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Retrieval of Simultaneous Water-Level Changes in Small Lakes With InSAR

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Key Points:

- We demonstrated the utility of synthetic aperture radar interferometry to track water level changes in small ungauged lakes simultaneously
- Regional precipitation and area of lakes conditioned the spatiotemporal patterns of changes in water level
- Irregular topography and surrounding elements on the lake shores were crucial for the use of radar interferometry

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Monitoring water level changes is necessary to manage, conserve and restore natural, and anthropogenic lake systems. However, the in-situ monitoring of lake systems is unfeasible due to limitations of costs and access. Furthermore, current remote sensing methods are restricted to large lakes and low spatial resolutions. We develop a novel approach using subsequential pixel-wise observations of the Sentinel-1B sensor based on interferometric synthetic aperture radar to detect water level changes in small lakes. We used 24 small ungauged lakes of the Cajas Massif lake system in Ecuador for development and validation. We found Differential Interferometric Synthetic Aperture Radar (DInSAR)-derived water level changes across lakes to be consistent with precipitation, capturing the peak of the wet seasons. Furthermore, accumulated water level changes could be explained by differences in lake area among lakes. Although with limitations, this study shows the underutilized potential of DInSAR to understand water level changes in small lakes with current radar data availability.

Plain Language Summary

Lakes are essential elements of the hydrological cycle, and changes in lakes water availability affect their aquatic and terrestrial ecosystems and their associated watersheds. Monitoring water level changes is necessary to manage lake systems worldwide; however, monitoring remote and small lakes is unfeasible due to limitations of costs and access. We develop a novel approach that combines satellite remote sensing radar imagery to detect water level changes in small lakes. We used 24 small and high-altitude unmonitored lakes in Ecuador for development and validation. We found the water level changes across lakes to be consistent with precipitation in the region. Furthermore, accumulated water level changes could be explained by differences in lake area among lakes. Our methodology underpins the underutilized potential of satellite radar observations to understand water level changes in small lakes. It also has considerable potential for the near real-time monitoring of lake systems worldwide from space observations.

1. Introduction

Lakes are essential elements of the hydrological and biochemical cycles (Prigent et al., 2012). They store a large proportion of surface freshwater (Woolway et al., 2020) and offer numerous ecosystem services such as fresh water supply, storage and regulation, food security, recreational opportunities, and transportation (Ye et al., 2017). Furthermore, lakes are strategic ecosystems and fundamental for analysis, monitoring, and achieving sustainable development (Jaramillo et al., 2019; UN General Assembly, 2015; Woolway et al., 2020). Changes in lake water availability affect the dynamics of their aquatic and terrestrial ecosystems and their associated watersheds (Woolway et al., 2020). These changes arise from accelerated Earth system change, driven by direct human activities and climate change. Lake water levels determine if their aquatic and related terrestrial ecosystems can withstand such threats, if the lakes turn from carbon sinks to sources, and if their freshwater can be used as a resource.

Monitoring lakes worldwide is a challenge. First, with almost 117 million still inland waters worldwide, the logistics and the costs required to monitor water level changes worldwide are enormous (Hegerl et al., 2015; Verpoorter et al., 2014). Second, the scarcity and discontinuity of long-term, homogenous hydrologic observations

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make it challenging to determine water level and storage changes worldwide (Alsdorf & Lettenmaier, 2003; Cao et al., 2018; Pontes et al., 2017; Woolway et al., 2020). Third, since most lakes are small (<10 km^2), there is an increasing need to develop technologies that can monitor their latest and ongoing hydrological changes (Alsdorf et al., 2003; Yao et al., 2018).

Satellite data offers a viable alternative for evaluating water level change in large lakes (Crétaux & Birkett, 2006), providing tools for calibrating and validating hydrodynamic models at regional scales (Fang et al., 2019; C. Tan et al., 2017), and improving the global understanding of lake changes with high spatial heterogeneity (Woolway et al., 2020). The main approaches used are radar and lidar altimetry (Chu et al., 2008; Song et al., 2015; Sulistioadi et al., 2014; Zhang et al., 2011), satellite gravimetry (Ramillien et al., 2014), and estimation of water extent (Ferrentino et al., 2020; Hong et al., 2010). However, with few exceptions, the most widely used altimetric approaches are currently spatially limited by resolution to large lakes and water bodies located directly under the orbit path, missing many small lakes worldwide (Alsdorf et al., 2007; Kuo & Kao, 2011; Mohammadimanesh et al., 2018; Sulistioadi et al., 2015).

