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Monitoring monthly variation of Tonle Sap Lake water volume using Sentinel-1 imagery and satellite altimetry data

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ABSTRACT

This work estimates the surface water volume variation of the Cambodian Tonle Sap Lake at a monthly scale from 2015-2022. To achieve this, radar Sentinel-1 imagery was processed using the Google Earth Engine platform to generate backscatter coefficient maps. The Otsu method was utilized to identify the optimal threshold to classify each backscatter coefficient map into water or non-water clusters. Additionally, altimetry data from three satellites (i.e., Sentinel-3, Jason-3, and Jason-CS/Sentinel-6) was processed to estimate Tonle Sap Lake's water level variation using the AlTiS software. Surface water maps of the lake, derived from MODIS and clear-sky Sentinel-2 imagery, were used to validate the lake's surface water extent time series, while in situ water level data collected at Prek Kdam station was used to validate the variation of the lake's water height. Our results estimated that the lake's open water area varies from 2200 to 6000 km^2, while its water level ranges from 3.1 to 10.9 m. Combining the two time series, we estimated that Tonle Sap Lake's water volume varies between approximately -7.2 and 9.4 km^3 $month^{-1}$, which shows high correlation with the variation of the water volume flowing through Chau Doc and Tan Chau stations (R = 0.9528 after removing the time lag). This study highlights the ability of satellite data for lake monitoring, which is very useful in remote areas where gauge stations are limited or unavailable. Future work aims to test the accuracy of the proposed methodology in other types of environments, particularly in mountainous regions of North Vietnam, where the terrain is very steep.

Keywords: Tonle Sap Lake; lake volume monitoring; Sentinel-1; altimetry data.

1. Introduction

Although occupying only a limited area on the Earth's surface, lakes and reservoirs are crucial sources of fresh water and a main component of the terrestrial hydrosphere (Crétaux et al., 2016). These water bodies play a vital role in governing both regional and global water equilibrium (Ji et al., 2018) and contribute significantly to the production of atmospheric carbon dioxide and methane, making them essential for ecosystem stability, human survival, and social development (Pham-Duc et al., 2022). Accurate information regarding the temporal and spatial distributions of global lakes and reservoirs is crucial for research related to climate change, water management, and environmental monitoring (Williamson et al., 2009). However, their temporal and spatial distribution remains incomplete regionally and globally, and their contribution to

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ecosystem processes is often ignored in global estimates (Downing et al., 2006). Over the past few decades, anthropogenic activities and climate change have caused significant changes in the expansion and shrinkage of lakes and reservoirs worldwide (Ji et al., 2018). Therefore, more and more researchers are focusing on studying changes in lake and reservoir areas (Chen & Zhao, 2022; Du et al., 2011; Steveson et al., 2010; Xing et al., 2018), as mapping their variations is essential for managing water resource and water security, especially for developing countries (Feng et al., 2012; Ma et al., 2014; Zeng et al., 2017).

Only a few databases provide information regarding location, dimensions, and the variations of lakes and reservoirs from regional to global scales. These databases include the Global Lakes and Wetlands Database (Lehner & Döll, 2004), the global abundance of surface water bodies (Downing et al., 2006), the Landsat-derived Global Surface Water dataset (Pekel et al., 2016), or the lake and reservoir database of the United States (McDonald et al., 2012). However, these global datasets typically omit small lakes with a size smaller than 10 km^2 from their maps (Downing et al., 2006). Conversely, regional databases can provide changes in lakes with a size of 0.001 km^2, but they are limited to small geographic regions (Hanson et al., 2007). High-resolution satellite observations are likely the most effective approach to accurately map the variation and distribution of lakes and reservoirs (Seekell et al., 2013; Seekell & Pace, 2011). Moderate to high-resolution satellite observations derived from optical MODIS and Landsat satellites are often utilized to generate global maps of wetlands and lakes (Pekel et al., 2016; Verpoorter et al., 2014). Landsat satellites have 30 m spatial resolution but an extended 16 day temporal resolution, making them unsuitable for continuously monitoring variations in wetlands and water bodies. On the other hand, MODIS imagery has shorter revisiting time and low cost, covers a larger swath and longer time series since 2000, making them suitable for monitoring changes in wetlands and water bodies with large seasonal variations (although having a coarse spatial resolution) (Feng et al., 2012). However, optical satellite observations are limited in regions with high cloud contamination, such as the Tropics (Pham-Duc et al., 2022).

Synthetic Aperture Radar (SAR) imagery provides significant advantages, as microwave wavelengths are not affected by weather and clouds and can monitor the variation of water bodies with temporal and spatial resolutions comparable to those provided by optical satellite observations (Pham Duc & Tong Si, 2021). In recent years, SAR imagery has become increasingly popular for monitoring surface water and wetlands in various studies, including surface water monitoring (Dasgupta et al., 2018; Reschke et al., 2012), flood monitoring (Martinis et al., 2015), shoreline identification (Bruno et al., 2016), and lake monitoring (Huth et al., 2020). However, these works have been limited by the lack of data availability, as most SAR imagery was acquired from commercial satellites (Ding & Li, 2011). Although the European SAR Sentinel-1 satellites offer free-of-charge observations to the community, their data coverage has been limited from 2014 onwards, when the Sentinel-1A satellite was first launched. Furthermore, data limitation has restricted the ability to perform global SAR observations (Pham-Duc et al., 2022). In 2015, the first global water map (150 m spatial resolution) was generated using ENVISAT ASAR observations acquired from 2002-2012 (Santoro et al., 2015).

Observations from optical and SAR satellites can be utilized to observe changes in a water body’s surface area, while satellite radar altimetry can observe changes in a water body's height. Initially developed for mapping geoid undulations over the ocean, satellite radar altimetry became extensively used to monitor changes in the topography of the sea surface (Benveniste, 2011). Subsequently, scientists discovered its ability to track temporal changes in the water level of large rivers, lakes, and reservoirs (Birkett et al., 2011). This technique has since become extensively applied for monitoring the fluctuations in surface water storage across diverse environments located on different continents (Bjerklie et al., 2003; Brisco et al., 2009; Frappart, Do Minh, et al., 2006; Papa et al., 2010; Pham-Duc et al., 2019; Pierdicca et al., 2013), including small reservoirs (Baup et al., 2014). By combining the changes in surface water extent and water level, one can estimate the variation in the volume of a water body. This estimation can be performed using the approach presented in (Crétaux et al., 2011), and applied in (Pham-Duc et al., 2022).

