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*Original research article*

# Water Balance Analysis of Tonle Sap Lake using WEAP Model and Satellite-Derived Data from Google Earth Engine

Phanit Mab, Ekasit Kositsakulchai*

*Department of Irrigation Engineering, Kasetsart University, Nakhon Pathom 73140, Thailand*

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## ABSTRACT

Water balance analysis in Tonle Sap (TLS) Lake was analyzed using Earth observation data from the Google Earth Engine (GEE) platform and the Water Evaluation and Planning System (WEAP) model. The WEAP model was used to estimate the interconnected water-balance components in the TLS system during 2000-2014. Two key inputs-TRMM satellite precipitation and MODIS evapotranspiration—covering the drainage basin were retrieved using the GEE. The simulation estimated the mean annual volume (69 km3) of total inflow to the lake. The highest inflow (89.6 km3) occurred in 2011 when one of the worst floods in the Mekong river basin was recorded. The Mekong River had a great impact on the availability of the lake's water resource, as it supplied 62% of total inflow to the lake. The inflow from the Mekong River occurred from June to September when water level in the river was higher than that in the lake. This research demonstrated an option to conduct a comprehensive water balance analysis in a large region using limited local measured data. Satellite-derived data adequately provided the required inputs for the simulation model.

**Keywords**: Google Earth Engine; Mekong River; Tonle Sap Lake; Water balance; WEAP

## 1. Introduction

Water balance is a key determinant for the distribution and productivity of terrestrial vegetation around the globe [1]. Water balance analysis can be used to: identify and quantify water inflows and outflows; identify and quantify changes in stocks of water; quantify components of the water balance that are difficult to measure or even estimate by assuming that they are the residual in the water balance equation; assess the potential impacts on water balance components; and assess whether current levels of consumptive water use within the specified domain are sustainable and if not, whether opportunities

***Corresponding author**: ekasit.k@ku.th
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exist for rebalancing net inflows and outflows [2].

The Mekong is the largest and most important transboundary river basin in Southeast Asia [3]. The Tonle Sap (TLS) Lake, located in central Cambodia, is the most extensive wetland habitat of the Mekong River Basin. The Lake and its surrounding floodplains form the largest freshwater body in Southeast Asia. The Lake was reported to be very productive [4, 5]. Over 3.6 million Cambodians depend on this lake for their livelihoods, which are linked directly to its natural resources [6]. The Mekong River system has been studied by many researchers [3, 7-14]. For example, a book edited by Campbell et al [9] -The Mekong-provides comprehensive information on the hydrology and water resources of the Mekong River [15, 16]; one chapter is devoted to the TLS Lake [17]. Other studies regarding TLS Lake comprise-the changes in the Lake's area and volume [18, 19], streamflow in the TLS Lake and its floodplains [20-23].

Water balance analysis for the Tonle Sap Lake was previously conducted from 1982 to 2004 by Inomata and Fukami [24] and from 1997 to 2005 by Kummu and Collaborators [25, 26]. Techniques for estimating water balance can range from very simple methods such as lumped models and field-experiment techniques, to highly complex computer-based models that can calculate water balance at various temporal (hourly, daily, monthly or yearly) and spatial scales [27, 28]. Selection of an appropriate technique depends on the objectives of the study and the availability of data. There are insufficient hydrological data available for the Mekong River Basin to determine its water budget from the past to the present. In addition, TLS Lake and its tributaries are mostly located in Cambodia, where the availability of hydrological data is very limited because of the prolonged civil war [24].

Precipitation is a critical variable in the hydrological cycle, and it influences our daily lives [29]. However, accessibility to the precipitation dataset for the TLS Lake region is one of the limitations to conducting a comprehensive hydrological analysis [30]. In recent times, the Google Earth Engine Platform (GEE) has leveraged cloud computing services to provide online analysis capabilities on satellite data [31]. Geospatial datasets are processed using the Application Programming Interface (API), which allows us to develop a code to obtain datasets of publicly available remotely sensed imagery and other data. As a remote sensing platform, its ability to analyze global data rapidly is a useful tool for data visualization [32].

Water resource system models are effective tools for addressing water management challenges [33]. Various water resource system models, such as AQUATOOL [33], HEC-RESSIM [34], HEC-WAT [35], MIKE-BASIN [36], RIBASIM [37], and WEAP [38, 39], have been developed and applied in a number of water resources systems including the Mekong River Basin [12, 40]. These models include temporal and spatial features that make them useful as tools for water resource management, water balance analysis, groundwater modelling, and urban and rural watershed management under different climatic conditions [41-45].

The current research investigated an option to conduct a comprehensive water balance analysis in a large region using limited local measured data. Recent Earth Observation (EO) data (precipitation and evapotranspiration) were retrieved from the Google Earth Engine (GEE) Platform. The Water Evaluation and Planning System model (WEAP) was used for calculating the inter-connected water balance components in the Tonle Sap Lake Basin.

