Changes in the Lake Area of Tonle Sap: Possible Linkage to Runoff Alterations in the Lancang River?

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Abstract: Tonle Sap Lake is the largest freshwater lake in Southeast Asia. Water development infrastructures are increasingly being constructed in the Lancang–Mekong River Basin, which is a major concern considering its potential impact on Tonle Sap Lake. This study aimed to investigate variations in the area of the lake and discuss their possible linkage to runoff alterations in the Lancang River (Upper Mekong) by comparing runoff at the Yunjinghong hydrological station before and after significant changes in runoff trends that occurred in 2008. First, four commonly used water body extraction methods (MNDWI, NDWI, NDVI, and EVI) were compared and MNDWI was found to provide a better and more stable performance. Based on MOD09A1 data, MNDWI was used to extract the water area of the lake from 2000 to 2014, and characteristics of variations in the area before and after 2008 were analyzed. The water area of Tonle Sap Lake displayed an overall decreasing trend, and specifically decreased by 8.3% during the flood season and by 1.5% on average during the dry season after 2008. Seasonal variations in the water area of Tonle Sap Lake were dominantly influenced by runoff from the Mekong River. Compared with the period 2000–2007, runoff at Yunjinghong station were increased during the dry season (20.74%) and decreased during the flood season (34.25%) between 2008 and 2014. Changes in upstream runoff contributed to runoff at the Stung Treng station in the lower Mekong River by 6.17% (dry season) and −2.41% (flood season). Evidently, the operation of dams in the Lancang River does not primarily account for the area decrease of Tonle Sap Lake during the flood season. In contrast, runoff increase during the dry season mitigates the area decrease of Tonle Sap Lake to a certain extent.

Keywords: Tonle Sap Lake; Lancang-Mekong River; MODIS; water index; international river

1. Introduction

Lakes are crucial sources of freshwater resources and are an important part of the terrestrial hydrosphere. They are involved in the natural water cycle and play an important role in regional water balance [1]. In particular, lakes not only provide water resources that support the life and production of human societies but also provide huge environmental and ecological benefits. In recent decades, significant changes have been observed in lake expansion and shrinkage around the world under the combined influence of global climate change and human activities. Thus, changes in lake areas have received the attention of many scientists [2–7].

Tonle Sap Lake, located within the territory of Cambodia, is the largest freshwater lake in Southeast Asia. It is a world-famous production area for freshwater fishes. For nearby residents, the pattern of life and means of livelihood are closely linked with this lake [8]. Thus, Tonle Sap Lake is considered to be a Lake of Life to the Cambodians and provides great resource assurance for the
survival and development of the Khmers [9]. To utilize and manage Tonle Sap Lake reasonably, it is necessary to monitor dynamic variations in its area accurately and understand the influence of natural factors and human activities on its water area.

Remote sensing is widely used to monitor dynamic variations in surface water bodies. Furthermore, abundant remote sensing data, such as Landsat, MODIS (Moderate Resolution Imaging Spectroradiometer) and SAR (Synthetic Aperture Radar) images, are available for investigating lake water bodies. Landsat images have a relatively high spatial resolution, but they are limited by the rather long 16 days repeat cycle. In addition, the frequent occurrence of cloud cover makes them unsuitable for detecting continuous variations. SAR imagery can provide sufficient spatial and temporal resolution for monitoring water areas, and as microwave remote sensing data, they are not affected by clouds [7,10]. With these advantages, SAR imagery and corresponding semi-automatic waterbody extraction methods have been used in some studies in recent years, such as for flood monitoring [11] and shoreline identification [12]. However, these studies were hindered by limited data availability, because most SAR satellites are commercial satellites [10,13]. In addition, some freely available SAR images cover only a short span of time, for example Sentinel-1 SAR data before 2014 are not available. In contrast, MODIS data are characterized by short revisit periods, low cost, large coverage areas, stable data sources, and availability of relatively long time series (since 2000). Despite their relatively low spatial resolution, MODIS data have widely been used in the dynamic monitoring of water bodies with large seasonal variations [4].

Most studies based on MODIS data were conducted using the water index method, which specifically involves the creation of index data according to differences and ratios between different wavebands and increases in the difference of radiation between water bodies and other ground objects, so as to extract water body information. One commonly used water index method is the Normalized Difference Vegetation Index (NDVI), which is usually used to distinguish water bodies from ground objects such as vegetation [14,15]. Similarly, the Enhanced Vegetation Index (EVI) method is also used to study the classification of ground surface covers, and it is somewhat effective in distinguishing water bodies from vegetation [16]. McFeeters [17] created the Normalized Difference Water Index (NDWI) based on findings that water bodies have characteristic high reflectivity in the green band and high absorptivity in the near-infrared (NIR) band. Xu [18] proposed the Modified Normalized Difference Water Index (MNDWI) after observing that water bodies have lower reflectivity in the short-wave infrared (SWIR) band than in the NIR band, and that the reflectivity of other ground objects increases sharply in the SWIR band. Previous studies have shown that the diverse water index methods have various characteristics and differ in regard to their ability to identify water bodies accurately. The NDVI enables rapid and simple extraction of water bodies, and is thus considered to be one of the most successful water index methods [19,20]. The NDWI and MNDWI have been widely used to extract water body information in a highly targeted manner [21–24]. In some studies, NDWI has been recommended for extracting water body information; however, NDWI may be unreliable for shallow-water areas with a varied boundary [4,25]. Li et al. [24] found that MNDWI is more effective than NDWI at distinguishing water bodies, and this may be attributed to the ability of MNDWI to distinguish built-up land areas from water bodies effectively [18]. Tonle Sap Lake is a shallow-water lake that is inundated by periodic flooding and contains aquatic plants as well as shoreside plants. To determine dynamic variations in the water area of such a lake, it is first necessary to compare the above water index methods and identify the optimal method for performing analyses.