Another space-based technology known as Differential Interferometric Synthetic Aperture Radar (DInSAR) can be used to determine water level change in tropical vegetated wetlands and river floodplains of large extent (Cao et al., 2018; Jaramillo et al., 2018; Palomino-Ángel, Anaya-Acevedo, Simard et al., 2019; Wdowinski et al., 2008; Zhang et al., 2016). However, there is the common assumption that DInSAR cannot be used to track changes in lakes since (a) DInSAR only provides relative changes in space and water level changes in lakes are mostly uniform, and (b) there is lack of reference structures that enable the double-bounce of the radar signal necessary to retrieve water level changes. Nevertheless, the increasing availability of SAR data in the last decade, as is the case with the European Space Agency's Sentinel-1 mission, and the future launch of other SAR missions with high temporal, and spatial resolution such as the NASA-ISRO Synthetic Aperture Radar (Kellogg et al., 2020) invite for a deeper analysis of the strengths and shortcomings of DInSAR to monitor water levels in small lakes (Brisco et al., 2017; Mohammadimanesh et al., 2018).

Our study aims to address this challenge by developing a methodology based on Sentinel-1B interferometric phase observations to track water level changes trends in a large set of small lakes. We used the Cajas Massif lake system in Ecuador for the study due to the considerable heterogeneity of lake characteristics. We selected 24 lakes across the lake system with varying elevation, size, and morphology. Since the lakes are ungauged, we attempted to associate the water level changes to precipitation and the variability of altitude and surface area among the lakes for cross-validation. We calculated relative water level changes in each lake based on selected pixels with the highest radar signal coherence.

2. Methodology and Datasets

2.1. Study Area

The Cajas Massif, located in the southern Andean region of Ecuador (Figure 1a), has approximately 5,955 water bodies (Mosquera et al., 2017), spanning from a few square meters to 775,000 m^2. More than 50% of the water stored is contained in the ten deepest lakes. The main soil types in the region are non-allophonic Andosols and Histosols from volcanic origin, characterized by high organic matter content, high porosity, low apparent density, and a high water retention capacity (Borja & Cisneros, 2009; Buytaert et al., 2005; Crespo et al., 2011). Thus, most of the rainfall is retained in soils and released gradually to the watercourses, regulating the hydrology of these ecosystems (Buytaert et al., 2005; Poulenard et al., 2003). The main vegetation is herbaceous with a dominating presence of the genera Stipa and Calamagrostis (Ramsay & Oxley, 1997), and *Polylepis* open forest, the only tree species present above 3,400 m above sea level (a.s.l.; Alvites et al., 2019). Annual precipitation is between 900 and 1,600 mm/year with contrasting seasons and high variation from year to year (Padrón et al., 2015; Vuille et al., 2000).

2.2. Open Surface Water Differential SAR Interferometry (DInSAR) Approach

We used a repeat-pass differential interferometry approach, DInSAR, for evaluating water level changes in 24 representative lakes during the entire annual period from October 2017 to October 2018, based on SAR satellite observations taken at the same spatial location but different time acquisitions. Vegetation structure has repeatedly