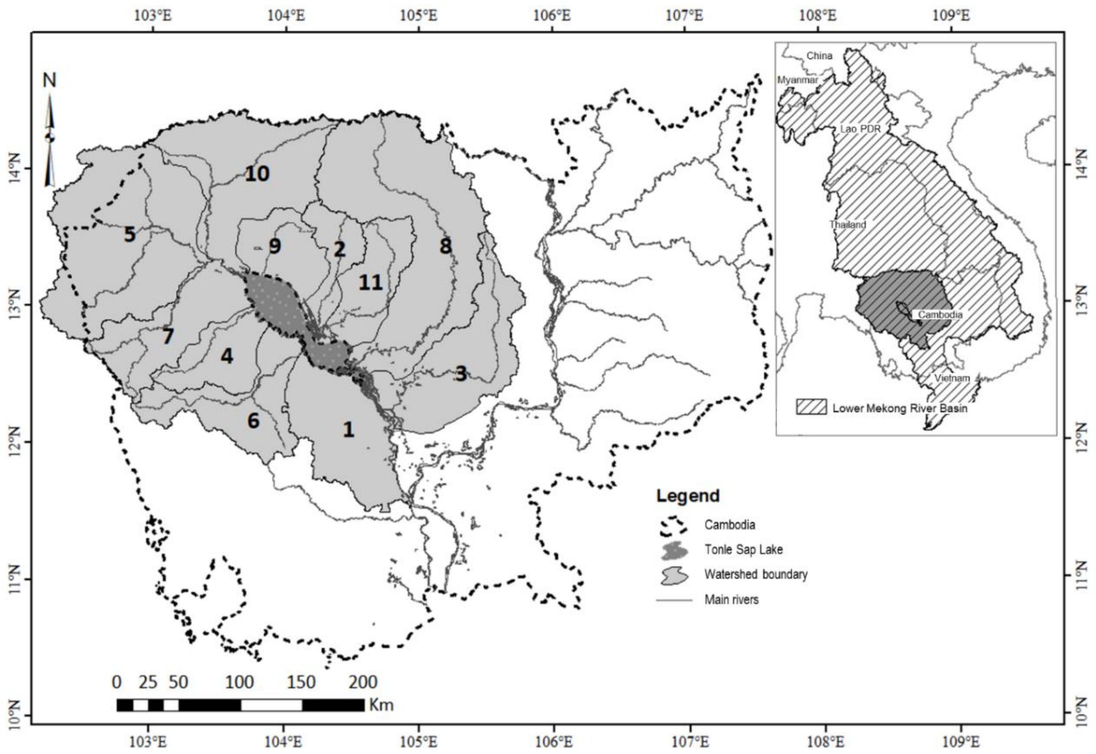


**Fig. 1.** Tonle Sap Lake and its watershed broken down into 11 sub-basins namely: (1) Stung Boribo [ST1], (2) Stung Chikreng [ST2], (3) Stung Chinit [ST3], (4) Stung Dauntri [ST4], (5) Stung Mongkolborey [ST5], (6) Stung Pausat [ST6], (7) Stung Sangke [ST7], (8) Stung Sen [ST8], (9) Stung Siemreap [ST9], (10) Stung Sreng [ST10], and (11) Stung Staung [ST11].

## 2. Materials and Methods

### 2.1 Study area

The Mekong River rises in the Himalayas in Tibet and flows through China, forming part of the Lao PDR borders with Burma and Thailand, before continuing through Cambodia and Vietnam to the South China Sea [46]. Out of total drainage area of 795,000 km$^2$, approximately 25% lies in the Lao PDR, 23% in Thailand, 21% in Yunnan (China), 20% in Cambodia, 8% in Vietnam, and only 3% in Myanmar [47]. This region has a tropical climate with wet and dry seasons. Average daily temperatures vary between 20°C and 36°C with the lowest in January and the highest in April [48].

The Tonle Sap ecosystem is a major component of the Mekong River Basin, consisting of the TLS Lake, the TLS River and the surrounding floodplains [49]. The TLS Lake is the largest permanent freshwater lake in Southeast Asia [17]. The drainage area of the TLS Basin is 85,796 km$^2$, extending over 44% of Cambodia. It is shared by Cambodia (95%) and Thailand (5%) of the drainage area [48, 50] (Fig. 1). During the dry season, the Lake is approximately 120 km long and 35 km wide with an area of 2,500 km$^2$. During the flood period, the Lake expands to 250 km long and 100 km wide with an area of 17,500 km$^2$, and the depth reaches 8-10 m. The Lake functions as a natural floodwater reservoir for the Mekong system during the dry season (November–April), when approximately half of the discharge to the Mekong Delta in Vietnam originates from the Lake [51].

The TLS Lake is linked to the Mekong River by the 100-km-long TLS River [49]. The TLS River, which flows from the southeastern end of TLS Lake, joins the Mekong River at the Chaktomuk confluence, in the vicinity of Phnom Penh. After the confluence, the river immediately splits into the smaller Bassac River and the larger Mekong River. In the wet season, from May to September, flooding and the associated water level increase in the Mekong River causes the TLS River to change flow direction and flow towards the northwest (upstream) into the Tonle Sap Lake [25].

## 2.2 Satellite data retrieved from Google Earth Engine platform

The GEE is a cloud-based platform that makes it easy to access high-performance computing resources for processing very large geospatial datasets [52]. Moreover, geospatial datasets are processed for the TLS Basin for rapid visualization of complex spatial analyses using the JavaScript API.

Precipitation and evapotranspiration are two hydrological components used to calculate the water balance in the Tonle Sap Lake. The pre-processed datasets are available from the GEE platform. Satellite data-the precipitation from the Tropical Rainfall Measuring Mission (TRMM) and the MODIS evapotranspiration-were selected in the study. The three-hourly TRMM 3B42V7 precipitation product [53] at 0.25° pixel resolution is available from 1998 to present. The precipitation estimates were produced from the combination and calibration of microwave estimates, gap filling, and bias correction. The estimated precipitation from the TRMM dataset over the TLS Basin was evaluated by Mab et al [30]. The three-hourly rain rates were processed using JavaScript in the GEE platform into daily rainfall, which is required for streamflow estimation by a rainfall-runoff model. The MOD16A2 product [54] provides information about 8-day evapotranspiration (ET) at 1-km pixel resolution. The 8-day ET data were processed into monthly ET data for this study.