Recently, some scientists have used remote sensing data to study Tonle Sap Lake or the surrounding flooding zones. Fujii et al. [26] used RADARSAT data ranging from 1999 to 2003 to extract the inundated area and estimate the water quantity of Tonle Sap Lake. Using a WFFI method (Wavelet-based Filter for detecting spatio-temporal changes in Flood Inundation), Sakamoto et al. assessed temporal changes in the extent of the inundated region in Cambodia and the Mekong Delta on the basis of MOD09 data from 2000 to 2004 [13]. Milne and Tapley [27] used AIRSAT data to classify vegetation and flooding zones in the northwestern region of Tonle Sap Lake. On the basis of water
level data, Kummu and Sarkkula [28] used the Digital Bathymetry Model (DBM) to estimate the water area of Tonle Sap Lake during the period from 1997 to 2005. Using ALOS (Advanced Land Observing Satellite) PALSAR (Phased Array type L-band Synthetic Aperture Radar) data, Choi et al. [29] analyzed flooding zones of Tonle Sap Lake from 2007 to 2008. Considering the great flood of Tonle Sap Lake in 2000, Chae [30] used Landsat ETM+ and RADASAT data to extract flooding zones and estimate the water quantity. Siev et al. [31] used MODIS data to analyze seasonal variations in and water quantity of the flooding area (excluding the water area of Tonle Sap Lake) between Tonle Sap Lake and the Mekong River during the years of 2003 to 2005. To explore the relationship between the construction of water conservancy facilities in the lower reaches of the Mekong River and hydrological variations, Dang et al. [32] used a method similar to the method proposed by Arias et al. [8]; considering typical water levels during the dry season and flood season from 2000 to 2013, this method was used to select the appropriate MODIS product (namely, MOD09A1) of the corresponding period and extract the flooding zones. Tangdamrongsub et al. used several satellite data products (included GRACE, MODIS, and TRMM) to estimate terrestrial water storage and quantify flood events over the Tonle Sap basin between 2002 and 2014 [33]. To determine the relationship between storage variations of Tonle Sap Lake and atmospheric forcing, Frappart et al. extracted the flood extent from MOD09A1 products and used them to estimate lake storage variations [34].

The strong relationship between changes in the lake area of Tonle Sap Lake and flooding of the Mekong River has been acknowledged. Lambert [35] description in detail flood-pulse parameters of Tonle Sap Lake susceptible to flow alterations in the Mekong River. Flow alterations in the Mekong mainstream would directly affect the flood pulse of Tonle Sap Lake [28] because the water level of the lake is controlled by the water level of the Mekong mainstream [36]. Water-balance calculations for Tonle Sap Lake have shown that more than half of the annual inflow to the lake originates from the Mekong mainstream [37].

During the last two decades, the flow regime of the Mekong River has been influenced significantly by human activities, especially hydropower development in the basin. At present, there are six main hydropower stations in operation along the main stream of the Lancang River. The Manwan and Dachaoshan hydropower stations, which were built early on, came into operation in 1996 and 2001, respectively, and the subsequently built Jinghong, Xiaowan, Gongguoqiao, and Nuozhadu hydropower stations came into operation in 2008, 2009, 2011, and 2012, respectively [38]. The potential impacts of cascade hydropower stations in the Lancang River have received wide attention [38–40]. Many studies have assessed transboundary effects of the Lancang cascade hydropower dams on water level and flow in the Mekong River. Lu et al. [36] investigated the impact of the Manwan dam on downstream water levels at the Chiang Saen and found that the dam caused a reduction in low water levels and discharge, whereas high water level alterations were insignificant. Räsänen et al. [41] simulated the effects of the Lancang cascade under three scenarios (no dam, completion of the first three dams, completion of six dams), and their results showed significant increases in dry season flows at Chiang Saen station; they concluded that the hydrological regime of the Mekong River has been significantly altered. Piman et al. [42] also investigated the effect of Chinese dams through hydrological modeling and reported potential increases in dry season water discharge as far downstream as Kratie in central Cambodia. More recently, Lu et al. [43] assessed alterations of monthly water discharge at that same station up until 2010 and found moderate alterations during March and April. However, Li et al. [44] found that damming in the upstream area led to a declining trend in the annual streamflow at the upstream Chiang Saen gauging station, whereas no clear effect was observed at the downstream Stung Treng station. Räsänen et al. [45] assessed discharge changes using observed discharge data and a distributed hydrological model, and found that the hydropower operations in the Upper Mekong Basin can only partially explain observed river discharge changes in Cambodia (Kratie), suggesting that river discharges are also affected by dam operations in the Lower Mekong Basin.

Previous studies mainly focused on changes in the hydrological regime and its effects on downstream areas of the Mekong River; however, few studies have investigated changes in the
lake area of Tonle Sap Lake and their linkage to upstream runoff. Therefore, this study employed satellite data to assess changes in lake area and analyzed their possible linkage with runoff alterations in the Lancang River. The main objectives of this study were: (1) to select the optimal method among commonly used water index methods for extracting water bodies; (2) to extract the water area of the lake and identify variation characteristics; (3) to assess the impact of runoff changes in the Lancang River on the area of Tonle Sap Lake, particularly the influence exerted by the operation of cascade hydropower stations along the Lancang River.

2. Study Area

Tonle Sap Lake is a world-famous production area for freshwater fishes, and it is also an important part of the Mekong River system. Since the Angkor era in the 9th century, the unique flood pulse system along with the high fishery yield has provided a powerful driving force for the social development of surrounding areas [8,9]. Tonle Sap Lake provides favorable irrigation conditions for thousands of farmlands in the ambient plain areas, such that the central region in Cambodia has become an internationally known granary [28].

The water area and quantity of the lake vary significantly from season to season. In the dry season, lake water flows out via the Mekong River and the water area decreases (specifically, the area is only 2500 km$^2$ when the water is at the lowest level); at this time, the average depth is less than 1 m. In the flood season, the water level increases, the water of the Mekong River flows back into the lake, the maximum water area expands up to 15,000 km$^2$, and the water depth is about 10 m on average and more than 15 m at maximum [46].