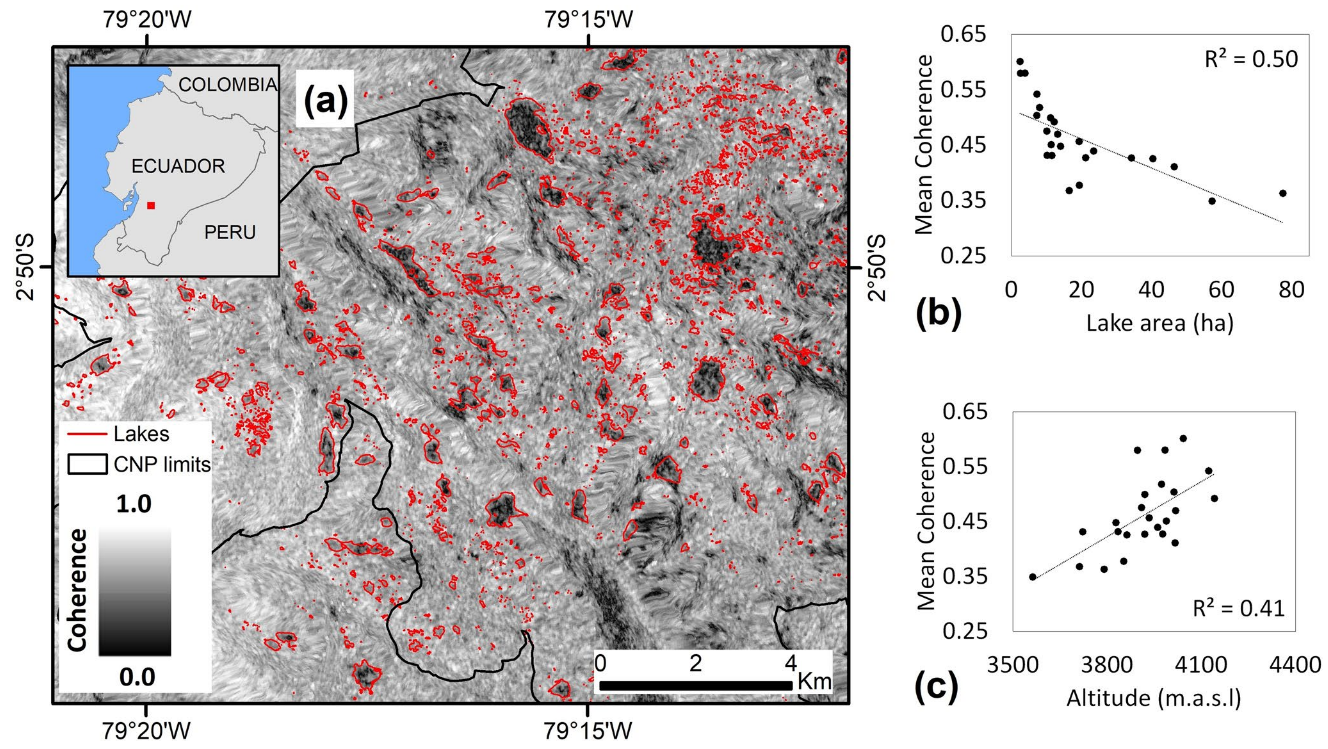

Figure 1. Lake system of the Cajas National Park in the Cajas Massif (a) coherence map for the interferogram generated with 23 August 2019 and 04 September 2019 Sentinel-1 acquisitions, where open water in lakes (red contour) usually has low coherence of the radar signal. Relation between mean coherence over the 24 lakes with (b) area; and (c) altitude.

played a fundamental role for the successful use of DInSAR in wetlands, as the specular reflection effect of the signal over the water is combined with the corner reflection of the elements on the vegetation to produce a coherent return of the signal or double bounce (Arnesen et al., 2013; Evans et al., 2010; Hoekman et al., 2010). When the water level between the observations of the satellite changes, the distance traveled by the microwave signal of the SAR also changes, producing a differential in the radar signal that can be transformed into relative water level changes. This principle has been applied successfully to track water level change in vegetated wetlands in primarily flat areas around the world (Alsdorf et al., 2001; Cao et al., 2018; Hong et al., 2010; Jaramillo et al., 2018; Kim et al., 2009; Liu et al., 2020; Palomino-Ángel, Anaya-Acevedo, Simard et al., 2019; Wdowinski et al., 2008).

However, as the smooth and flickering surface of open water surfaces of lakes can cause the return of minimum backscatter signal (O'Grady et al., 2014), an element close to the water body, or inside, is necessary to generate a coherent return of the signal to the sensor. In the case of the high-mountain lakes located above 3,500 m in the Cajas Massif, an irregular topography is present around or within the lakes, in many cases with rocky formations on the slopes of the shorelines of lakes and, sometimes, with natural rocky walls (cliffs) that can reach more than 40 m of elevation (Figure S1 in Supporting Information S1). In addition, herbaceous vegetation and Polylepis tree species on the shores may also generate pockets of signal coherence. We initially hypothesized that these characteristics yield a coherent double-bounce due to the corner reflection of the surrounding elements and topography.

2.3. Image Pre-Processing

The Sentinel-1 mission has satellites A and B launched on April 2014 and April 2016, respectively; both are currently operating. The sensors operate at C-band (Center frequency of 5.405 GHz) with a wavelength of approximately 5.55 cm, single and cross polarization (VV, VH), and a revisiting time of 12 days for the study area. In the present study, we used Sentinel-1B single look complex (SLC) data using the interferometric wide swath (IW) mode with single polarization VV. The SLC images retain both the amplitude and phase of the radar signal. Pairs of images were selected to generate interferograms and analyze the time series of cumulative DInSAR phase for evaluating water level changes over time. The Sentinel-1B IW data were obtained from the Alaska Satellite Facility online portal (https://vertex.daac.asf.alaska.edu/).