## 2.3 Water balance analysis of the Tonle Sap Lake

Water balance analysis relies on the Law of Conservation of Mass, which requires that for a specified domain over a specified period of time, water inflows are equal to water outflows, plus or minus any change of storage [2]. The water balancing of Tonle Sap Lake was based on the equation:

$$S_i = S_{i-1} + I_i + I_{MK,i} - O_{MK,i} - NET_i, \qquad (2.1)$$

where $S_{i-1}$ and $S_i$ are the storage of TLS Lake at the beginning and the end of each time step, $I_i$ is the inflow from the Tonle Sap watershed, $I_{MK,i}$ is the inverse flow in the Tonle Sap River from the Mekong River, $O_{MK,i}$ is the outflow to the Mekong River, and $NET_i$ is the net evaporation which equals the difference between the potential evapotranspiration ($PET_i$) and rainfall ($P_i$) over the lake surface area. The lake surface area and volume were estimated using the relationships proposed by Kummu et al. [25, 26]:

$$A = -5.5701 \times WL_{KL}^3 + 137.40 \times WL_{KL}^2 + 470.29 \times WL_{KL} + 1680.2, \qquad (2.2)$$

$$V = 0.7307 \times WL_{KL}^2 - 0.3554 \times WL_{KL} + 0.9127, \qquad (2.3)$$

where, $A$ is the surface area of the lake (km$^2$), $V$ is the volume of the lake (km$^3$) and $WL_{KL}$ represents the water level of TLS Lake measured at the Kampong Loung (KL) station in meters above mean sea level (m MSL).

The balancing of inflows and outflows was calculated using the WEAP model that was developed by the Stockholm Environment Institute [38, 39]. The model fundamentally operates on a monthly time-step. The watershed of TLS Lake was divided into 11 sub-basins and represented as a model.

### 2.4 Estimation of exchanged flow between the Mekong River and Tonle Sap Lake

The Mekong River and TLS Lake have a substantial level of exchanged flow. The water levels of the river and the lake are related to seasonal patterns. The TLS River functions naturally as a tributary of the Mekong River. Outflow from TLS Lake takes place between mid-September and early May. Between early May and mid-September, reverse flow in the TLS River occurs when the water level in the Mekong River is higher than in the lake. Estimations of the exchanged flow between TLS Lake and Mekong River followed the relationships proposed by Kummu et al. [25]:

$$F = \left(WL_{PK}\right)^{1.2} \times \left(\left|WL_{PP} - WL_{KL}\right|\right)^{0.5}, \qquad (2.4)$$

$$Q_{in} = -0.15.0467 \times F^2 + 859.839 \times F - 782.264, \qquad (2.5)$$

$$Q_{out} = 8.784 \times F^2 + 434.465 \times F + 167.151, \qquad (2.6)$$

where, $WL$ is the water level (m MSL), $WL_{PK}$ at Prek Kdam, $WL_{PP}$ at Phnom Penh Port, $WL_{KL}$ at Kampong Loung, $Q_{in}$ is the reverse flow into the TLS Lake, $Q_{out}$ is outflow from the Lake.

### 2.5 Estimation of streamflow of Tonle Sap Tributaries

The WEAP model implements several rainfall-runoff methods from a simple coefficient, soil moisture, or a complex plant-growth simulation. The current study selected the MABIA method, which is based on the FAO-56 dual crop-coefficient approach [55]. Although the time-step for MABIA is daily, the time-step for the rest of the WEAP analysis does not need to be daily. For each simulation time-step, for example, monthly, MABIA would run every day in that time-step and then aggregate its results for that time-step. Groundwater-surface water interactions were also taken into account. Groundwater flow to the stream was estimated as the percentage of monthly streamflow, first derived by the built-in Parameter Estimation Tool (PEST) calibration module in WEAP.

### 2.6 Model set-up and evaluation

The input data of rainfall and ET were derived from satellite data retrieved from the GEE. Soil and crop characteristics, required by the MABIA module, were selected according to available information in the WEAP-MABIA library. Four land-use classes were developed by reclassifying land-use data: forest, perennial crop, upland crop, and paddy rice. Silty clay soil was selected for paddy rice, while loam soil was applied for the others. All required input data were prepared for water balance analysis from 2000 to 2014.

After having set up the model, the estimated water-balance components were evaluated. Two types of observation were available: daily water level of TLS Lake measured at Kampong Loung (KL) station and monthly discharge measured at gage stations in tributaries of the TLS Lake. The daily water level was converted to lake volume using Equation (3) [25] and this was then used during tuning of WEAP model parameters with the PEST module in the WEAP model. The evaluation of model performance used $R^2$ and the Nash and Sutcille efficiency index [56].

## 3. Results and Discussion

### 3.1 Water balance results of the watershed area of Tonle Sap Lake

The annual water balance in the watershed area of TLS Lake, estimated using the WEAP model is summarized in Fig. 2, while Fig. 3 shows monthly means of the components. The water balance components included rainfall, surface evaporation, crop transpiration, surface runoff, and deep percolation to groundwater storage.

Fig. 2 shows that the annual rainfall of the watershed was 1,763.5 mm. The driest year was in 2010 with annual rainfall of 1,395.8 mm, while the highest rainfall (1,978.7 mm) occurred in 2000. Evapotranspiration (ET) represented about 80% (1,411.7 mm) of water depletion from the watershed. The module MABIA in the WEAP model estimated independently the surface evaporation (E) and crop transpiration (T). The annual mean evaporation (E) was 384.4 mm, indicating approximately 22% water depletion; it varied from 355.8 mm (2010) to 429.8 mm (2000). The annual transpiration (T) of 1,027.3 mm represented the largest fraction of water depletion (58%) and it ranged from 902.9 mm (2010) to 1179.8 mm (2000). Only 12.7% of rainfall (224.7 mm) was transformed to surface runoff. The minimum runoff was estimated at 47.5 mm (2010); the maximum was estimated at 428.2 mm (2013). Deep percolation to groundwater storage represented 7.6% of rainfall (135.4 mm) with values ranging from 86.4 mm (2010) to 184.2 mm (2008).

The seasonal pattern based on the monthly distribution (Fig. 3) suggested that high rainfall occurs during the wet season from May to October (200 mm or higher). The highest rainfall (383 mm) was in September. The seasonal variation of ET correspondingly followed the rainfall pattern; indeed, crop transpiration increased during the wet season. An important amount of surface runoff was formed at the end of the wet season (September and October).