The study area comprises a permanent lake area and floodplains. The permanent lake area consists of the Large Lake and Small Lake. Located in the southeastern part, the Small Lake is approximately 35 km in length and 28 km in width. The Large Lake lies northwest of the Small Lake, and is approximately 75 km in length and 32 km in width. The floodplains include large areas of inundated forests and shrubs, which form an important part of the ecological system of Tonle Sap Lake [28], as shown in Figure 1.

Figure 1. Location and Map of Tonle Sap Lake.
3. Data and Methods

3.1. Data

3.1.1. MODIS Products

In this study, four commonly used water index methods (NDWI, MNDWI, NDVI, and EVI, see Section 3.2.1) were compared, and two types of MODIS products were selected accordingly.

The NDWI and MNDWI require data in the green, NIR, and SWIR bands. In this study, the associated bands in the MOD09A1 data were selected; in particular, the green band corresponds to band 4 (545–565 nm), the NIR band corresponds to band 2 (841–876 nm), and the SWIR band corresponds to band 6 (1628–1652 nm). MOD09A1 provides MODIS band 1–7 surface reflectance at a resolution of 500 m. Each product pixel contains the best possible higher-order gridded level-2 (L2G) observation during an 8-day period as selected on the basis of the high observation coverage, low view angle, low absence of clouds or cloud shadows, and also low aerosol loading [47].

For the NDVI and EVI methods, this study directly used the MOD13Q1 products. MOD13Q1 data are provided every 16 days at a spatial resolution of 250 m as a gridded level-3 product in the Sinusoidal projection. The MOD13Q1 dataset mainly contains files of NDVI, EVI, red band (band 1), NIR band (band 2), blue band (band 3), and intermediate infrared band (band 7), as well as a series of files with data quality descriptions. Lacking a 250-m blue band, the EVI algorithm uses the 500-m blue band to correct residual atmospheric effects, with negligible spatial artifacts [48].

For the MOD09A1 data, the spatial resolution is 500 m; for the MOD13Q1 data, the spatial resolution of NDVI and EVI products is 250 m. To compare these methods, the different types of data required preliminary consistency processing. In this study, the results obtained by NDWI and MNDWI were re-sampled according to the spatial resolution of 250 m, so as to facilitate the comparison of results.

Using the approach summarized in Frappart et al. [34], the cloud noise of the MODIS data were processed. First, pixels flagged with cloud cover or fill values were masked based on the data quality control information. Then, a linear interpolation was performed to limit information loss over the study area.

3.1.2. HJ-1A/1B Images

Through visual interpretation of high-resolution remote sensing imagery, accurate boundaries of Tonle Sap Lake could be determined. Then the accurate boundaries could be used as the benchmark for comparing the four water index methods. In this study, HJ-1A/1B CCD image data were collected.

The HJ-1A/1B CCD data, which have a high spatial resolution (30 m), short revisiting period (2 days), and large swath (720 km), are designed for mapping the land surface and coastal water quality in environmental and disaster monitoring/forecasts [4]. These data can be obtained from the China Center for Resources Satellite Data and Application (http://www.cresda.com/EN/).

To improve the geometric accuracy of HJ-1A/1B CCD images, they were first subjected to orthorectification. And then using prominent landmarks along the bank of Tonle Sap Lake, the rectified HJ-1A/1B CCD images were then subjected to geometric registration to ensure the spatial consistency of different data sources. Finally, the processed data were used for the visual interpretation of water bodies of Tonle Sap Lake.

Considering the extremely large seasonal variations in the water level and area of Tonle Sap Lake, the optimal method for extraction of water body information should provide good results for different seasons. To compare the performance of the four water body extraction methods, we selected images in two representative seasons for the analysis, namely, the dry season (when the lake is at near minimum) and the flood season (when the lake is at near maximum). In the image for dry season, there were very little cloud over the surrounding region of Tonle Sap Lake and did not affect the identification of water bodies through visual interpretation. In the image for flood season, there are only a few thin clouds on
the edge of the study area, and another image (HJ/1B CCD1 image (DOY275 in 2011) was referred for this region.

Table 1 lists basic information on the selected remote sensing data used for the evaluation of the four methods.

Table 1. Basic Information on the selected remote sensing data.

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Path/Row</th>
<th>Date</th>
<th>Spatial Resolution</th>
<th>Representative Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>HJ/1B CCD2</td>
<td>8/104</td>
<td>1 October 2011</td>
<td>30 m</td>
<td></td>
</tr>
<tr>
<td>MOD09A1</td>
<td>28/7</td>
<td>30 September 2011</td>
<td>500 m</td>
<td>Flood Season</td>
</tr>
<tr>
<td>MOD13Q1</td>
<td>28/7</td>
<td>30 September 2011</td>
<td>250 m</td>
<td></td>
</tr>
<tr>
<td>HJ-1A CCD2</td>
<td>8/104</td>
<td>14 May 2013</td>
<td>30 m</td>
<td>Dry Season</td>
</tr>
<tr>
<td>MOD09A1</td>
<td>28/7</td>
<td>9 May 2013</td>
<td>500 m</td>
<td></td>
</tr>
<tr>
<td>MOD13Q1</td>
<td>28/7</td>
<td>9 May 2013</td>
<td>250 m</td>
<td></td>
</tr>
</tbody>
</table>

3.1.3. Monthly Precipitation Data of TRMM 3B43

The Tropical Rainfall Measuring Mission (TRMM) is jointly carried out by the USA and Japan. On the basis of TRMM data, the National Aeronautics and Space Administration (NASA) has launched multi-version rainfall data products suited to different formats. The TRMM 3B43 product used in this study is related to monthly precipitation data. The spatial resolution is $0.25^\circ \times 0.25^\circ$, and the time series ranges from 1998 to the present.