Our study focuses on monitoring changes in the open water of Tonle Sap Lake - the largest lake in Cambodia and Southeast Asia (Kummu & Sarkkula, 2008). Tonle Sap is an essential water resource for local communities and is commonly called the "Lake of Life" by Cambodians (Kummu, 2009). Tonle Sap Lake and its ecosystem are facing multiple challenges, such as pollution, overfishing, habitat degradation, and the impacts of climate change (Ziv et al., 2012). These challenges threaten the sustainability of the lake's ecosystem and the livelihoods of the local communities. In addition, it is well known that Tonle Sap Lake and its Lower Mekong Delta are negatively impacted by the development of hydropower dams built along the Mekong River, causing severe social and environmental impacts to the local communities (Soukhaphon et al., 2021). Therefore, it is essential to frequently monitor changes in the lake to protect this unique and valuable natural resource. Over the years, many scholars have utilized satellite observations to track the variations of the lake and its surrounding flooding zones. For example, (Sakamoto et al., 2007) employed MODIS observations to identify temporal variations of annual flooding in Cambodia from 2000 to 2004, including Tonle Sap Lake. (Siev et al., 2016) analyzed annual variations in both surface water area and volume of Tonle Sap Lake and its floodplain using MODIS observations from 2003 to 2005. (Ji et al., 2018) investigated the variations of the lake's surface water from 2000 to 2014, using MODIS observations, and discussed their potential connection to changes in runoff within the Lancang River. (Pham-Duc et al., 2019) used MODIS imagery and ENVISAT satellite altimetry data to calculate the variation of water volume in the surface and subsurface within the Lower Mekong Basin, including Tonle Sap Lake. (Frappart et al., 2018) estimated Tonle Sap's water storage using MODIS observations and multi-satellite altimetry data acquired during 1993-2017 and analyzed the connection between its annual variations and atmospheric forcing. Higher spatial resolution satellite observations (i.e., Landsat) were also used separately or in combination with MODIS data to monitor Tonle Sap Lake for a more extended period (Dao & Liou, 2015; Wang et al., 2020). Some scientists used radar imagery to monitor the lake to avoid the effects of clouds. (Fujii et al., 2003) estimated the inundated lake area using RADARSAT imagery from 1999 to 2003. (Zhang et al., 2014) mapped surface water area of the lake, along with different land-cover types, using RADARSAT-2 imagery. (Pham-Duc et al., 2017) monitored changes in surface water areas of Tonle Sap Lake and the Lower Mekong Delta using 1-year of Sentinel-1 observations. (Chang et al., 2020) forecasted daily inundation extents of Tonle Sap Lake by combining Jason altimetry data and Sentinel-1 observations.

The primary aims of this work were to assess the variations of Tonle Sap Lake's water resource, utilizing the most up-to-date multi-satellite altimetry data and SAR Sentinel-1 imagery. Sentinel-1 imagery was processed in the Google Earth Engine (GEE) platform to benefit from the advantages of powerful cloud computing platforms. The study duration was constrained to 2015-2022 due to the availability of all datasets utilized in this study. Section 2 provides an overview of the study area and details of all datasets employed. Section 3 presents our methodology for estimating the variations in the lake's water volume, while our findings and validations are presented and discussed in Section 4. Section 5 highlights our conclusions and outlines future perspectives.

2. Study Area and Dataset

2.1. The Study Area - Tonle Sap Lake

Tonle Sap Lake, located in Cambodia, is the biggest lake in Southeast Asia (Kummu & Sarkkula, 2008) (see Figure 1). The lake is linked to the Mekong River and the Mekong Delta via the Tonle Sap River. The lake's surface water extent varies significantly from season to season due to its unique hydrological regime, driven by the monsoon precipitation and water from the Mekong River (Arias et al., 2012). In the dry season, spanning from November to May, water exits the lake via the Mekong River, and the lake's area decreases to approximately 2500 km^2 when the water level is lowest. Conversely, during the wet season, from June to October, water from the Mekong River re-enters Tonle Sap Lake, allowing the lake to expand its area up to five times its dry season size (Kummu, 2009).