A total of 27 acquisitions were processed for the study period. All the acquisitions were geocoded to a spatial resolution of 15×15 m^2, with incident angles ranging between 20° and 45°. We used a standard processing chain to obtain the interferograms, using the SARscape/ENVI version 5.5 (Harris Geospatial Solutions, Inc.). Starting from the SLC, we co-registered the images to guarantee that the position of the objects in the field was accurate in both images. Subsequently, we determined the DInSAR phase (interferogram) for each selected interferometric pair. In this process, the pair's oldest image was considered the master image, whilst the most recent one was considered the slave image to obtain a temporal consistency for phase difference analysis (see the list of pairs in Figure S2 in Supporting Information S1).

We applied a Goldstein 5×5 phase filter to remove temporal and geometric effects (Goldstein & Werner, 1998). This filter has been widely used for InSAR (Alexakis et al., 2019; Cao et al., 2018; Palomino-Ángel, Anaya-Acevedo, Simard et al., 2019, Song et al., 2014). The coherence (i.e., the similarity between the two images of the interferometric pair) was estimated from the filtered interferogram. Interferometric coherence limits the quality of the estimation of water level changes with low coherences found mainly over water bodies (Figure 1a). However, some pixels within lakes present medium-to-high coherence due to the surrounding elements (rocks, vegetation) and rocky topography. It is these pixels that we used for the analysis. Finally, we geocoded and stacked the interferograms as a time series. We used the wrapped phase (i.e., the phase ranges in a 2π-cycle) for the analysis, considering the low coherence within the lake that limits the performance of the unwrapping and the lack of continuous fringes of coherent phase change—more common in wetlands with herbaceous and woody vegetation and with good hydraulic connectivity (e.g., Jaramillo et al., 2018; Palomino-Ángel, Anaya-Acevedo, Simard et al., 2019). The interferogram contains the phase information from the flat Earth-surface, topography, surface displacement, atmospheric effect, and noise (Bamler & Hartl, 1998; Lee et al., 2020). In this case, the phase component of the surface displacement is related to the water level change between the two acquisitions of the interferogram. Among the other phase components, the flat Earth-surface, topography and baseline noise can be removed during the interferometric process through the reference ellipsoid model, an external digital elevation model (DEM) and the orbit information, respectively (Lee et al., 2020; Massonnet & Feigl, 1998). This study used the Shuttle Radar Topography Mission's DEM in the interferogram processing.

Additionally, the radiation ionizes neutral atoms in the atmosphere, forming a layer of free electrons around the Earth, the ionosphere, which depends highly on the sun's activity (Zolesi & Cander, 2014). This effect can cause a delay in the SAR signal (atmospheric effect) and affect the interferometric phase. However, we did not expect a significant impact of the ionosphere on the interferograms as this effect is more characteristic of L-band sensors (Gray et al., 2000; Meyer et al., 2006; Rosen et al., 2010) and that the acquisition time of the satellite was consistently around 23:35 local time.

2.4. Spatiotemporal Patterns of Water Level Change in Lakes

We focused on 24 lakes presenting high interferometric coherence for the evaluated period—all unmonitored to date (Table S1 in Supporting Information S1). The lakes are distributed throughout the area of the Cajas National Park (CNP), representing different areas and altitudes. In addition, the lakes will be monitored in future field campaigns, becoming an opportunity for future calibration and validation. An inverse relationship between lake area and altitude was evident at the hydrological basin scale (Table S1 in Supporting Information S1). The spatiotemporal analysis of water level change patterns in each lake was based on the interferograms. First, the coherence of the different interferograms in every lake was analyzed. Since low coherence generates errors in estimation (Bamler & Hartl, 1998; Lee et al., 2020; Mohammadimanesh et al., 2018; Wdowinski & Hong, 2015), we selected the pixels within the area of the lakes that presented a coherence above 0.4 across all interferograms, based on a previous lake delineation obtained from orthophotography analysis (Mosquera et al., 2017; e.g., Figure S3 in Supporting Information S1 shows the case of one lake). The spatially averaged phase values for each lake were calculated, and the time series of DInSAR phase was extracted.