The accuracy of TRMM precipitation data for the Tonle Sap Lake region has been verified by few studies. Huoy [49] conducted a regression analysis of TRMM precipitation data and precipitation data for the Tonle Sap Lake basin acquired at 65 nearby ground stations, and the $R^2$ value was found to be as large as 0.84. Phoeurn and Ly [50] also found close correlation between the TRMM precipitation data and precipitation data acquired at ground stations around Tonle Sap Lake. In this study, areal precipitation data based on TRMM 3B43 were used for building the regressive relationship between the water area of Tonle Sap Lake and the precipitation of the Tonle Sap Lake basin and runoff of the Mekong River basin.

3.1.4. Runoff Data

In this study, runoff data measured at three hydrological stations were collected. Monthly average runoff data (from 2000 to 2002) at the Kompong Cham station were collected to build the regressive relationship with the water area of Tonle Sap Lake. The Kompong Cham station is located 200 to 300 km away from the watercourse of Tonle Sap Lake (as shown in Figure 1), and thus a certain delay effect was observed regarding the influence of runoff on the area variation of Tonle Sap Lake. To build the regressive relationship, therefore, runoff data from the previous month were required for regression simulations.

The Yunjinghong hydrological station is situated along the main stream of the Lancang River, quite close to the China-Myanmar border. Runoff data at the Yunjinghong station represent the runoff of the Lancang River from China. In total, monthly average runoff data for 55 years (1960–2014) from the Yunjinghong station were collected. Data for the last 15 years (2000–2014) were used to calculate the flow contributions of the Lancang River to Lower Mekong in order to maintain the same period with the extracted lake area.

The Stung Treng hydrological station is located in the Stung Treng Province, Cambodia, and it lies in the lower reaches of the confluence of the 3S rivers (namely, the Sesan River, Srepok River, and Sekong River) and the Mekong River. In this study, runoff data from the Stung Treng hydrological station were compared with those from the Yunjinghong hydrological station (too much data acquired by the Phnom Penh and Kratie hydrological stations, which are nearer to Tonle Sap Lake, were missing; therefore, the data acquired by the Stung Treng hydrological station were selected for the analysis). Average monthly runoff data from the Stung Treng hydrological station covered the period from
January 2007 to December 2014. It is noteworthy that runoff data from January to September 2013 were missing. Therefore, runoff during this period was calculated on the basis of a robust discharge–water level relationship.

3.2. Methods

3.2.1. Water Index

Tonle Sap Lake is characterized by a large seasonal variation in the water area and high diversity of aquatic plants and shoreside plants. Accordingly, four commonly used methods (namely, NDWI, MNDWI, NDVI, and EVI) were compared in this study for extracting variations in the water area and then determining the optimal method.

The NDWI [17] is defined as follows:

$$\text{NDWI} = \frac{\rho_{\text{Green}} - \rho_{\text{NIR}}}{\rho_{\text{Green}} + \rho_{\text{NIR}}}$$

where $\rho_{\text{Green}}$ and $\rho_{\text{NIR}}$ are the reflectance of the green and NIR bands, respectively.

The MNDWI [18] is defined as follows:

$$\text{MNDWI} = \frac{\rho_{\text{Green}} - \rho_{\text{SWIR}}}{\rho_{\text{Green}} + \rho_{\text{SWIR}}}$$

where $\rho_{\text{SWIR}}$ is the reflectance in the SWIR band.

The NDVI [51] is defined as follows:

$$\text{NDVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{\rho_{\text{NIR}} + \rho_{\text{RED}}}$$

where $\rho_{\text{RED}}$ is the reflectance in the RED band.

The EVI [52] is a modified NDVI, and it is defined as follows:

$$\text{EVI} = 2 \cdot \frac{\rho_{\text{NIR}} - \rho_{\text{RED}}}{L + \rho_{\text{NIR}} + C_1 \cdot \rho_{\text{RED}} + C_2 \cdot \rho_{\text{BLUE}}}$$

where $\rho_{\text{BLUE}}$ is the reflectance in the BLUE band, $L$ is a soil adjustment factor, and $C_1$ and $C_2$ describe the use of the blue band in the correction of the red band for atmospheric aerosol scattering.

3.2.2. Evaluation Method

The accuracy of the four methods was mainly evaluated using two indices.

The first index involved the measurement of the proportion of omitted water area, and it was calculated by the following formula:

$$\text{OR} = \frac{A_M - A_C}{A_M} \cdot 100\%$$

where $A_M$ refers to the lake water area identified by visual interpretation, $A_C$ refers to the overlapping area of water body identified by both water index and visual interpretation, and OR refers to the omission rate.

The second index involved the measurement of the proportion of area of ground objects that were erroneously categorized as water bodies, and it was calculated by the following formula:

$$\text{FR} = \frac{A_{NW}}{A_W} \cdot 100\%$$
where $A_w$ refers to the total water area in the study area identified by the water index method, $A_{NW}$ refers to the false water area that is identified as water area by the water index but identified as non-water area by visual interpretation, and FR refers to the false rate.

The two indices were calculated based on spatial analysis of the extracted water area. The values of both OR and FR range from 0 to 1; smaller values indicate better performance.

According to the overall performance of the four water index methods in the dry and flood seasons, this study determined the optimal method for extracting dynamic variations in water area of Tonle Sap Lake.

3.2.3. Separation of Lake Body and Flooding Area

For the same zone, the relative value of the water covered area was used to describe variations in lake area between different periods. This was performed to reduce the uncertainty of analysis results arising from the long observation interval and seasonal variation. Based on the detection statistics within a certain time range, the Water Covered Index (WCI) can be used to determine the inundation frequency:

$$WCI (i, j) = \frac{N_w (i, j)}{N_t (i, j)}$$

where $N_w (i, j)$ refers to the number of times that pixel $(i, j)$ is detected as a water body, and $N_t (i, j)$ refers to the total number of times that pixel $(i, j)$ is detected. For land, the WCI value is 0, whereas it is 1 for the permanent lake area. The WCI value for the seasonal lake area varies within the range of 0 to 1. Larger WCI values represent longer inundation periods. In this manner, the value of detected pixel statuses can be normalized as the flooding ratio, and thus, comparative analyses of the variations in water area during different stages can be conducted.