Although only a very limited observation dataset was available, model-parameter tuning and result validation were carried out to a certain degree. Fig. 4 shows an example of streamflow validation at the gage station in Stung Sen Basin (ST8)—the largest sub-basin of the Tonle Sap Lake. Streamflow estimated from the WEAP model was the combination of surface runoff and groundwater flow. It is worth noting that the flow routing scheme was not implemented in the last version of WEAP (Jan 2019); hence only monthly results can reasonably be interpreted. The hydrograph of the simulated streamflow was compared with that of the observed data (2000-2011) (Fig. 4). The scatter plot between simulation and observation of streamflow is shown in Fig. 5. The model performance in streamflow estimation was satisfactory [57] with an $R^2$ value close to 0.6.

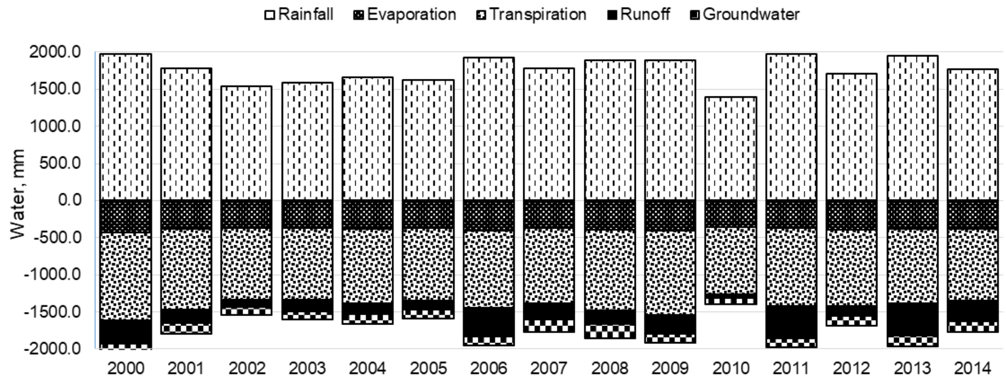


**Fig. 2.** Inter-annual variation of water balance components (inflow positive, outflow negative) in the watershed area of the Tonle Sap Lake.

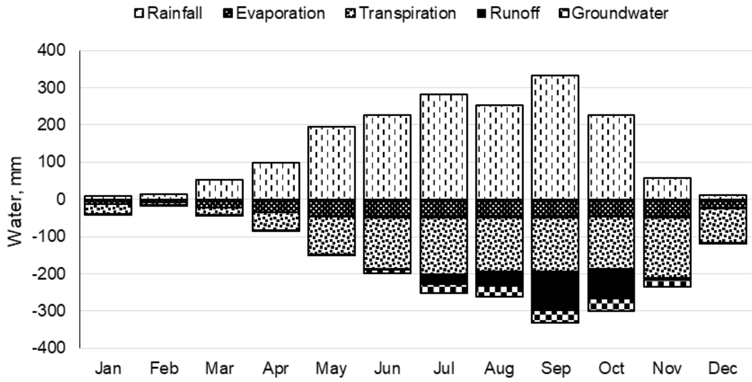


**Fig. 3.** Monthly variation of water balance components (inflow positive, outflow negative) in the watershed area of the Tonle Sap Lake.

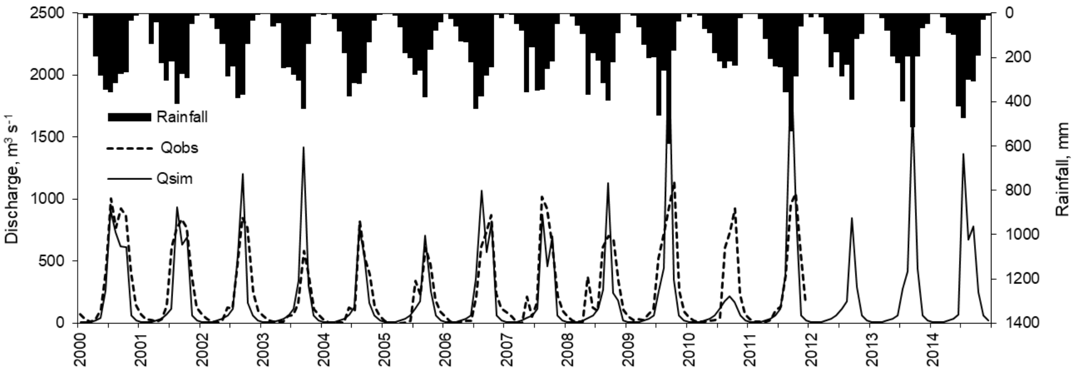


**Fig. 4.** Monthly simulated streamflow (Qsim) from 2000-2014 compared to observed data (Qobs) at the Stung Sen Basin gage station (ST8).

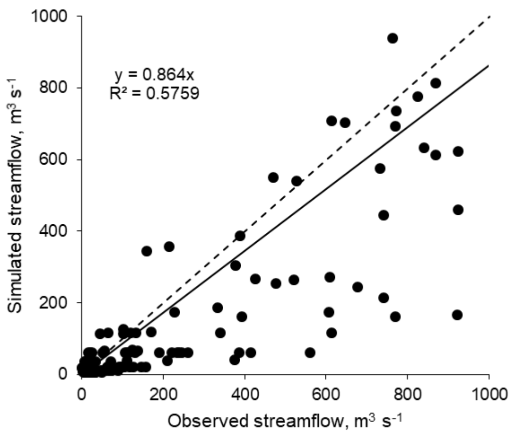


**Fig. 5.** Scatter plot between simulated and observed streamflow at the Stung Sen Basin gage station (ST8).

## 3.2 Water balance results of the Tonle Sap Lake

The simulation results of water balance in TLS Lake using satellite-derived inputs and WEAP model are summarized in Table 1 and shown in Fig. 6 and Fig. 7. The water balance components comprised inflow from the watershed, inflow from the Mekong River, and outflow from the Lake.