The averaged DInSAR phase was used to follow the trends in water level change in the lakes between the two acquisitions. We used the DInSAR phase ($\Delta\varphi$) between the two acquisitions to obtain the water level change (Δh) using the following equation (Lu & Kwoun, 2008):

$$\Delta h = \frac{\lambda * \Delta\varphi}{4\pi\cos\theta} \quad (1)$$

where, λ is the wavelength in centimeters (Sentinel-1 operates in C band with 5.55 cm), $\Delta\varphi$ is the DInSAR phase in radians and θ is the incident angle in degrees (for the images used, the incident angle ranges between 20° and 45°). Therefore, we obtained Δh for each consecutive interferogram and then accumulated the values during the whole period to obtain the series of water level changes for each lake relative to its initial value. It is worth mentioning that if the change was more than the Δh corresponding to the wavelength of the radar signal (i.e., $\Delta h = 3.49$ cm when $\Delta\varphi = 2\pi$ in Equation 1), the real value of water level change could not be retrieved since the analyzed interferograms were not unwrapped in space. Hence, we expected to obtain realistic water level change estimates when $\Delta h < 3.49$ cm. To validate the DInSAR water level data (i.e., if change did not exceed the Δh corresponding to the wavelength of the radar signal), we assessed the congruence of estimated water level change upon temporal variation of precipitation and the magnitude of area and elevation of each study lake. This form of validation was considered in the light of unavailable water level, runoff or rain gauge observations for these lakes.

We used the Integrated Multi-satellite Retrievals for GPM (IMERG) daily precipitation product with a spatial resolution of 0.1° (Chen & Li, 2016; Huffman et al., 2015; Xu et al., 2017) to calculate total precipitation over the area between SAR acquisition pairs (12 days). This product has been widely validated around the world (Asong et al., 2017; Guo et al., 2016; Li et al., 2017; Prakash et al., 2018; J. Tan et al., 2017) and specifically over the Andes region (Hobouchian et al., 2017; Palomino-Ángel, Anaya-Acevedo, & Botero, 2019), showing the good spatial and temporal distribution of mean daily precipitation. The Cajas Massif lake system is covered by six cells of the IMERG product, from which a spatial average of the cells was calculated. We calculated the Pearson correlation between precipitation and water level change for each lake from all interferograms. We hypothesized that since these lakes are located in the headwaters of the Andes, in response to precipitation variations, lake level would fluctuate accordingly around the same date, yielding high correlations. Further, lakes were grouped upon their main hydrological basins to differentiate patterns of water level change.

3. Results and Discussion

We found a significant negative relation between mean coherence and water surface area across the 24 lakes ($R^2 = 0.50$; Adjusted $R^2 = 0.48$; F-statistic = 22.38; $p = 1.0 \times 10^{-4} < 0.01$; Figure 1b). In addition, a significant positive relation between mean coherence and altitude of the lake was also evident ($R^2 = 0.41$; Adjusted $R^2 = 0.39$; F-statistic = 15.50; $p = 7.0 \times 10^{-4} < 0.01$; Figure 1c). These relationships hold for the entire set of lakes larger than one ha in the CNP (Figure S4 in Supporting Information S1). Small and high-altitude lakes appear to be the best aquatic environments for interferometric application. In the Andes, particularly owing to glacier processes, the increase in altitude is related to the outcrop of rocky topography (Coltorti & Ollier, 2000; Gonzalez & Pfiffner, 2012; Kober et al., 2007), with the presence of small cliffs on the littorals of some of the lakes, and also with less presence of vegetation (Escobar et al., 2005). These factors may increase the coherence due to specular reflection on the water and the double-bounce effect with the surrounding rocky topography. This high coherence enables InSAR to track water level changes in these small lakes.

Figure 2a presents the evolution of accumulated relative water level change in the 24 selected lakes (Table S1 in Supporting Information S1) between October 2017 and October 2018 based on the wrapped DInSAR phase of pixels with coherence above 0.4. Although water level changes exceeding 3.49 cm could not be adequately represented due to the limitations of the radar wavelength, we found that the water level trend agreed with precipitation in most lakes. Furthermore, water levels across all study lakes were consistent and followed a general pattern, even though DInSAR calculations for each lake were based on independent SAR observations. In general, the lake water level started increasing in February to reach its peak at the beginning of April, followed by a steady decrease until June—this behavior mirrored the variation of precipitation across the study period. Furthermore, the lakes belonging to the same hydrological basin presented similar patterns of temporal variation of water levels. Figures 2b–2d shows the evolution of accumulated relative water level change in basins with at least three lakes. The increasing variability of water level changes in time is explained by the accumulation of errors from changes exceeding 3.49 cm or simply by hydrological variability among lakes.