In an ideal case, the pixel is a water body if the WCI value is greater than 0, and it is a permanent lake area in the synthesis stage if the WCI value is equal to 1. Considering diverse influencing factors, such as, the quality of remote sensing data, short-term variation in water area, and uncertainty of the detection algorithm, during the analysis of seasonal and interannual variations in the lake area, a pixel was assigned as a permanent lake area only when the WCI value was greater than a specific value. A pixel was defined as lake body in the synthesis stage when the WCI value was greater than 0.9 and was defined as a flooding area when the value was greater than 0.1.

3.2.4. Assessment of the Contributions of Upstream Changed Flow to Lower Mekong

We assessed the impact of runoff changes in the Lancang River on the lake area of Tonle Sap based on the contribution of upstream flow to the lower Mekong River.

First, considering the schedule of the operation of Chinese dams and annual average runoff at the Yunjinghong Station that showed a significant change point in 2008, the time series of runoff data was divided into two parts: the pre-change periods (2000–2007) and the post-change periods (2008–2014). The change point was detected using the Mann-Kendall method, and details are provided in Supplementary Materials (Figure S1). Then, the contributions can be calculated according to the following equations:

$$C = R_{changed} \cdot P \cdot 100\%$$

$$R_{changed} = \frac{D_{post,up} - D_{pre,up}}{D_{pre,up}}$$

$$P = \frac{D_{post,up}}{D_{post,down}}$$

where $C$ is the contribution of changes in upstream flow to the runoff of the lower Mekong River; $R_{changed}$ is the change rate of discharge measured at the upstream hydrological station (Yunjinghong Station) and $P$ is the proportion of upstream discharge to downstream discharge during the post-change periods. $D_{post,up}$, $D_{pre,up}$ and $D_{post,down}$ are upstream discharge (Yunjinghong Station) during the
post-change periods, upstream discharge during the pre-impact periods, and downstream discharge (Stung Treng station) during the post-change periods, respectively. We calculated the contributions for each flood and dry seasons. As 80–90% of the Mekong River’s discharge occurs from May to October [53], we considered the flood period from May to October and the other months were considered as the dry season.

To analyze how the Tonle Sap lake area responds to a significant change in upstream runoff, we divided time series of the extracted areas into two corresponding time periods. And as the changes in lake area between the two periods were calculated, we can analyze the possible linkage between changes in the lake area and changes in upstream flow.

4. Results

4.1. Comparison of the Performance of the Four Water Body Extraction Methods

Visual interpretation was performed on the HJ-1A/B satellite imagery, which had a resolution of 30 m, and the results were used as the benchmark. Against the benchmark, we compared the performance of the four water body extraction methods. First, the threshold of each water index was determined when values are taken to ensure that both OR and FR are reasonable and acceptable in the flood and dry seasons. Through multiple attempts adjustments, the optimal threshold values were obtained, which are as follows: 0.14 (EVI), 0.15 (NDVI), 0.17 (NDWI), and 0 (MNDWI). Based on the optimal threshold values, the lake area was then extracted for the two representative seasons (A comparison of the water boundary extracted by four water index methods are provided in Supplementary Materials-Figure S2), and the omission rate and false rate of each method were measured in accordance with the lake area combined with visual interpretation results (as described in Table 2).

<table>
<thead>
<tr>
<th>Water Body Index</th>
<th>OR (%)</th>
<th>FR (%)</th>
<th>Water Body Index</th>
<th>OR (%)</th>
<th>FR (%)</th>
</tr>
</thead>
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<tr>
<td>EVI</td>
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<td>7.2</td>
<td>EVI</td>
<td>8.5</td>
<td>14.4</td>
</tr>
<tr>
<td>NDVI</td>
<td>34.2</td>
<td>3.3</td>
<td>NDVI</td>
<td>12.9</td>
<td>5.2</td>
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<tr>
<td>NDWI</td>
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<td>10.3</td>
<td>NDWI</td>
<td>9.1</td>
<td>6.4</td>
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<td>8.5</td>
<td>MNDWI</td>
<td>7.2</td>
<td>6.5</td>
</tr>
</tbody>
</table>

Table 2. Comparison of the Four Water Body Extraction Methods.

During the flood season, the omission rate was low for MNDWI and NDWI. As for NDVI, the false rate was extremely low, but the omission rate was extremely high. Regarding EVI and MNDVI, there was an overall balance between the omission rate and false rate. During the dry season, the false rate and omission rate were very high with EVI and NDVI, respectively. In contrast, MNDWI showed a stable performance in terms of the false rate and omission rate. Considering to the performance of the four methods during the flood and dry seasons, MNDWI provided the most stable performance and best results. Thus, in this study, MNDWI was selected for extracting the water area of Tonle Sap Lake during the period of 2000–2014.

4.2. Variation in Water Area of Tonle Sap Lake

The water area of Tonle Sap Lake (2000–2014) was extracted using MOD09A1 data (Figure 2). Overall, the water area displayed a decreasing tendency through the 15 years, although it is not significant at a significance level of 0.05. The average annual water area was 5513.9 km$^2$ during 2000–2007, and it was 5172.5 km$^2$ during 2008–2014, showing a decrease of 6.19% (approximately 341.4 km$^2$).
Among the 15 years (2000–2014), there were 2 years (2001 and 2007) in which the minimum water area was, in general, more than 3000 km$^2$, and after 2008, the minimum water area did not exceed, approximately, 3000 km$^2$ (Table 3). Evidently, the water area of Tonle Sap Lake has decreased significantly in recent years.