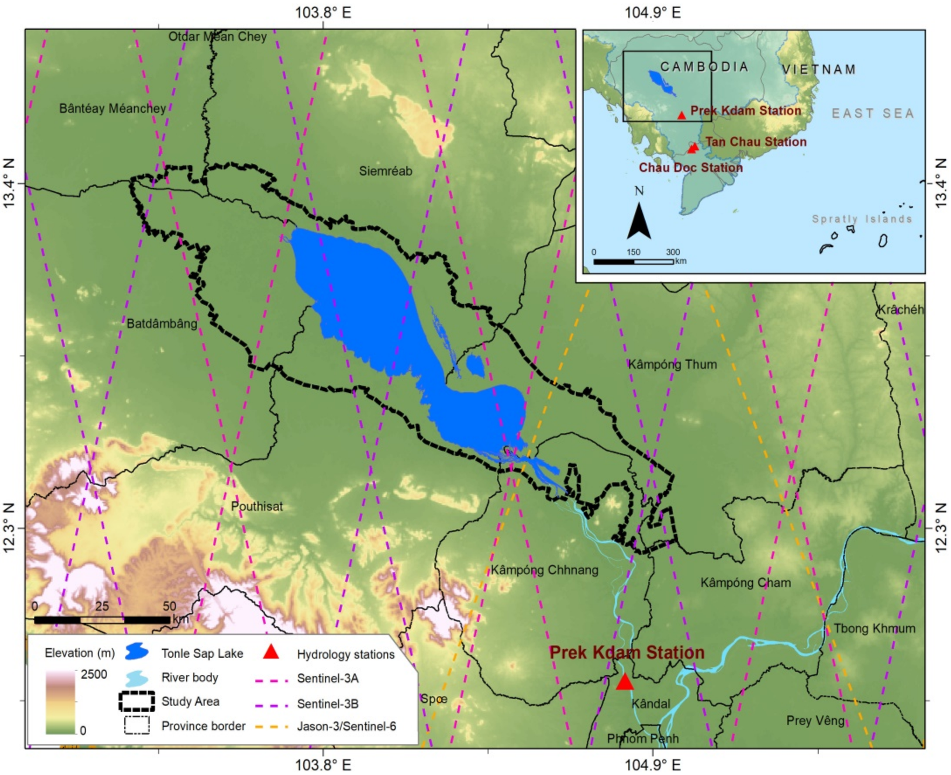

Figure 1. Location of the study area

This study mainly focuses on monitoring changes in the surface water area of the Tonle Sap Lake, which comprises the Small Lake in the southeastern part and the main Large Lake (see Figure 1) (Ji et al., 2018). Tonle Sap Lake and its surrounding wetlands support a rich and diverse ecosystem, including over 300 freshwater fish species and diverse bird and animal species. Tonle Sap Lake is also an essential source of livelihood, food, and freshwater for locals who depend on the lake for fishing and agriculture (Salmivaara et al., 2016).

2.2. Radar Sentinel-1 and Optical Sentinel-2 Satellites

Sentinel-1 is a European Union (EU)-funded satellite project that is implemented by the European Space Agency (ESA). The mission includes two identical SAR satellites, Sentinel-1A and -1B, launched in April 2014 and April 2016. Sentinel-1 satellites operate at C-band (5.405 GHz), and the satellite sensor's incidence angle can vary from 29° to 46°. The two satellites orbit in a near-polar sun-synchronous orbit (about 693 km above sea level). The temporal resolution of one Sentinel-1 satellite is 12 days and reduces to six days with both satellites. Sentinel-1 satellites enable a wide range of land and ocean surface observations and monitoring applications in all weather conditions, day and night (ESA, 2015).

As the Sentinel-1B satellite does not provide observations within the study area, only Sentinel-1A Ground Range Detected (GRD) Level-1 imagery has been utilized in this work. Sentinel-1 imagery is available in the GEE platform, and they were already preprocessed before being uploaded to the platform for post-processing by its users. The preprocessing includes five basic steps (ESA, 2016): Firstly, the orbit metadata is updated and corrected for each acquisition. Secondly, GRD border noise removal is applied to eliminate invalid signals and noise along the image edges. Thirdly, thermal noise removal is applied to minimize disconnections between sub-swaths within the images. Next, radiometric calibration is conducted to produce a backscatter coefficient map. Lastly, distortions caused by the side-looking geometry of the satellites are corrected using the terrain correction tool. In this work, 218 Sentinel-1A observations acquired from 2015 to 2022 have been utilized to track the variations of Tonle Sap Lake's surface water extent during this period.

To validate surface water maps of the lake obtained from Sentinel-1 imagery, a few unclouded Sentinel-2 imagery have been used. Sentinel-2 is another satellite mission developed by ESA, which consists of two sun-synchronous satellites known as Sentinel-2A & -2B (launched in June 2015 and March 2017, respectively). The two satellites have a mean orbital altitude of 786 km, which allows an excellent temporal resolution of 5 days with both satellites. Sentinel-2 satellites are equipped with the Multispectral Instrument (MSI) instrument, which can take imagery in 13 different spectral bands covering from visible (400 nm) to short-wave infrared wavelengths (SWIR; 2200 nm). The two satellites can provide observations at three different spatial resolutions (10, 20, and 60 m) depending on the wavelengths. In this study, we used Sentinel-2 Bottom-Of-Atmosphere reflectance imagery, also available in the GEE platform. Surface reflectance values of green and SWIR wavelengths (band 3 and band 11) were utilized to obtain the Modified Normalized Difference Water Index (MNDWI) for mapping and monitoring changes in the lake's water area (H. Xu, 2006).

2.3. The moderate resolution imaging spectroradiometer (MODIS) observations

MODIS is one instrument installed on both the NASA's Terra and Aqua satellites, launched in December 1999 and May 2002, respectively. These two satellites orbit near-polar sun-synchronous at approximately 705 km above sea level. With their frequent coverage, the twin satellites scan the surface of the Earth every single day. In this work, we used MODIS/Terra land surface reflectance Level-3 products (500 m spatial resolution), version 6.1 (MOD09A1 V6.1) to monitor the variations of Tonle Sap Lake's surface water area during 2015-2022. Each MODIS image was produced by choosing the best Level-2 gridded images over 8 days based on several criteria, including the absence of clouds, low view angle, and high observation coverage (Vermote, 2015). Similar to Sentinel-1 data, MODIS observations can be accessed in the GEE platform.

2.4. Landsat Global Surface Water (GSW) dataset

The Landsat-derived GSW is a comprehensive dataset that provides information on the spatial and temporal distribution of global water surfaces and detailed insights into changes in these water surfaces over time (Pekel et al., 2016). This dataset was constructed from more than 4.7 million scenes acquired by Landsat-5, -7, and -8 satellites from March 1984 to December 2021. The GSW dataset provides six different types of maps, namely occurrence, re-occurrence, changes, transitions, seasonality, and maximum extent of surface water (Pekel et al., 2016). The occurrence map at 30 m spatial resolution was extracted for comparison with similar maps constructed by Sentinel-1 and MODIS observations. The GSW dataset is openly accessible (European_Commission, 2022) and can be accessed on the GEE platform.