The annual results shown in Fig. 6 and Table 1 indicate that the estimated mean volumes of total inflow and total outflow were 69 km$^3$ per year. Nevertheless, WEAP did not report the rainfall and evaporation volumes over the lake surface. Based on the annual balance, the net evaporation was neutral with approximately 10 km$^3$ lost by evaporation and 10 km$^3$ gained from rainfall.

The total inflow varied from 46.2 to 89.6 km$^3$. The highest inflow (89.6 km$^3$) occurred in 2011 during one of the worst floods in the Lower Mekong River Basin.

The total outflow to the Mekong River was estimated between 49.2 km$^3$ and 86.5 km$^3$ per year. The annual mean inflow from the Mekong River to the TLS Lake was estimated at 43.1 km$^3$ and varied from 32.4 km$^3$ to 51.6 km$^3$. The lake water balance revealed the Mekong River has a great impact on the availability of the TLS Lake's water resource, as it represented more than half of the total inflow to the Lake. Another important component was the inflow from the watershed of the TLS Lake, which was estimated to be between 11.8 km$^3$ and 36.2 km$^3$ per year and 25.3 km$^3$ on average.

**Table 1.** Inter-annual water balance of Tonle Sap Lake.

| Year | Watershed Rainfall (mm) | Inflow from watershed (km$^3$) | Inflow from Mekong river (km$^3$) | | Total inflow (km$^3$) | Total outflow (km$^3$) | Lake storage on 31 Dec (km$^3$) |
|---|---|---|---|---|---|---|---|
| 2000 | 1,978.7 | 34.73 | 51.62 | 59.74%* | 86.42 | -86.55 | 27.38 |
| 2001 | 1,778.5 | 25.20 | 51.59 | 67.14% | 76.84 | -79.18 | 25.62 |
| 2002 | 1,545.2 | 20.39 | 53.43 | 72.34% | 73.86 | -75.17 | 23.23 |
| 2003 | 1,590.7 | 20.45 | 38.32 | 65.15% | 58.82 | -62.29 | 17.60 |
| 2004 | 1,656.7 | 19.90 | 47.95 | 70.62% | 67.90 | -62.32 | 19.92 |
| 2005 | 1,625.4 | 16.09 | 53.15 | 76.35% | 69.60 | -66.75 | 21.96 |
| 2006 | 1,924.8 | 34.55 | 36.70 | 49.57% | 74.04 | -73.52 | 22.64 |
| 2007 | 1,778.6 | 27.17 | 33.42 | 54.34% | 61.49 | -60.83 | 22.13 |
| 2008 | 1,885.5 | 21.63 | 40.21 | 64.25% | 62.59 | -62.59 | 23.44 |
| 2009 | 1,885.2 | 28.53 | 37.11 | 56.49% | 65.69 | -68.83 | 21.18 |
| 2010 | 1,395.8 | 11.83 | 34.30 | 74.27% | 46.19 | -49.21 | 15.57 |
| 2011 | 1,976.7 | 35.19 | 51.45 | 57.40% | 89.62 | -77.27 | 31.28 |
| 2012 | 1,703.0 | 18.08 | 33.58 | 64.94% | 51.71 | -65.73 | 16.76 |
| 2013 | 1,953.3 | 36.17 | 32.43 | 44.42% | 73.01 | -68.30 | 23.65 |
| 2014 | 1,774.7 | 29.43 | 51.91 | 63.71% | 81.48 | -80.19 | 26.37 |
| Mean | 1,763.5 | 25.29 | 43.14 | 62.72% | 69.28 | -69.25 | 22.58 |