### Table 3. Maximum/Minimum Area of Tonle Sap Lake from 2000 to 2014.

<table>
<thead>
<tr>
<th>Year</th>
<th>Maximum Area (km$^2$)</th>
<th>Minimum Area (km$^2$)</th>
<th>Year</th>
<th>Maximum Area (km$^2$)</th>
<th>Minimum Area (km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>15,579.51</td>
<td>3029.23</td>
<td>2008</td>
<td>9957.95</td>
<td>2910.67</td>
</tr>
<tr>
<td>2001</td>
<td>13,689.56</td>
<td>2885.05</td>
<td>2009</td>
<td>12,253.40</td>
<td>2907.55</td>
</tr>
<tr>
<td>2002</td>
<td>14,246.87</td>
<td>2884.44</td>
<td>2010</td>
<td>8626.43</td>
<td>2657.36</td>
</tr>
<tr>
<td>2003</td>
<td>8492.13</td>
<td>2772.51</td>
<td>2011</td>
<td>16,507.63</td>
<td>2689.48</td>
</tr>
<tr>
<td>2004</td>
<td>11,389.50</td>
<td>2771.08</td>
<td>2012</td>
<td>12,689.21</td>
<td>2544.85</td>
</tr>
<tr>
<td>2005</td>
<td>11,998.29</td>
<td>2444.62</td>
<td>2013</td>
<td>14,795.17</td>
<td>2596.96</td>
</tr>
<tr>
<td>2006</td>
<td>10,847.94</td>
<td>2821.83</td>
<td>2014</td>
<td>8871.19</td>
<td>2508.77</td>
</tr>
<tr>
<td>2007</td>
<td>10,175.86</td>
<td>3061.81</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

In addition, as shown in Table 3, there were extreme drought and flood years during 2000–2014. The flooding area was as large as 14,246.87 km$^2$ in 2002, but it rapidly decreased to 8492.13 km$^2$ in 2003, which represents a decrease of 40%. Droughts and floods were particularly typical in 2010 and 2011. In 2010, the maximum water area was only 8626.43 km$^2$, but significantly expanded to 16507.63 km$^2$ in 2011 (an increase of 47%), which was the largest increase among the 15 years. In 2013 and 2014, the maximum flooding area suddenly decreased by 41%, but the minimum water area did not significantly vary.

On the basis of the extracted area, this study calculated the ratios at which the flooding area was larger than 10,000 km$^2$ and smaller than 3000 km$^2$ ((number of such occurrences) divided by (total number of observation times)). During 2000–2007, the ratio at which the flooding area was larger than 10,000 km$^2$ was 11.6%, and the ratio at which the flooding area was smaller than 3000 km$^2$ was 1.1%; during 2008–2014, the two ratios were 7.8% and 1.9%, respectively. Thus, the findings suggest a decrease in the frequency of floods and an increase in the frequency of droughts.

Intra-annual variations in the water area of Tonle Sap Lake were more significant during the post-change period (2008–2014) than during the pre-change period (2000–2007); in particular, the water area decreased markedly in July, August, and September (as shown in Figure 3). During the pre-change period, the average water area decreased by 534.53 km$^2$ (a decrease of 8.3%) in the flood season.
(as shown in Figure 4). In addition, the average water area decreased slightly (1.5%) in the dry season (November to April next year). Overall, the average annual water area of Tonle Sap Lake decreased during the pre-change period; in particular, the lake area significantly decreased during the flood season.

4.3. Variation in the Lake Body and Flooding Area of Tonle Sap Lake

By superimposing the raster images of extracted water areas for each period, 2000–2007 and 2008–2014, the lake body area (WCI > 0.9) and flooding area (WCI > 0.1) could be determined, and the result and changes are shown in Figures 5 and 6. According to these figures, combined with the information presented in Table 4, the main-body of Tonle Sap Lake has decreased by 28.25 km² (variation rate of −1.1%), and the flooding area has decreased by 1752.75 km² (variation rate of −12.8%) after 2008. This shows once again that the overall water area of Tonle Sap Lake tended to decrease, particularly during the flood season.
4.4. Relationship between the Water Area of Tonle Sap Lake and Precipitation and Runoff of the Mekong River

On the basis of the TRMM3B43 product, the average monthly areal precipitation over Tonle Sap Lake was calculated. Figure 7 shows variations in the annual precipitation over the Tonle Sap Lake basin. The annual average precipitation during the pre- and post-change periods were 1812.23 mm and 1831.63 mm, respectively, which amounts to an increase of about 19 mm (1.1%).

As shown in Figure 8, after 2008, the average precipitation in the flood season decreased by approximately 22 mm (about 1.41%), and the average precipitation in the dry season increased by approximately 49 mm (19%). The opposite change trends of precipitation and lake area in the dry season indicate that precipitation in the dry season did not account for changes in the lake area after 2008. During the flood season, the decrease in precipitation was very small, and thus, it would not have significantly affected changes in the lake area.
basin. The annual average precipitation during the pre-change period was 1812.23 mm and 1831.63 mm, respectively, which amounts to an increase of about 19 mm (1.1%).

Figure 7. Variations in the Annual Precipitation over the Tonle Sap Lake Basin.

As shown in Figure 8, after 2008, the average precipitation in the flood season decreased by approximately 22 mm (about 1.41%), and the average precipitation in the dry season increased by approximately 49 mm (19%). The opposite change trends of precipitation and lake area in the dry season indicate that precipitation in the dry season did not account for changes in the lake area after 2008. During the flood season, the decrease in precipitation was very small, and thus, it would not have significantly affected changes in the lake area.

Figure 8. Comparison of the Average Precipitation in the Flood Season and Dry Season before and after 2008.

To further explore the relationships between lake area and regional precipitation and the runoff in the Mekong River, the average monthly runoff from the Kompong Cham hydrological station on the main stream of the Mekong River and average monthly precipitation of the Tonle Sap Lake basin were jointly used to fit the water area of Tonle Sap Lake. The regression equation is as follows:

\[
A = 0.20981 \times Q - 1.656 \times P + 2679.50501
\]

where \(A\) refers to the water area of Tonle Sap Lake, \(Q\) refers to the runoff of the previous month at the Kompong Cham hydrological station, and \(P\) refers to the average monthly precipitation of the Tonle Sap Lake basin. For the regression equation, the \(R^2\) value was equal to 0.953 and the adjusted \(R^2\) value was equal to 0.951.