2.5. Satellite Radar Altimetry Data

Radar altimetry data from Jason-3, Sentinel-3, and Jason-CS/Sentinel-6 satellites, provided by the Center for Topographic Studies of the Ocean and Hydrosphere (CTOH, 2022), was utilized to track the variations of Tonle Sap Lake's water level between 2015 and 2022, using the AlTiS software. Jason-3 satellite, launched on January 16 2016, with a 10-day revisiting time, was placed at an altitude of approximately 1336 km. Jason-3 satellite composed of several instruments: Poseidon-3B altimeter - the main satellite's device, the Advanced Microwave Radiometer-s (AMR-2); precise orbit tracking systems (including DORIS, GPSP, and LRA), and two experimental systems (Carmen-3 by CNES, and LPT by NASA). Sentinel-3 project is a part of the ESA's Copernicus program, which includes two satellites, namely Sentinel-3A & -3B (launched in February 2016 and April 2018, respectively). The two satellites orbit the Earth at an altitude of approximately 814.5 km, with a sun-synchronous inclination of 98.65° and a 27-day repeat cycle. The main instruments installed on Sentinel-3 satellites include a SAR Radar Altimeter, a Microwave Radiometer, and an accurate orbit determination package (including GNSS, DORIS, and LRR). Jason-CS/Sentinel-6 project is an international collaboration between NOAA, NASA, ESA, and EUMETSAT, with technical and science support from CNES. The project includes two identical satellites, the first (Sentinel-6 Michael Freilich) launched in November 2020 and the second (Sentinel-6B) scheduled for launch in 2025. Jason-CS/Sentinel-6 is the next radar altimetry mission to continue the scientific objectives of Jason-3. Jason-CS/Sentinel-6 satellites contain three scientific measuring instruments, including a multi-frequency Advanced Microwave Radiometer for Climate with a High-Resolution Microwave Radiometer and a Ku/C-band nadir-pointing SAR altimeter (Poseidon-4). Radar altimetry data from these satellites were handled using the Offset Center Of Gravity tracking algorithm (Wingham et al., 1986) following recommendations from (Frappart, Calmant, et al., 2006).

2.6. Hydroweb and G-REALM datasets

Time series of Tonle Sap Lake's water level, provided by two global lakes/reservoirs datasets, i.e., G-REALM and Hydroweb, were collected to validate results derived from satellite altimetry data. G-REALM product uses altimetry data from Topex/Poseidon, Jason-1, Jason-2, Jason-3 and Jason-CS/Sentinel-6 satellites. It can be downloaded from https://ipad.fas.usda.gov/cropexplorer/global_reservoir/, whereas Hydroweb product uses altimetry data from ERS-2, ENVISAT, SARAL, Sentinel-3A, Sentinel-3B, and Cryosat-2 satellites, and can be requested from https://hydroweb.theia-land.fr/ (N. Xu et al., 2022).

2.7. In situ Data of Water Level and River Discharge

Daily in situ water level data was collected at Prek Kdam station in Cambodia (about 120 km from the southern part of the lake). Daily in situ river discharge data was collected at two stations located in Vietnam (Tan Chau and Chau Doc) to compare with results obtained from satellite observations. The total volume of discharge flowing through these two Vietnamese stations is nearly equal to that of discharge flowing out of Tonle Sap Lake (Pham-Duc et al., 2019). Water level data was provided by the Mekong River Commission (https://www.mrcmekong.org/), while river discharge data was ordered from the Viet Nam Southern Regional Hydrometeorological Center (http://www.kttv-nb.org.vn/), respectively.

3. Methodology

This work employs a methodology based on our previous publications (Pham-Duc et al., 2022; Pham Duc & Tong Si, 2021), which comprises four phases. This section only briefly presents the methodology, but details should be found in (Pham-Duc et al., 2022). **In phase 1**, Sentinel-1 and MODIS observations and altimetry data are processed to estimate changes of open water area and lake water level, respectively. Using the GEE platform, each VH-polarized image of Sentinel-1 is spatially subset to cover the study area, and speckle noises are reduced using the Refined Lee filter (Pham-Duc et al., 2017). The Otsu threshold selection method is utilized to identify the best threshold to classify each pixel in the backscatter image into water and non-water clusters (Otsu, 1979). At times, the threshold generated by the Otsu method may not give a satisfactory outcome, manual intervention is required to determine the optimal threshold. The resulting binary water map is then exported to Google Drive for post-processing. For MODIS observations, each image is subset using the same predefined shape file as Sentinel-1, and the MNDWI is calculated using green (band 4) and SWIR wavelengths (band 6) to map the lake's surface water area as the MNDWI has a better performance compared to other water indices (Ji et al., 2018). The MNDWI and blue bands are exported to Google Drive for cloud-pixel removal using MATLAB software. Cloud-covered pixels are detected using surface reflectance values of blue wavelength. Next, these pixels are interpolated using linear interpolation, and then a simple weight function is called to smooth the MNDWI (Aires et al., 2020). Finally, the smoothed MNDWI map is classified into a binary water map using a threshold of 0 (water if smoothed MNDWI > 0, and non-water if smoothed MNDWI < 0) (Ji et al., 2018). In parallel, using the Altimetric Time Series (AlTiS) software, Jason-3, Sentinel-3, and Sentinel-6 altimetry data is processed individually to estimate changes in the lake's water level (Frappart et al., 2021). Satellite altimetry data is corrected for biases between each satellite and merged to construct a completed time series representing the lake's water level variations. **In phase 2**, time series of the lake's surface water area, obtained from Sentinel-1 and MODIS observations, are compared together, and some free-cloud Sentinel-2 images are also utilized to confirm the accuracy of the resulting surface water maps. The comparison of the time series from Sentinel-1 and MODIS observations provides an opportunity to detect any inconsistencies and assess the precision of the satellite-derived water extent maps. In addition, daily in situ water level data of the Mekong River, collected at the Prek Kdam station, are employed to validate the results derived from satellite altimetry data. These validation processes enhance the reliability of our results and ensure that the methodology used is robust and accurate. **Phase 3** involves converting the time series of water level and extent obtained in the previous steps into a monthly scale. These monthly data are then utilized to construct the monthly variations of the lake's water volume using Equation (1) (Crétaux et al., 2011).

$$\Delta V = \frac{(H_{i+1} - H_i) \times (S_{i+1} + S_i + \sqrt{S_{i+1} \times S_i})}{3} \quad (1)$$

Where ΔV is the difference of the lake's surface water volume, *S* and *H* are the lake's water extent and level, respectively, and *i* and *i+1* are two consecutive months. **In the final phase**, the monthly variations of the lake's water volume, obtained in phase 3, are validated using daily in situ data of the total discharge volume of Chau Doc and Tan Chau stations.

