shown in this study). Finally, we showed that the effect of bed aggradation in bathymetry variation is small. Aggradation is negligible when averaged over the large area of the river basin (approximated as ~1 cm/year), and insignificant when compared with the annual water level variability.

The proposed approach has two unique advantages over conventional methods that retrieve bathymetry from remote sensing. Firstly, it can be applied in turbid waters since it uses binary information (water or non-water pixels) instead of the electromagnetic radiation or light reflected by the water surface or riverbed to estimate the depth. This overcomes most of the conventional bathymetric imaging limitations caused by environmental factors and can solely use remote sensing data for any seasonal lake, whether turbid or deep. Secondly, the newly proposed approach uses the publicly available global IF maps and a simple Geographic Information System (GIS) workflow to compute the depth, and it does not require sophisticated analyzing capacity or expertise processing/interpreting remote sensing data. Therefore, the proposed technique can be easily applied by environmental scientists, engineers, and managers from diverse technical and scientific backgrounds to retrieve bathymetry for environmental studies, such as flood mapping, habitat analysis, and storage capacity, among other wide sets of applications.

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References