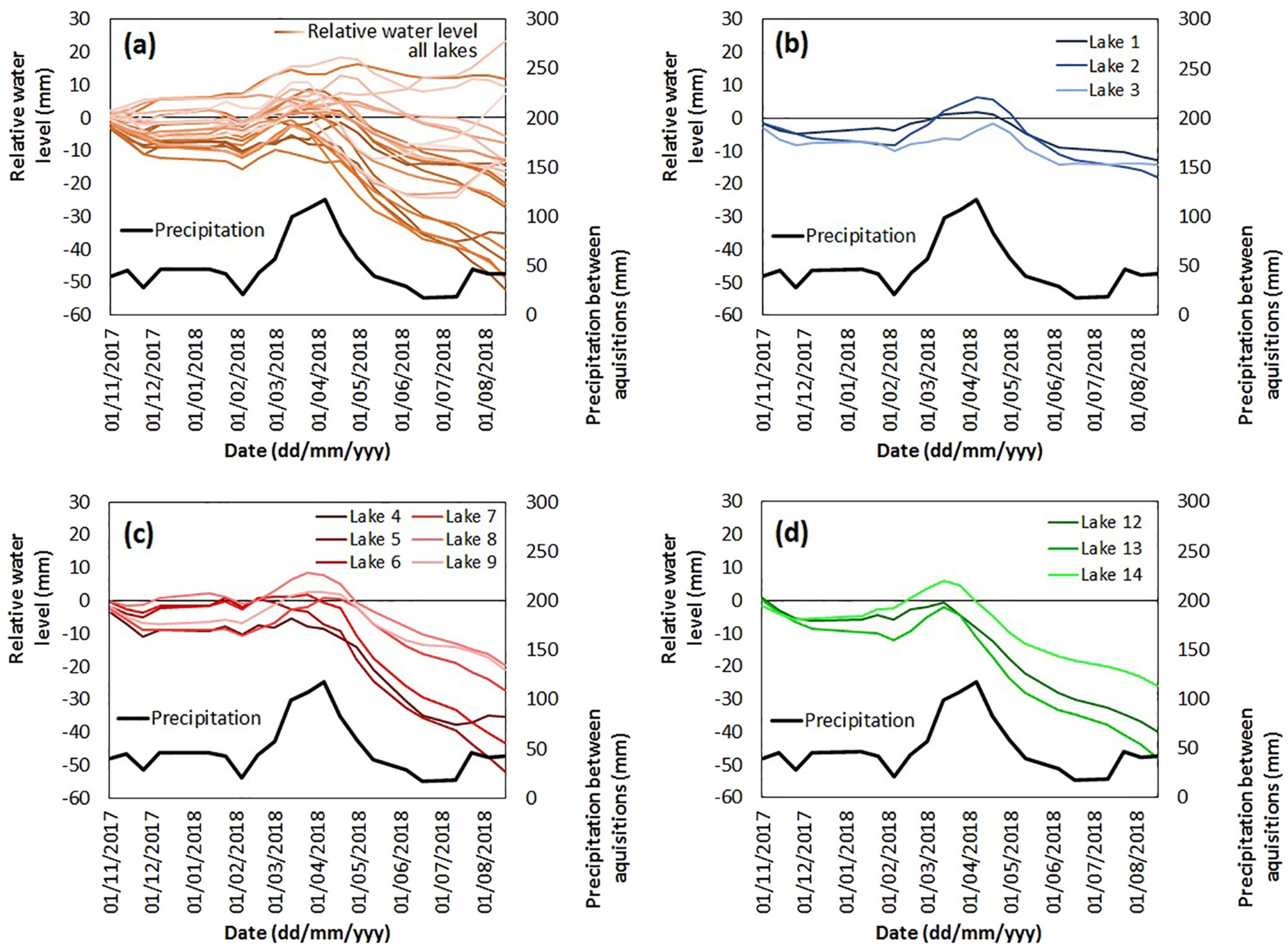

Figure 2. The water level in 24 lakes relative to the initial value of the series (a) total precipitation falling between acquisition pairs (black) and water level changes in all lakes (orange), and for hydrological basins with at least three lakes: (b) lakes 1–3 (blue), (c) lakes 4–9 (red), and (d) lakes 12–14 (green).