Figure 9 shows a comparison between the fitting results and the water area extracted from MODIS data. The fit between the two types of data could be considered good. These results demonstrate that the two factors can basically be used to account for seasonal variations in the water area of Tonle Sap Lake.

Using the Multiple Linear Regression analysis method \[54\], the relative contribution of each variable was calculated through the regression equation with data standardization (specifically, 95% for
Q and 5% for P). Although these values cannot totally represent the absolute quantity of influence, it showed that the seasonal variation in water area of Tonle Sap Lake was only slightly influenced by precipitation over the Tonle Sap Lake basin; it was dominantly influenced by the runoff of the Mekong River. This result corroborates previous findings [28,37].

![Figure 9](image_url)  
**Figure 9.** Comparison between the Simulated Water Area and Extracted Water Area by Modified Normalized Difference Water Index (MNDWI).

### 4.5. Flow Contributions of Lancang River to Lower Mekong River

As shown in Figures 10 and 11, monthly runoff measured at the Yunjinghong hydrological station sharply varied between the pre- and post-change periods. Overall, monthly runoff increased during the dry season but decreased during the flood season. Monthly runoff during the dry season increased by 20.74%; in particular, runoff increased the most significantly in March (nearly 40%). The monthly average runoff during the flood season decreased by 34.25%; in particular, runoff decreased the most significantly in July (49.59%).

![Figure 10](image_url)  
**Figure 10.** Intra-annual Variation in Runoff Measured at the Yunjinghong Hydrological Station before and after 2008.
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**Figure 10.** Intra-annual Variation in Runoff Measured at the Yunjinghong Hydrological Station before and after 2008.

**Figure 11.** Variation in Runoff during the Flood and Dry Seasons Measured at the Yunjinghong Hydrological Station before and after 2008.

Figures 12 and 13 show the ratio of the average monthly runoff measured at the Yunjinghong hydrological station to that measured at the Stung Treng hydrological station during the flood and dry seasons. Overall, the ratio was relatively high (19.87%) during the dry season, especially in April (almost 30%). The ratio was 8.85% on average during the flood season, and it reached as high as 26.19% in May and as low as 7.05% in September.

![Graph showing monthly runoff ratios](image1)

**Figure 12.** Ratio of Monthly Runoff Measured at the Yunjinghong station to that Measured at the Stung Treng Hydrological Station (Upper Part); Comparison of the Monthly Average Runoff between the Yunjinghong and Stung Treng Hydrological Stations (Lower Part).

In accordance with the above results, the contribution of outbound flow from China after 2008 to variations in monthly runoff of the lower Mekong River were calculated (Figure 14). Overall, after 2008, changes in the upstream flow (Lancang River) contributed to the increase in runoff of the lower Mekong River by approximately 6.17% during the dry season, and they contributed to the runoff increase by as much as 11.31% in March. Meanwhile, it contributed to the runoff decrease of the lower Mekong River in May by 26.19%.

![Graph showing runoff contributions](image2)
The Mekong River by only 2.41% during the flood season, and the contribution rate was the highest (4.57%) in June.

![Image](image.png)

**Figure 13.** Ratio of Runoff Measured at the Yunjinghong to that Measured at the Stung Treng Hydrological Station in the Flood and Dry Seasons (Upper Part); Comparison of the Average Runoff between the Yunjinghong and Stung Treng Hydrological Stations in the Flood and Dry Seasons (Lower Part).

**Figure 14.** Contribution of Changes in Upstream Flow (Lancang River) to the Monthly Runoff Measured at the Stung Treng Hydrological Station after 2008.

5. Discussion

5.1. Uncertainties of the Water Index Method

This study compared the performance of four commonly used water index methods: EVI, NDVI, NDWI, and MNDWI. These water index methods can often effectively distinguish large categories of information such as vegetation, land, and water. Limited by the low resolution of remotely sensed data, it is difficult to identify the specific category of objects, which may partly account for errors in water body identification. In parts of the flooding zones of Tonle Sap Lake, forests, shrubs, and other wetland plants exist [29]. In the flood season, the roots and necks of the plants are inundated, but some of the canopies are not submerged. All of these features will affect the extraction of water body information. While the NDVI and EVI methods can identify vegetation accurately, emergent crowns may lead to errors in the identification of water bodies using the two methods. NDWI results may also be affected by this problem. Ji et al. [25] suggested that the NDWI may not be suitable in complex areas, especially...
where vegetation is partially submerged. This may be attributed to NDWI using the NIR band, which is very sensitive to the vegetation water content \[55\]. In addition, because of the low resolution of MODIS data, the inundation area contained many mixed pixels, thus increasing the sensitivity of the NDWI to vegetation \[56\]. Comparing the results of the water index methods with those of the visual interpretation, the MNDWI provided more stable results than the other methods.

The lake area extracted by the MNDWI method was compared with those from previous studies (see Supplementary Materials-Table S1 and Table S2). Kummu and Sarkkula \[28\] calculated the annual maximum and minimum lake area of Tonle Sap during 1997–2005 based on water level data and a DBM (digital bathymetry model). Arias et al. \[8\] used two methods to delineate the annual maximum and minimum water extent: one combining a DEM with water level records and the other based on a classification of MOD09Q1 images using an unsupervised classification method. The lake area extracted by four different methods (including this study) have a ±5% deviation from their average in both the maximum and minimum values. It is difficult to determine which result is more accurate because of the uncertainties in the methods and data. Nevertheless, the four results reflected a consistent trend of interannual variation in the minimum-maximum area of Tonle Sap Lake, and the results of this study could provide a reliable description of the dynamic variations in the water area of Tonle Sap Lake.