**Note**: *Percentage of inflow from Mekong River into Tonle Sap Lake compared to total inflow.

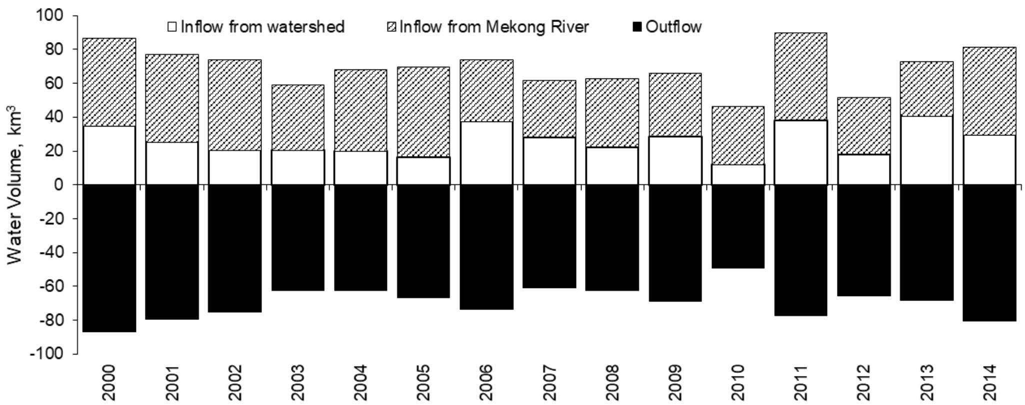


**Fig. 6.** Inter-annual variation of inflows (positive) and outflow (negative) of the Tonle Sap Lake.

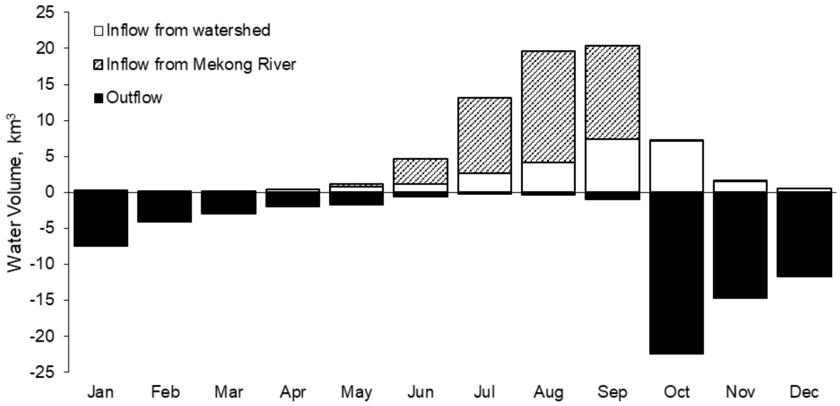


**Fig. 7.** Monthly variation of inflows (positive) and outflow (negative) of the Tonle Sap Lake.

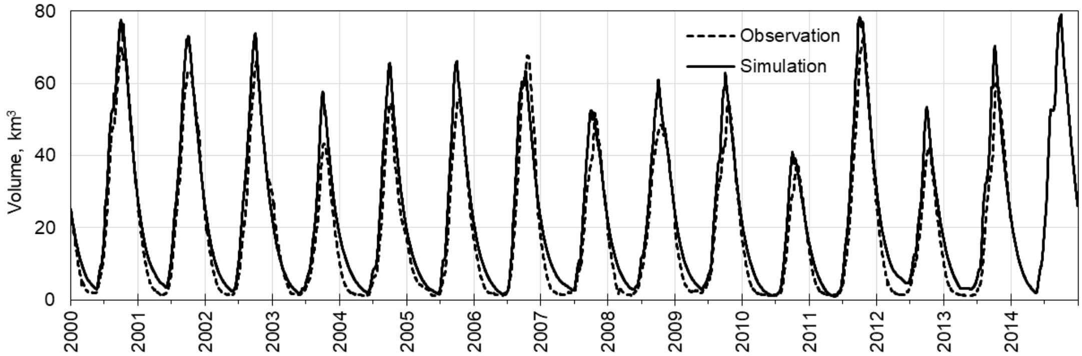


**Fig. 8.** Changes in storage of the Tonle Sap Lake (2000-2014).

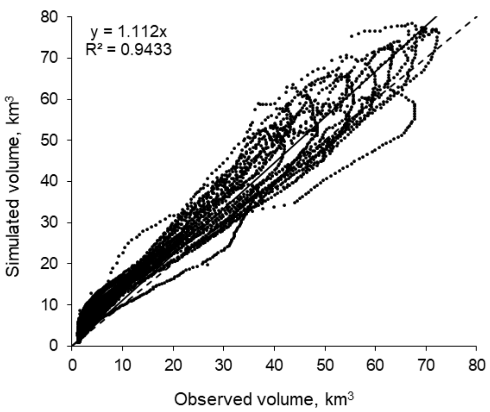


**Fig. 9.** Scatter plot of simulation and observation of storages of the Tonle Sap Lake ($km^3$).

To compare the current water-balance analysis to the previous study [25], Kummu et al (2014) analyzed the water balance in TLS Lake from 1997 to 2005. They reported the inflow into the lake ranged from 51.1 $km^3$ to 109.0 $km^3$ with an average of 83.1 $km^3$ (including the lake rainfall of 10.4 $km^3$), and the outflow from the lake ranged from 60.8 to 114.4 $km^3$ with an average of 81.9 $km^3$ (including the lake evaporation of 10.6 $km^3$). The current study estimated the comparable means (69 $km^3$ + 10 $km^3$) of both inflow and outflow. Regarding the mean of monthly components (Fig. 7), the seasonal variation of inflow pattern from the watershed corresponded to that of the rainfall pattern. The major flows occurred from May to

November, whereas the high flows were observed in September and October. Positive and negative flows were produced from the Lake to the Mekong River. A positive flow signifies the direction of inflow from the Mekong River to the Lake. A negative flow indicates the reverse directions of flow. In general, outflow from the Lake to the Mekong through the TLS River occurs from January to May and from October to December. The flow from the Mekong River reaches the Lake from June to September, when the water level in the Mekong River is higher than in the Lake.

Lake storage with a maximum volume not exceeding 80 $km^3$ represents a considerable component in the TLS Lake system. The reference volume was calculated from the observed water level using the relationships in equation (2.3). Fig. 8 shows the comparison between the observed and simulated volumes of the Lake. Fig. 9 shows the scatter plot between the simulation and observation. Based on a 15-year simulation from 2000 to 2014, the model performed very well ($R^2$=0.94 and NSE=0.91) in simulating the changes in the lake volume. The rise and fall of the simulated volumes fitted very well with the observations, except during the dry period from January to April, where the simulated fall appeared slower.

## 4. Conclusion and Recommendations

In conclusion, this research investigated an option to conduct a comprehensive water balance analysis in a large region using satellite-derived data. Two key inputs—TRMM precipitation and MODIS evapotranspiration—were retrieved using the GEE platform. The WEAP model successfully estimated the water-balance components in the TLS system. Using contemporary data and tools, the water balance analysis of TLS Lake was extended to 2014. It was found that the mean annual rainfall for the period 2000-2014 in the TLS watershed was 1,763.5 mm. Surface runoff represented 12.7% of rainfall (224.7 mm). The simulation estimated the mean annual volume of surface inflow to the lake was 69 $km^3$. The Mekong River had a great impact on the availability of the lake's water resource, since it supplied 62% of surface inflow to the lake. The bi-directional flow in the Tonle Sap River was induced by the water level differences between the TLS Lake and the Mekong River. Outflow from the lake produces a normal flow in the direction of the TLS River. The reverse flow direction occurred from June to September when water levels in the Mekong River were higher than those in the lake.

Although knowledge of the hydrology of the TLS system has increased rapidly [25], a fundamental analysis of the hydrology (water balance) still presents a challenge in this area. Kummu et al. [25] investigated the water balance of TLS Lake from 1997 to 2004. The current study extended the analysis to 2014 using inputs from satellite-derived data (TRMM precipitation and MODIS ET). Although the satellite data have been evaluated in earlier studies [30, 58], further validation with ground observations are recommended.

WEAP's performance in simulating the water balance of the TLS system was satisfactory. However, the model has certain limitations for a detailed analysis of evaporation and rainfall associated with the lake because WEAP combines the two components into one input variable (net evaporation). Moreover, the lack of a module to represent the flow-routing process reduces WEAP's applicability for the sole analysis of the water balance, and not the full rainfall-runoff relationship. Further research is urgently required to develop a model capable of simulating a large hydrological system based on limited observed data. In addition, we still require more sophisticated tools to represent exchange flows between the TLS Lake and the Mekong River.