4. Results and Discussions

4.1. Monthly variations of surface water of Tonle Sap Lake

Figure 2 displays the monthly time series and annual cycle of surface water extent of Tonle Sap Lake from 2015 to 2022, obtained from Sentinel-1 and MODIS data. From May to June, the lake's open water surface is at its minimum extent, being approximately 2350 km^2. Subsequently, the lake's open water extent increases rapidly from July and peaks in October before decreasing swiftly until January next year. Between January and April, the lake's open water extent decreases gradually. The correlation of the two-time series is high (R = 96%), with better agreement in the dry season. During this period, the backscatter coefficient and the surface reflectance of the lake are distinct from the background environment (mostly land, vegetation, and paddy rice), leading to precise results of the lake's open water surface from both Sentinel-1 and MODIS observations. During the wet season, Sentinel-1 generally detects more surface water than MODIS sensors, with a significant difference in some years (2018, 2020, 2021, and 2022). Free-cloud Sentinel-2 imagery was utilized to produce a reference surface water map to validate results derived from Sentinel-1 and MODIS imagery. Figure 3 displays an example of the open water extent of Tonle Sap Lake in November 2020 obtained from the three satellites. Sentinel-1 observations were acquired on 20, while Sentinel-2 and MODIS observations were acquired four days later, on November 24 2020. Results obtained from Sentinel-1 imagery were compared to the reference maps obtained from cloud-free Sentinel-2 imagery. Sentinel-1 detected a total surface water area of 4224 km^2, while Sentinel-2 detected 4216 km^2, and MODIS 4142 km^2 (see Table 1). Sentinel-1 and Sentinel-2 imagery, with 10 m spatial resolution, allows a much better detection of small water areas around the lake, which MODIS sensor failed to capture due to its coarse resolution of 500 m. Differences between results obtained from Sentinel-1 and Sentinel-2 observations (see Figure 3d and Table 2) were minimal and primarily occurred at the land/water boundary of the lake, as expected (Pham-Duc et al., 2022). To conclude, results obtained from Sentinel-1 observations are more accurate than those from MODIS data and is used to calculate the variations in the lake's volume in the next step.

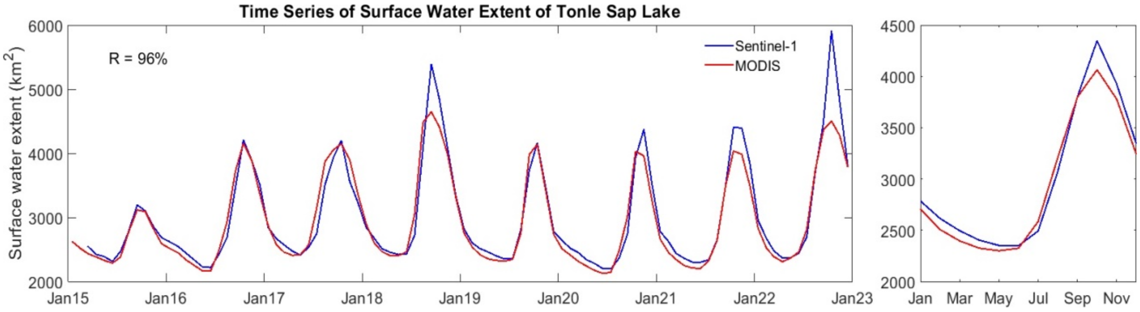

Figure 2. The monthly time series and annual cycle of Tonle Sap Lake's surface water area were obtained from Sentinel-1 (blue) and MODIS (red) observations for 2015-2022

Table 1. Number of water pixels and the corresponding surface water area derived from Sentinel-1, Sentinel-2 and MODIS observations in Figure 3

	Spatial Resolution (m)	No. of water pixels	Surface water area (km^2)
Sentinel-1	10	42,240,114	4224
Sentinel-2	10	42,163,615	4216
MODIS	500	16,086	4142

Table 2. Confusion matrices of Tonle Sap Lake's surface water maps shown in Figure 3d

	Non-Water (0) (Sentinel-2)	Water (1) (Sentinel-2)
Non-water (0) (Sentinel-1)	234,663,823 (98.45%)	3,691,223 (1.55%)
Water (1) (Sentinel-1)	3,767,722 (8.92%)	38,472,392 (91.08%)