5.2. Impacts of Chinese Dams?

According to the results of this study, the water area of Tonle Sap Lake decreased by 1.5% on average during the dry season after 2008, but changes in upstream flow contributed to increased runoff by 6.17% in the dry season as measured at the Stung Treng hydrological station. Therefore, the decrease in the water area of Tonle Sap Lake during the dry season was not attributed to the development of the Lancang cascade hydropower stations. Conversely, the increase in upstream runoff during the dry season may have mitigated the decrease in the water area of Tonle Sap Lake. After 2008, the water area of Tonle Sap Lake decreased by 8.3% during the flood season, but the change in upstream flow contributed to the decrease in the runoff of the lower Mekong River by only 2.41%. Moreover, the changes in flow are not entirely influenced by the operation of hydropower stations but also by climate change \[57\]. These results indicate that the development of the Lancang cascade hydropower stations do not primarily account for the decrease in the water area of Tonle Sap Lake in the flood season.

In recent years, the 3S rivers have undergone vigorous hydropower development, and this may be an important reason for the decrease in the runoff of the lower reaches of the Mekong River in the flood season as well as for the decrease in the water area of Tonle Sap Lake in the flood season. Although the area of the basins of the 3S rivers accounts for only 10% of the total area of the Mekong River basin, the 3S rivers contribute approximately 17–20% of the annual flow of the Mekong main stream \[38\]. Along the 3S rivers, there are approximately 42 dams under various stages of completion, i.e., completed, under construction or in prospect \[59\]. Arias et al. \[60\] estimated the impacts of the 3S dams using a hydrological model and found considerably higher levels of alterations in Tonle Sap Lake than observed or simulated before. Cochrane et al. \[40\] suggested that the alterations observed downstream from Stung Treng will be exacerbated by the ongoing development in the 3S basin. Piman et al. \[59\] believe that large-scale hydropower development along the 3S rivers will bring about a decrease of 22% in wet season flows at the outlet. Because the 3S rivers are closer to Tonle Sap Lake than the Lancang river, such changes will affect the hydrological and ecological conditions of Tonle Sap Lake and the Mekong River delta more significantly.

Flow alterations observed in lower Mekong also could be partly attributed to irrigation development, especially in the Chi–Mun basin, in which the largest irrigation scheme in the Mekong Basin has been implemented \[40\]. The Chi–Mun Basin is the largest tributary of the Mekong river in terms of area, and contributes an average annual flow of more than 3 billion cubic meters, which discharges immediately above Pakse in Laos \[61\]. The irrigated area in Chi-Mun Basin is close to
1,266,000 ha with an annual water demand of 0.8963 billion cubic meters [62]. Cochrane et al. [40] reported a significant reduction in the rise rate of water level at Pakse, and much of this could be attributed to irrigation operation in the Chi–Mun basin during the dry season as water demand for agriculture increases. This may be further related to the decrease in the water area of Tonle Sap Lake in the dry season. Nevertheless, further research is necessary to confirm this.

Our study had some limitations in that part of our analyses on the changes in upstream runoff were based on data from a relatively short time period (2000–2014). As the largest dam (Nuozhadu) in the Lancang River became fully operational in 2014, analyses with longer data periods would provide a better understanding of the flow regime alteration.

6. Conclusions

On the basis of MODIS data products, this study attempted to find a simple, efficient, and accurate method for extracting remote-sensing data on lake water area. For this purpose, the performances of four methods (namely, MNDWI, NDWI, NDVI, and EVI) in extracting water bodies during the flood and dry seasons were compared. Among the four methods evaluated, MNDWI displayed the most stable performance and highest accuracy, and thus, it was selected for further analysis of the Tonle Sap basin.

The water area of Tonle Sap Lake during 2000–2014 was determined using MOD09A1 data, and the characteristics of variations in the water area variation before and after 2008 were analyzed. After 2008, the annual average water area of Tonle Sap Lake decreased by 341.4 km² (6.19%). The average water area in the flood season (May to October) decreased by 534.53 km² (8.3%), and the average water area in the dry season decreased by 1.5%. The main-body area (minimum average annual area) of Tonle Sap Lake decreased gradually over time, and after 2008, it decreased by 28.25 km² (−1.41%). The maximum flooding area (maximum average annual area) decreased by 1752.75 km² (−12.8%). On the whole, the water area of Tonle Sap Lake displayed a decreasing tendency, particularly during the flood season.

Changes in the precipitation of the Tonle Sap Lake basin only slightly affected the monthly variation in the water area of Tonle Sap Lake, whereas the runoff of the Mekong River had a dominant influence on the area variation of Tonle Sap Lake. In the dry season, outbound runoff of the Lancang River measured at the Yunjinghong hydrological station accounted for 19.87% of the runoff measured at the Stung Treng hydrological station; in the flood season, this proportion was 8.85%. It can be concluded that changes in upstream flow after 2008 contributed to the increase in runoff by about 6.17% during the dry season and to the decreased in runoff by about 2.41% during the flood season in the lower Mekong River. Evidently, the decrease in the water area of Tonle Sap Lake during the dry season is not attributable to the operation of cascade hydropower stations in the Lancang River. Conversely, increases in runoff during the dry season attributable to the operation of cascade hydropower stations has mitigated the decrease in the water area of Tonle Sap Lake to a certain extent. Moreover, the operation of cascade hydropower stations in the Lancang River (after 2008) does not primarily account for the decrease in the area of Tonle Sap Lake during the flood season.

**Supplementary Materials:** The following are available online at http://www.mdpi.com/2072-4292/10/6/866/s1, Figure S1: Change point in the time series of annual average runoff at Yunjinghong Station (1960–2014) detected by Mann-Kendall test, Figure S2: Comparison of the water boundary extracted by four water index methods (A/B/C/D for flood season, E/F/G/H for dry season), Table S1: Comparison of the minimum lake area extracted by four different methods, Table S2: Comparison of the maximum lake area extracted by four different methods.

**Author Contributions:** Conceptualization, D.H.; Formal analysis, X.L.; Investigation, X.J.; Methodology, X.J.; Writing—original draft, X.J.; Writing—review & editing, Y.L.

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**Conflicts of Interest:** The authors declare no conflict of interest.
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