The range of water level change between consecutive radar acquisitions for the whole period $\Delta h_{max} - \Delta h_{min}$ (<3.49 cm) agreed well with basin-scale precipitation in some lakes, reaching Pearson correlations of 0.65. However, other lakes presented very low correlations, such as Huananchi or Estrellas Cocha lakes (lakes number 11 and 20 in Figure 3a, respectively). We found significant negative relationships between $\Delta h_{max} - \Delta h_{min}$ and lake area ($R^2 = 0.59$; Adjusted $R^2 = 0.58$; F-statistic: 33.61; $p < 0.01$; Figure 3b), but a poor relationship with altitude ($R^2 = 0.18$; Adjusted $R^2 = 0.15$; F-statistic: 5.08; $p = 0.03$; Figure 3c).

The magnitude of water level change decreases with lake area since there is a direct relationship between the volume and area in each lake (Mosquera et al., 2017) and because due to the abrupt topography, hydraulic connectivity between lakes is low. Thus, the same precipitation event will yield smaller water level changes for lakes with greater differential volume. This finding is consistent with studies on large lakes using altimetry and optical satellite data, where variations in the water level were related to the area and volume of the lakes (Duan & Bastiaanssen, 2013; Ye et al., 2017; Zhang et al., 2017). We showed how lake morphological conditions and satellite-derived precipitation could be used to validate remote hydro-geodetic technologies in the absence of in-situ measurements of water level. The method can be used for similar high-altitude lakes in the region and globally (Buytaert et al., 2006; Adrian et al., 2009; Fang et al., 2019; C. Tan et al., 2017).

Contrary to other DInSAR assessments detecting relative water level changes in wetlands, we used the wrapped phase of the interferograms for lakes. Since, we used selected pixels with high coherence and the lakes have a small spatial extent, spatial unwrapping of the radar signal was challenging to execute. We assumed that the wrapped phase taken from interferometry directly could be related with water level change without the need of

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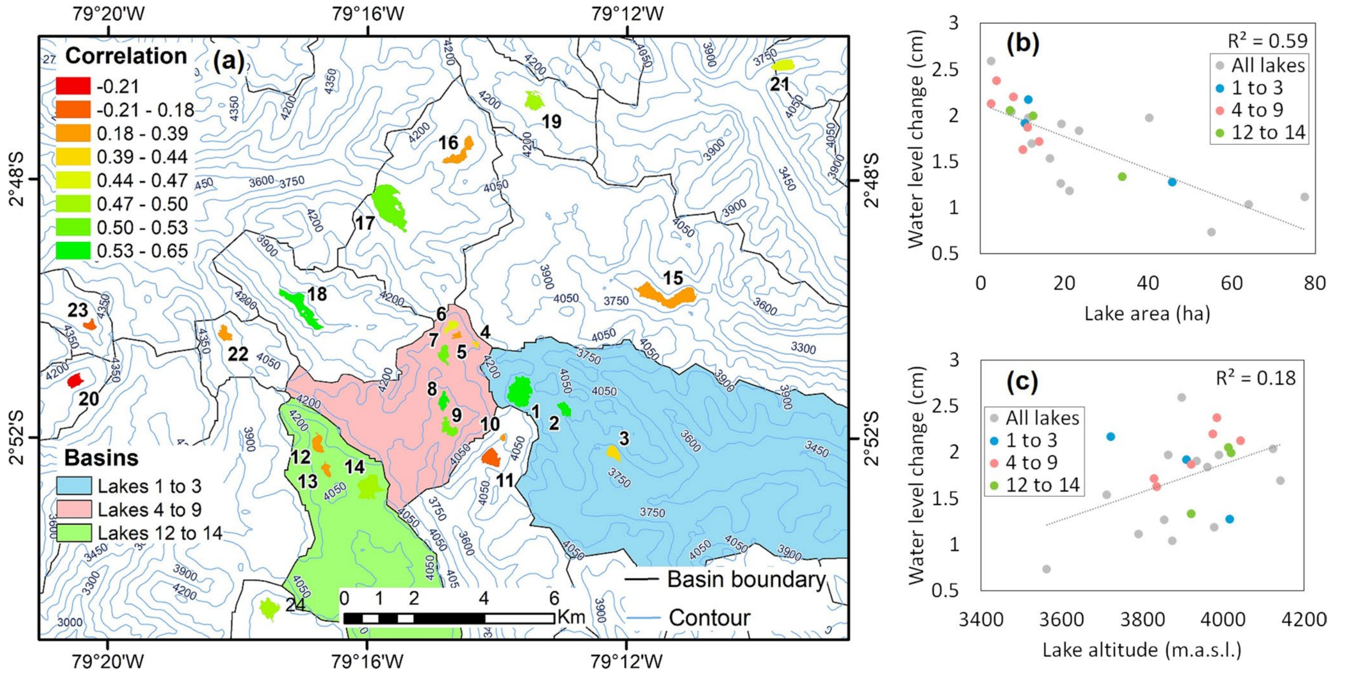