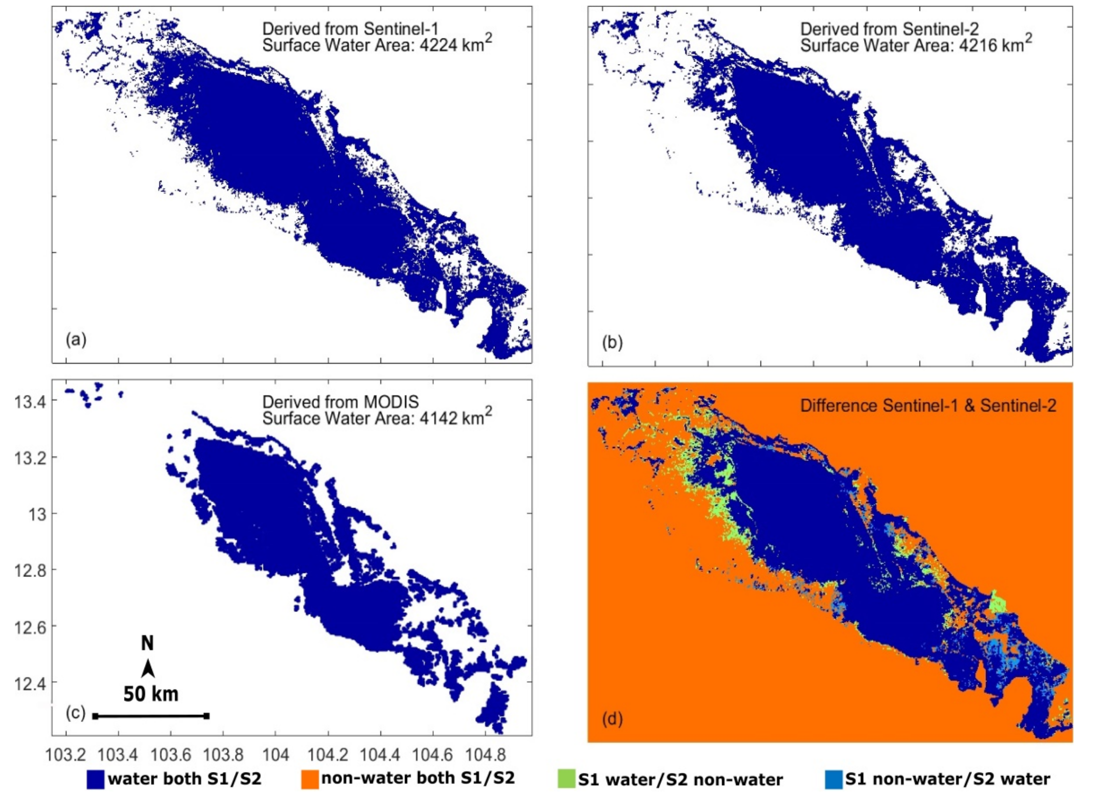

Figure 3. Comparison of Tonle Sap Lake's surface water maps in November 2020, obtained from SAR Sentinel-1 imagery (a), cloud-free Sentinel-2 imagery (b), MODIS imagery (c), and the difference between Sentinel-1 and Sentinel-2 maps (d)

4.2. Minimum and maximum water extent of Tonle Sap Lake

The annual minimum and maximum of Tonle Sap Lake's surface water area obtained from Sentinel-1 imagery during the 2015-2022 period are presented in Figure 4. The minimum extent of the lake exhibited little variation, remaining within the range of 2200-2400 km^2. There were four years when the minimum extent occurred in May (in 2017, 2018, 2021, and 2022), three years occurred in June (in 2015, 2016, and 2019), and only once in July during 2020. In contrast, the maximum extent of the lake displayed significant fluctuations depending on the water volume coming from the Mekong River each year. The maximum extent was at its lowest in September 2015, when it spanned an area of approximately 3200 km^2, representing only a 40% increase from its minimum extent in the same year. The 2015 extreme drought resulted from a decrease of rainfall and an increase of temperature in the area caused by a super strong El Nino phase, and a deficit of water in the lake since the previous year (Frappart et al., 2018). Another reason contributing to this severe drought is that water was kept by hydropower dams along the upper part of the Mekong River, causing a decrease of upstream flood flow into Tonle Sap Lake by 33% from its average (Ngoc Anh Nguyen, 2017). Except for the years 2018 and 2022, when the maximum extent reached approximately 5400 and 6000 km^2, respectively, while in other years, it remained within the 4200-4400 km^2 range. The lake's maximum extent occurred in September for two years (in 2015 and 2018), in October for five years (in 2016, 2017, 2019, 2021, and 2022), and only once in November, in the year 2020, when the arrival of water from the upper Mekong River was delayed compared to the normal situation.

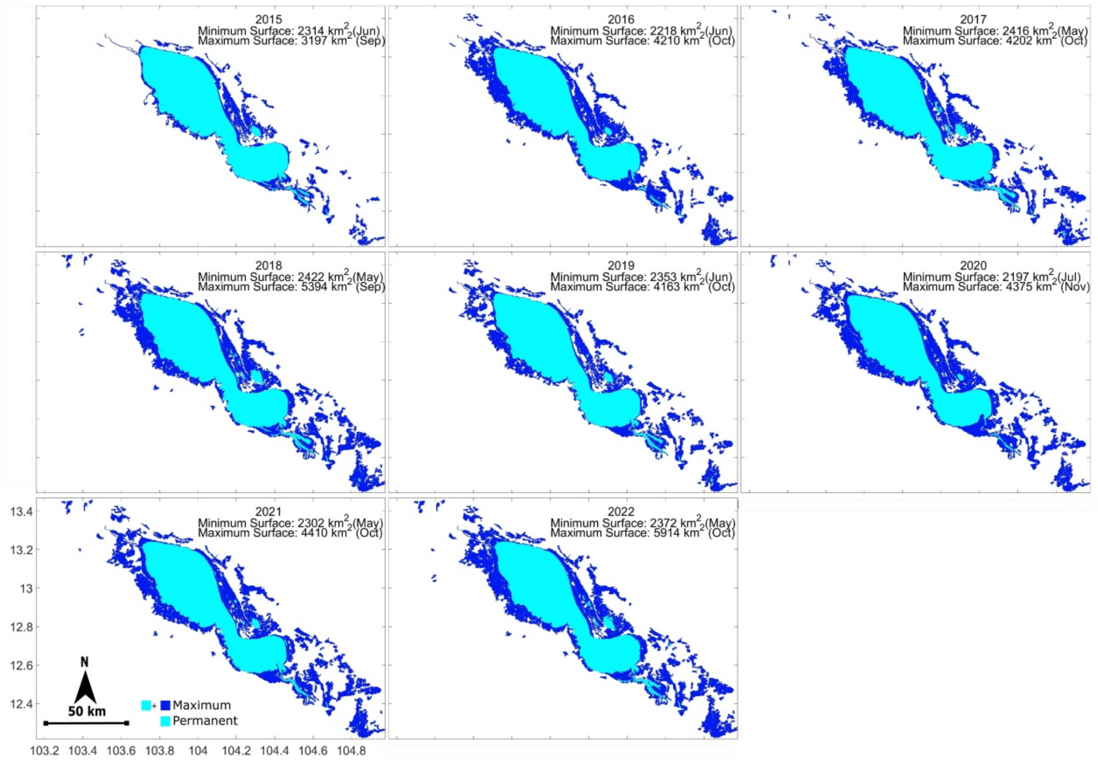

Figure 4. Annual minimum and maximum of Tonle Sap Lake's surface water area, obtained from Sentinel-1 imagery during the 2015-2022 period

4.3. Surface water occurrence of Tonle Sap Lake derived from Sentinel-1, Landsat, and MODIS imagery

A comparison of the occurrence of Tonle Sap Lake's surface water, derived from 8 years of Sentinel-1, 38 years of Landsat, and 22 years MODIS observations, is presented in Figure 5. The integration of these maps has provided a more comprehensive and accurate understanding of the lake's surface water dynamics for a long time. The lake's surface water dynamics are pretty similar in all three maps, with higher occurrence in the lake's center and lower occurrence towards the land/water boundary and surrounding areas. However, the inundation frequency of the lake is higher in the Sentinel-1 and MODIS maps compared to results derived from Landsat observations. Sentinel-1 imagery can penetrate clouds, while potential cloud pixels in MODIS observations were already detected and filled. In contrast, cloud removal has not been performed for Landsat observations. The advantage of higher spatial resolution in Sentinel-1 and Landsat compared to MODIS is apparent, as many small water bodies around the lakes were detected successfully in the Sentinel-1 and Landsat maps but not in the MODIS map.