Challenges in the Mekong River Basin management in the future environment are obvious—climate change, hydropower development, and intensification of agricultural water use. Their impacts on the Mekong's flows have been investigated [3, 7, 16, 20, 59]. In addition, the impacts of changes in the Mekong's flow regime on the Lake's water resource need to be addressed [13].

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## References

[1] Churkina G, Running SW, Schloss AL. Comparing global models of terrestrial net primary productivity (NPP): The importance of water availability. Global Change Biology 1999;5(S1):46-55

[2] Batchelor C, Hoogeveen J, Faurès JM, Peiser L. Water accounting and auditing. A sourcebook. Rome: Food and Agriculture Organization of the United Nations (FAO); 2017.

[3] Hoang LP, van Vliet MTH, Kummu M, Lauri H, Koponen J, Supit I, et al. The Mekong's future flows under multiple drivers: How climate change, hydropower developments and irrigation expansions drive hydrological changes. Science of The Total Environment 2019;649:601-9.

[4] Rainboth WJ. FAO species identification field guide for fishery purpose. Fish of the Cambodian Mekong, Rome. 1996;265.

[5] MRC. Fisheries in the Lower Mekong Basin: status and perspectives. Phnom Penh, Cambodia: Mekong River Commission; 2002.

[6] ADB. The Tonle Sap Basin Strategy. Manila, the Philippines: Asian Development Bank; 2005. 54 p.

[7] Hoang LP, Lauri H, Kummu M, Koponen J, van Vliet MTH, Supit I, et al. Mekong River flow and hydrological extremes under climate change. Hydrology and Earth System Sciences 2016;20(7):3027-41.

[8] Campbell IC. Perceptions, data, and river management: Lessons from the Mekong River. Water Resources Research 2007;43(W02407)

[9] Campbell IC. The Mekong. San Diego: Academic Press; 2009 2009.

[10] Campbell IC. Integrated management in the Mekong River Basin. Ecohydrology & Hydrobiology 2016;16((4):255-62.

[11] Piman T, Cochrane TA, Arias ME, Green A, Dat ND. Assessment of Flow Changes from Hydropower Development and Operations in Sekong, Sesan, and Srepok Rivers of the Mekong Basin. Journal of Water Resources Planning and Management 2013;139(6):723-32.

[12] Kite G. Modelling the Mekong: hydrological simulation for environmental impact studies. Journal of Hydrology 2001;253(1-4):1-13.

[13] Arias ME, Piman T, Lauri H, Cochrane TA, Kummu M. Dams on Mekong tributaries as significant contributors of hydrological alterations to the Tonle Sap Floodplain in Cambodia. Hydrology and Earth System Sciences 2014;18(12): 5303-15.

[14] Lu XX, Siew RY. Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams. Hydrology and Earth System Sciences 2019;10(2): 181-95.

[15] Adamson PT, Rutherfurd ID, Peel MC, Conlan IA. Chapter 4-The Hydrology of the Mekong River. In: Campbell IC, editor. The Mekong. San Diego: Academic Press; 2009. p.53-76.

[16] Campbell IC. Chapter 16-Development Scenarios and Mekong River Flows. In: Campbell IC, editor. The Mekong. San Diego: Academic Press; 2009.p.389-402.

[17] Campbell IC, Say S, Beardall J. Chapter 10-Tonle Sap Lake, the Heart of the Lower Mekong. In: Campbell IC, editor. The Mekong. San Diego: Academic Press; 2009. p.251-72.

[18] Siev S, Paringit EC, Yoshimura C, Hul S. Seasonal Changes in the Inundation Area and Water Volume of the Tonle Sap River and Its Floodplain. Hydrology 2016;3(4):33.

[19] Ji X, Li Y, Luo X, He D. Changes in the Lake Area of Tonle Sap: Possible Linkage to Runoff Alterations in the Lancang River? Remote Sensing 2018;10(6):866.

[20] Oeurng C, Cochrane TA, Chung S, Kondolf MG, Piman T, Arias ME. Assessing Climate Change Impacts on River Flows in the Tonle Sap Lake Basin, Cambodia. Water 2019;11(3):618.

[21] Ly S, Kim L, Demerre S, Heng S. Flood Mapping along the Lower Mekong River in Cambodia. Engineering Journal 2018;22(1):269-78.

[22] Arias ME, Cochrane TA, Piman T, Kummu M, Caruso BS, Killeen TJ. Quantifying changes in flooding and habitats in the Tonle Sap Lake (Cambodia) caused by water infrastructure development and climate change in the Mekong Basin. Journal of Environmental Management 2012;112:53-66.

[23] Ang R, Oeurng C. Simulating streamflow in an ungauged catchment of Tonlesap Lake Basin in Cambodia using Soil and Water Assessment Tool (SWAT) model. Water Science 2019;32(1):89-101.

[24] Inomata H, Fukami K. Restoration of historical hydrological data of Tonle Sap Lake and its surrounding areas. Hydrological Processes 2008;22(9):1337-50.

[25] Kummu M, Tes S, Yin S, Adamson P, Józsa J, Koponen J, et al. Water balance analysis for the Tonle Sap Lake-floodplain system. Hydrological Processes 2014;28(4):1722-33.

[26] Kummu M, Tes S, Yin S, Adamson P, Józsa J, Koponen J, et al. Erratum-Water balance analysis for the Tonle Sap Lake-floodplain system. Hydrological Processes 2015;29(26):5477-.

[27] Xu CY, Singh VP. A review on monthly water balance models for water resources investigations. Water Resources Management 1998;12(1):20-50.

[28] Zhang L, Walker GR, Dawes WR. Water balance modelling: concepts and applications. ACIAR Monograph Series 2002;84:31-47.