Figure 3. Agreement of water level change and precipitation. (a) Spatial distribution of Pearson correlation coefficient between accumulated water level change and total precipitation, where the three study hydrological basins are highlighted in blue, red, and green. Scatter plots of water level change between consecutive acquisitions and (b) lake area, and (c) lake altitude.

unwrapping or even the combination with altimetry to determine absolute changes in water level (Kim et al., 2009; Lee et al., 2020). The agreement of phase change with precipitation found in this study points to unknown processes related to the SAR signal occurring on the shores of lakes and even within the size of the pixel, which can relate directly to water level changes or serve as their proxy in the conditions of these lakes.

Additional analyses should be developed in the future to explore factors associated with the coherence of these lakes and possible techniques and data that could contribute to the estimation of absolute water level changes. For example, integrating auxiliary information such as backscatter, or spectral indices from optical data, could provide information on seasonal processes that could favor or limit coherence, such as the presence of vegetation inside or around the lakes (Alexakis et al., 2019). Other data, such as radar altimetry, could help calibrate DInSAR observations. Altimetry data has shown good performance in large water bodies due to its coarse spatial resolution (Alsdorf et al., 2007; Chawla et al., 2020). The upcoming surface water and ocean topography (SWOT) is expected to allow important hydrological observations over lake systems to provide information on water surface elevation, slope and water level change, and estimate discharge and water storage (Biancamaria et al., 2016). The SWOT observations can be used to validate and calibrate the observations derived from other sources as the once obtained using the method in the present study.

Another limitation of our DInSAR study is the accurate retrieval of water level changes between acquisitions that are smaller than the change corresponding to the radar signal's wavelength. Despite this caveat, the method could recognize a large part of the water level changes, probably since most were smaller than the wavelength. This finding suggests an accuracy of InSAR methods with recent C-band missions such as Sentinel-1 to values of less than 3.49 cm. It also calls for the use of L-band sensors to determine water level changes in lakes, as their lower frequencies may detect larger water level changes.

In situ gauge data on water level changes is essential to validate estimating the magnitude of water level changes from interferograms (Alsdorf et al., 2007). Nevertheless, the monitoring difficulty in the high Andes mountains associated with accessibility (i.e., remoteness), meteorological conditions, high elevations (above 3,000 m) and steep topography (Mosquera et al., 2017) reinforces the need to explore the potential of space-based geodetic technologies.

4. Conclusions

This study presents a new methodology based on DInSAR to retrieve relative water level change in small lakes. We present the first attempt to describe the temporal evolution of a set of relatively small ungauged lakes with DInSAR observations. The relationship between the DInSAR-derived water level changes and precipitation over the study area validates the hydrological response of the changes to the atmospheric hydrological driver. Furthermore, topographic conditions in Ecuador's Cajas Massif lakes system provided favorable conditions of high signal coherence due to the specular reflection of the water and the double bounce effect generated by the surrounding elements. Although the lakes are ungauged due to their remoteness, the DInSAR application revealed that (a) the water level changes between consecutive acquisitions agreed with average precipitation; (b) the water level change patterns were similar across the 24 study lakes, and (c) significant relationships were observed between water level change and lake area. Despite some limitations related to the technology, our results support the idea that the herein proposed methodology may constitute a basis for monitoring strategies for small lakes worldwide, lacking in situ limnological data.

Data Availability Statement

Sentinel-1 data was obtained from the Vertex data portal of the Alaska Satellite Facility (Product S1B_IW_SLC__1SDV, Path 18, Frame 1170, for the period Oct 2017 to Oct 2018, https://search.asf.alaska.edu). IMERG data were acquired from Goddard Earth Sciences Data and Information Services Center (GES DISC) from NASA (Product GPM_3IMERGDF 06, for the period Oct 2017 –Oct 2018, https://gpm1.gesdisc.eosdis.nasa.gov/data/GPM_L3/GPM_3IMERGDF.06/).

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