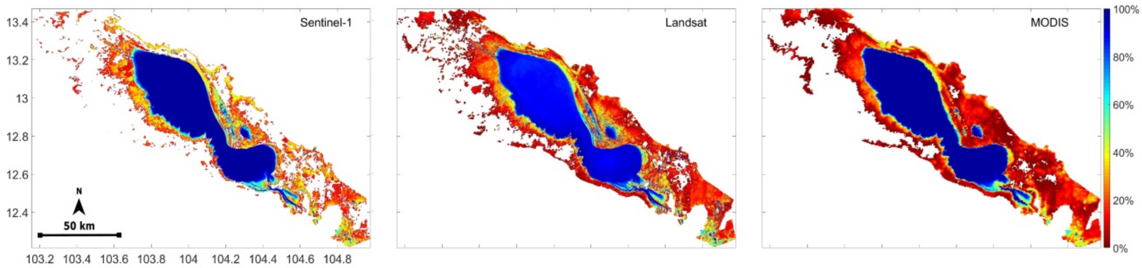

Figure 5. Tonle Sap Lake's surface water occurrence was obtained from 8 years of SAR Sentinel-1, 38 years of optical Landsat, and 22 years of optical MODIS observations

4.4. Monthly variations of the water level of Tonle Sap Lake

The monthly variation of Tonle Sap Lake's water level, derived from altimetry data, is shown in Figure 6, along with data obtained from G-REALM and Hydroweb products after removing any biases between the three datasets. As shown in Table 3, the correlations between our results and the two other time series are high (R = 0.9922 and RMSE = 0.278 m with G-REALM, and R = 0.9941 and RMSE = 0.2355 m with Hydroweb, respectively), indicating that our results are highly accurate. The lake's water level increased from 2015 to 2018, followed by a decrease from 2018 to 2021 and a subsequent increase in 2022. To better validate our results, the water level of the Mekong River at the Prek Kdam station is also included in Figure 6. Although Prek Kdam station's water level is a 1-month lag compared to the lake's, the correlation of these two datasets remains high (R = 0.9635) after removing the time lag. It is worth noting that G-REALM and Hydroweb products are limited to lakes with an open surface more significant than 100 km^2, and there may be months when data from these two lake datasets are unavailable (Pham-Duc et al., 2022). Therefore, we highly recommend that other scholars request and process satellite altimetry data to achieve the best accuracy for the final results.

Table 3. Correlations of surface water height of Tonle Sap Lake as derived from our multi-satellite altimetry data, external G-REALM and Hydroweb datasets, and Prek Kdam station's in situ water level

	Our data	G-REALM	Hydroweb	In situ data (1-month lag)
Our data	1	**0.9922**	**0.9941**	**0.9635**
G-REALM		1	**0.9835**	**0.9612**
Hydroweb			1	**0.9646**
In situ data (1-month lag)				1

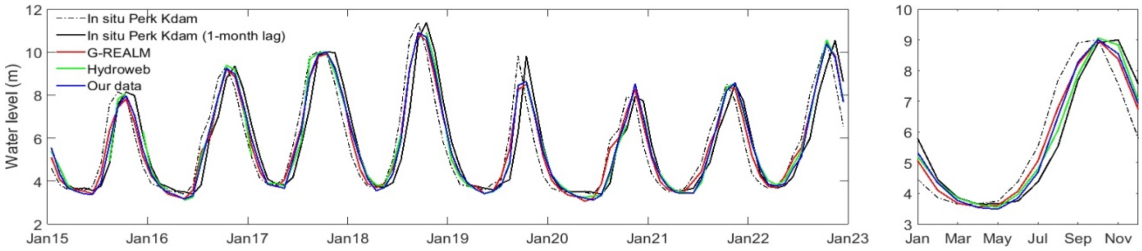

Figure 6. Monthly time series variations and annual cycle variations of surface water height of Tonle Sap Lake derived from our multi-satellite altimetry data (blue), G-REALM (red), and Hydroweb (green) datasets, as well as the reference data of in situ water level of the Prek Kdam station (black) during the 2015-2022 period

4.5. Monthly variations of the water volume of Tonle Sap Lake

The monthly time series of Tonle Sap Lake's water extent and water level, calculated and validated in the previous steps, were utilized to estimate the fluctuations of its water volume by applying Equation (1). For validation, we compared the monthly variations of the lake's water volume (blue) with the total discharge flowing through Chau Doc and Tan Chau stations (red), assuming that the total discharge at these two stations almost equals the total water volume flowing out from the lake (Pham-Duc et al., 2019). Figure 7 shows our comparison for the 2015-2022 period. There is a 1-month lag between the two time series, so the correlation is only 0.8410. However, after removing the time lag, their correlation increases to 0.9528, indicating good agreement with in situ measurements. This delay can be explained by the fact that during the rainy season, it takes time for the Tonle Sap Lake to expand its surface area, whereas during the dry period, the lake slowly releases its water downstream. Overall, the lake shows a positive trend from June to October and a negative trend from November to May. Although the amplitudes did not fit perfectly, especially at the lower and higher water stages of some years (high peaks in 2015, 2020, and 2022, and low peaks in 2016 and 2019), our analysis suggests that satellite observations and satellite altimetry can be used to estimate the water variations of lakes with high accuracy. This is very important for water resource management, especially in remote areas in developing countries where in situ data are unavailable due to the lack of gauge stations.