[29] Langella G, Basile A, Bonfante A, Terribile F. High-resolution space-time rainfall analysis using integrated ANN inference systems. Journal of Hydrology 2010;387(3-4):328-42.

[30] Mab P, Ly S, Chompuchan C, Kositsakulchai E. Evaluation of Satellite Precipitation from Google Earth Engine in Tonle Sap Basin, Cambodia. THA 2019 International Conference on Water Management and Climate Change towards Asia's Water-Energy-Food Nexus and

SDGs, 23-25 January 2019; 2019 2019; Bangkok, Thailand. Bangkok.

[31] Dong J, Xiao X, Menarguez MA, Zhang G, Qin Y, Thau D, et al. Mapping paddy rice planting area in northeastern Asia with Landsat 8 images, phenology-based algorithm and Google Earth Engine. Remote sensing of environment 2016;185:142-54.

[32] Patel NN, Angiuli E, Gamba P, Gaughan A, Lisini G, Stevens FR, et al. Multitemporal settlement and population mapping from Landsat using Google Earth Engine. International Journal of Applied Earth Observation and Geoinformation 2015;35:199-208.

[33] Andreu J, Capilla J, Sanchís E. AQUATOOL, a generalized decision-support system for water-resources planning and operational management. Journal of Hydrology 1996;177(3-4):269-91.

[34] Klipsch JD, Hurst MB. HEC-ResSim Reservior System Simulation User's Manual. Davis, CA: US Army Corps of Engineers; 2013. 556 p.

[35] USACE. HEC-WAT Watershed Analysis Tool User's Manual. Davis, CA: US Army Corps of Engineers; 2017.

[36] Jha MK, Gupta AD. Application of Mike Basin for water management strategies in a watershed. Water International 2003;28(1): 27-35.

[37] Delft H. RIBASIM River basin simulation program operating manual and description. Netherlands: Delft; 2004.

[38] SEI. WEAP-Water Evaluation And Planning System: User Guide. Somervill, MA: Stockholm Environment Institute (SEI), U.S. Center; 2015. 400 p.

[39] SEI WEAP-Water Evaluation And Planning System: Tutorial-A collection of stand-alone modules to aid in learning the WEAP software. Somervill, MA: Stockholm Environment Institute (SEI), U.S. Center; 2016.286 p.

[40] Try S, Lee G, Yu W, Oeurng C, Jang C. Large-Scale Flood-Inundation Modeling in the Mekong River Basin. Journal of Hydrologic Engineering 2018;23(7):05018011.

[41] Legesse D, Abiye T, Vallet-Coulomb C, Abate H. Streamflow sensitivity to climate and land cover changes: Meki River, Ethiopia. Hydrology and Earth System Sciences 2010;14(11):2277.

[42] Makhlouf Z, Michel C. A two-parameter monthly water balance model for French watersheds. Journal of Hydrology 1994;162(3-4):299-318.

[43] Vandewiele G, Elias A. Monthly water balance of ungauged catchments obtained by geographical regionalization. Journal of Hydrology 1995;170(1-4):277-91.

[44] Vandewiele G, Xu CY. Methodology and comparative study of monthly water balance models in Belgium, China and Burma. Journal of Hydrology 1992;134(1-4):315-47.

[45] Xu CY, Seibert J, Halldin S. Regional water balance modelling in the NOPEX area: development and application of monthly water balance models. Journal of Hydrology 1996;180(1-4):211-36.

[46] Campbell IC. Managing international river basins: successes and failures of the Mekong River Commission. In: Grafton RQ, Hussey K, editors. Water Resources Planning and Management. Cambridge: Cambridge University Press; 2011. p. 724-40.

[47] Eastham J, Mpelasoka F, Mainuddin M, Ticehurst C, Dyce P, Hodgson G, et al.

Mekong river basin water resources assessment: Impacts of climate change. Australia: Water for a Healthy Country National Research Flagship; 2008.

[48] Campbell IC, Poole C, Giesen W, Valbo-Jorgensen J. Species diversity and ecology of Tonle Sap Great Lake, Cambodia. Aquatic Sciences 2006;68(3):355-73.

[49] Welcomme R. River fisheries, Food and Agriculture Organization Fisheries Technical Paper 262. FAO, Rome. 1985;330.

[50] Junk WJ, Brown M, Campbell IC, Finlayson M, Gopal B, Ramberg L, et al. The comparative biodiversity of seven globally important wetlands: a synthesis. Aquatic Sciences 2006;68(3):400-14.

[51] Fujii H, Garsdal H, Ward P, Ishii M, Morishita K, Boivin T. Hydrological roles of the Cambodian floodplain of the Mekong River. International Journal of River Basin Management 2003;1(3):253-66.

[52] Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R. Google Earth Engine: Planetary-scale geospatial analysis for everyone. Remote Sensing of Environment 2017;202:18-27.

[53] Huffman GJ, Bolvin DT, Nelkin EJ, Wolff DB, Adler RF, Gu G, et al. The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. Journal of Hydrometeorology 2007;8(1):38-55.

[54] Running SW, Mu Q, Zhao M, Moreno A. MODIS Global Terrestrial Evapotranspiration (ET) Product (NASA MOD16A2/A3) NASA Earth Observing System MODIS Land Algorithm. NASA: Washington, DC, USA. 2017.

[55] Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration-Guidelines for computing crop water requirements. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO); 1998.

[56] Nash JE, Sutcliffe JV. River flow forecasting through conceptual models part I-A discussion of principles. Journal of Hydrology 1970;10(3): 282-90.

[57] Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE 2007;50(3):885-900.

[58] Phoeurn C, Ly S. Assessment of Satellite Rainfall Estimates as a Pre-Analysis for Water Environment Analytical Tools: A Case Study for Tonle Sap Lake in Cambodia. Engineering Journal 2018;22(1):229-41.

[59] Räsänen TA, Someth P, Lauri H, Koponen J, Sarkkula J, Kummu M. Observed river discharge changes due to hydropower operations in the Upper Mekong Basin. Journal of Hydrology 2017;545:28-41.