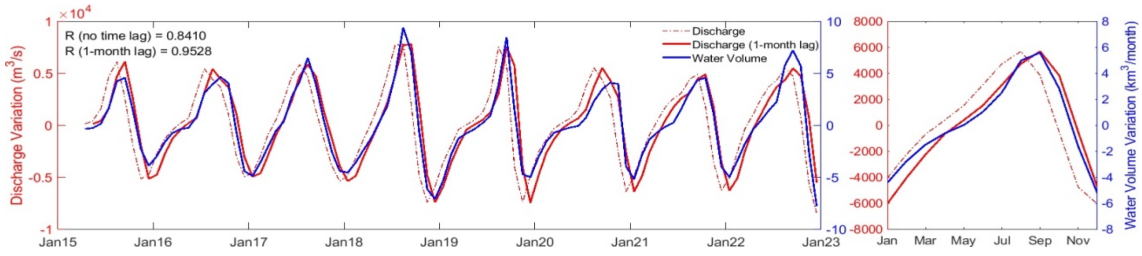

Figure 7. Monthly time series and annual cycle of the water volume of Tonle Sap Lake (blue) in comparison with the total water discharge at Chau Doc and Tan Chau stations (red) during the 2015-2022 period

4.6. Combining MODIS and Sentinel-1 observations for lake's surface water monitoring

Sentinel-1 observations, with their 10 m spatial resolution, have proved very effective in monitoring minor variations of lakes, reservoirs, and wetlands of different sizes (Huth et al., 2020). With the support of GEE, users can carry out all the preprocessing of SAR Sentinel-1 imagery on the platform, eliminating the need to download data to local computers, which can be time-consuming. However, until now, GEE only provides radar observations acquired from the two Sentinel-1 satellites; therefore, SAR imagery is limited for the years before 2014, when the first Sentinel-1A satellite was launched. While MODIS and Sentinel-1 observations captured similar trends and seasonal cycles of Tonle Sap Lake's surface water extent, Sentinel-1 sensors have higher accuracy in detecting small water bodies than MODIS, especially during the rainy season (as illustrated in Figs. 2, 3). The difference in surface water detected from Sentinel-1 and MODIS sensors can be partly explained by the spatial resolutions of the two systems and the limitation of linear interpolation to identify and fill values of cloud pixels. However, MODIS provides a longer and continuous historical data dating back to 2000 when the Terra satellite was launched. Therefore, combining observations from both MODIS and Sentinel-1 satellites can maximize the advantages of both systems. Downscaling techniques can create a higher spatial resolution and longer time series of surface water extent products (Aires et al., 2017). However, it is important to mention that the Otsu threshold selection method used to determine the backscatter threshold is not always optimal, and users should carefully examine the resulting surface water maps derived from Sentinel-1 imagery. Sometimes, the Otsu threshold may not give a satisfactory outcome; manual intervention is required to determine the optimal value for each case. In this study, we modified the threshold of 27 out of 218 Sentinel-1 observations (12.38%), and 18 out of 27 observations (66.66%) were acquired between February and April. Manual selection of the backscatter threshold was required for the majority of observations acquired during the dry season. This is because of the low water level during this period makes the land/water boundaries of the lake more heterogeneous, which in turn affects the SAR backscatter coefficient (Pham-Duc et al., 2022).

5. Conclusions

This work estimated the monthly variations of Tonle Sap Lake's surface water volume during the 2015-2022 period by combining the changes in the lake's open surface water extent and level. SAR Sentinel-1 imagery was completely preprocessed in the GEE platform to convert raw images into backscatter coefficients before the Otsu method was utilized to classify each pixel as water or non-water. Altimetry data of Jason-3, Sentinel-3, and Jason-CS/Sentinel-6 satellites was processed separately to estimate the lake's water level fluctuation and construct a unique time series by removing biases between the three datasets. The variation of water extent was validated using results of surface water maps obtained from MODIS, Landsat, and Sentinel-2 imagery. In contrast, the variation of water level was validated using in situ measurement of Mekong River's water level collected at Prek Kdam station. We estimated that Tonle Sap Lake's water volume varies between approximately -7.2 and 9.4 km^3 $month^{-1}$ and shows a high correlation with in situ data of the total river discharge flowing through Tan Chau and Chau Doc stations (R = 0.9586 after removing the time lag).

Several limitations of this type of work were discussed in previous studies (Pham-Duc et al., 2022). These limitations include the complexity of the lake's surrounding environment, the assumption that the variation of the lake's water height is constant across its entire area, and the lack of in situ measurements with the lake itself. The first limitation related to the effectiveness of SAR Sentinel-1 observations in mapping water located in the lake's surrounding environment. These areas is a mix of various types of vegetation (aquatic and flooded forest), grassland and wetlands which may reduce the accuracy of the methodology. The second limitation involves the assumption that the lake's water height is a constant number across its entire area. Consequently, it could result in errors in our estimation of the changes of the lake's water volume. In addition, the quality of satellite altimetry measurements is not always perfect as it is affected by many factors, including the topography, type, and temporal resolution of altimetry sensors on board of the satellites (Biswas et al., 2019). Details on the limitations and potential of satellite altimetry constellations can be found in recent articles (Dettmering et al., 2020). The third limitation relates to the lack of in situ measurements of water level within the lake, which makes it more challenging to validate the accuracy of our methodology in this area, as data from downstream stations in Vietnam may not reflect exactly the variation within the lake itself.

In our future work, we plan to focus on two critical areas of development. Firstly, we intend to improve the accuracy of our lake monitoring by reducing the observing frequency from monthly to every 10 days. The revisiting time of the Sentinel-1A satellite is 12 days, meaning that the satellite provides 2-3 observations per month, while 6-7 observations of water level can be provided using a combination of different satellite altimetry data. By reducing the observing frequency, we can better capture the lake's water volume changes and contribute to a more comprehensive understanding of its dynamics. On December 16 2022, the Surface Water and Ocean Topography (SWOT) satellite was launched successfully. When its data is released, it would be advantageous with Sentinel-1 observations in monitoring global inland water variations. Secondly, we aim to test the effectiveness of our monitoring methodology in other environments, particularly in mountainous regions of North Vietnam, where the terrain is very steep. Lakes such as Hoa Binh and Thac Ba serve as potential testing sites. By conducting this method in other lakes, it is possible to gain a broader understanding of how this methodology may perform in different environments.

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