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Estimation of Water Elevation Using ICESat-2 Satellite

Chandima Madumalsha, Isuru Nawoda, Panduka Neluwala and Menaka Revel

Abstract: Due to the lack of in-situ gauge data, remote sensing is crucial for water level monitoring. This study presents a thorough examination of water level variations in nine main Sri Lankan reservoirs over the past five years, using data from the Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) Advanced Topographic Laser Altimeter System (ATLAS). An initial data filtering was done focusing on key quality flags in ICESat-2 ATL13 products to ensure data reliability by eliminating outliers and significant elevation errors. An approach to assessing uncertainty in satellite-derived elevation readings is introduced, using photon counts to quantify uncertainty and enhance data interpretation. The evaluation of ICESat-2 data, in comparison to gauge measurements of nine reservoirs, confirms ICESat-2's higher accuracy in water level estimation, yielding a correlative coefficient as high as 0.99 for all reservoirs, though it has a low temporal resolution of 91 days.This study highlights the potential of ICESat-2 for comprehensive water level measuring in small reservoirs, offering valuable insights for effective water resource management and hydrological modelling efforts. Furthermore, the developed methodology can be used for reservoir water level measuring, highlighting the advantage of satellite products, especially in data-scarce regions.

Keywords: ICESat-2, Remote Sensing, ATLAS, Reservoir Water Level, Quality Flag

1. Introduction

Reservoirs are vital for local water supply, agriculture, and ecosystem preservation. Sri Lanka has many important reservoirs that are crucial for managing water resources. To enhance our understanding of reservoirs for more effective scientific studies and water resources management, it is crucial to create a comprehensive, publicly accessible reservoir dataset. This necessity is particularly pronounced due to the impacts of climate change and the growing human population. However, limited in-situ water level data in remote areas hinders resource management. Traditionally, water levels in reservoirs have been estimated through in-situ gauging, which involves physically measuring water levels using gauges or staff [1]. However, this method has limitations, including the need for frequent site visits and the potential for errors due to human factors [2]. Therefore, another approach involves satellite-based remote sensing techniques, such as radar or laser altimeter, which provide non-contact measurements.

Remote sensing techniques provide the opportunity to observe reservoirs from space, describing their features globally even in the absence of readily available on-site records. Hence, there is a trend towards utilizing satellite altimetry techniques for water level estimation in the modern world. However, it encounters challenges when applied to small-scale lake studies [3]. Firstly, there are significant spatial gaps between tracks, leading to the omission of many lakes. Secondly, traditional altimeters typically exhibit substantial temporal gaps, limiting their ability to capture lake seasonality intricately. Thirdly, due to their larger footprint size, conventional altimeters often introduce considerable altimetric errors in lake surface height (LSH) measurements for smaller lakes [4].

Among various satellites employing satellite altimetry techniques, the ice, cloud, and land elevationsatellite-2 (ICESat-2) stands out for its remarkable potential[5]. ICESat-2 is equipped with the Advanced Topographic Laser Altimeter System (ATLAS),launched in 2018.

Eng. Chandima Madumalsha, AMIE(SL), B.Sc.Eng. (Peradeniya), Dept. of Civil Engineering, University of Peradeniya, Sri Lanka.
Email:e17197@eng.pdn.ac.lk
ORCID ID: https://orcid.org/0009-0004-8205-8958
Eng. Isuru Nawoda, AMIE(SL), B.Sc.Eng. (Peradeniya), Dept. of Civil Engineering, University of Peradeniya, Sri Lanka.
Email:e17221@eng.pdn.ac.lk
ORCID ID: https://orcid.org/0000-0002-2044-7737
Eng. (Dr.) Panduka Neluwala, AMIE(SL), B.Sc.Eng. (Peradeniya), M.Eng., Ph.D. (Tokyo), Senior Lecturer, Dept. of Civil Engineering, University of Peradeniya, Sri Lanka.
Email:pandukaneluwala@eng.pdn.ac.lk
ORCID ID: https://orcid.org/0000-0002-1686-3412
Eng. (Dr.) Menaka Revel, AMIE(SL), B.Sc.Eng. (Peradeniya), M.Eng., Ph.D. (TIT), Postdoctoral Fellow Dept of Civil and Env. Engineering, University of Waterloo
Email:menak.arevel@uwaterloo.ca
ORCID ID: https://orcid.org/0000-0003-0390-8279

In this study, we utilized ICESat-2 satellite data to comprehensively assess water elevations within nine major reservoirs in Sri Lanka. Compared to global reservoirs used for ICESat-2 water elevation measurements in the literature, these reservoirs exhibit a smaller water surface area. Therefore, our focus was mainly on analyzing the performance of this satellite product on smaller reservoirs that have not been studied previously. For this study, we utilized in-situ data from nine reservoirs as a reference, enhancing confidence in data quality and improving our understanding of the accuracy of existing satellite datasets. The developed methodology can be applied to calculate reservoir levels for specific applications or other regions. The outcomes of this study contribute to the effective management of reservoirs and support various related studies, including hydrological modelling and environmental assessments at the reservoir catchment level.

2. Literature Review

2.1 Estimation of Reservoir Water Levels Using Remote Sensing

The satellite altimetry technique proves valuable in overcoming limitations in traditional water level estimation methods. There are two main types of satellite altimetry: radar satellite altimetry and laser satellite altimetry [5]. Satellite radar/laser altimetry is a promising technique for directly detecting water levels of open water bodies from space [6]. Satellite altimeters transmit a series of pulses toward the terrestrial surface in the nadir direction and receive the echo reflected by the surface. The two-way travel time of radar or laser is measured and used to calculate the distance between the satellite and the target surface, called "range" [7]. Through repeated measurements over time, satellite altimetry generates a time series of water level data, facilitating the monitoring of changes [6]. Satellite altimetry possesses global coverage, the ability to provide long-term data records, and the capacity to measure large water bodies [8].

Traditional radar altimeter sensors (e.g., Topex/Poseidon, Jason, ENVISAT, ERS, CryoSat-2, Sentinel-3, and Sentinel-6) have large footprints (hundreds of meters to a few kilometers). In many aspects, they struggle to measure water levels in small lakes and reservoirs due to land interference [9]. In comparison, ICESat-2 has a higher resolution [10], which is why it was selected for this study.

2.2 ICESat-2 Satellite Data

ICESat-2, a NASA satellite launched in 2018, is dedicated to measuring Earth's elevation, including water bodies and ice surfaces, equipped with ATLAS [11]. While its main scientific goals focus on monitoring polar glaciers, sea ice, and forests, the technology is also applicable to monitoring inland waters. Featuring six beams arranged in three pairs, the system offers broader global coverage compared to its predecessor. The cross-track interval between beam pairs is approximately 3 km. Each pair consists of a strong and weak beam positioned 90 m apart on either side of the reference ground track. Additionally, the system boasts a small footprint of around 17 meters [12]. ICESat-2 transmits laser pulses and precisely measures the time it takes for the pulses to reflect [13]. ICESat-2's single-beam GLAS lidar uses 1064 nm laser light, while ICESat-2's six-beam ATLAS lidar uses 532 nm laser light. The full-waveform GLAS lidar transmitted pulses at 40 times per second, yielding a 175 m along-track spacing with a 70 m diameter footprint on the Earth's surface. The photon counting strategy of ATLAS includes a much higher laser pulse repetition frequency (10 kHz), which results in a 0.7 m along-track spacing with <17 m diameter footprints for each of its six beams simultaneously [14]. This process allows the satellite to generate highly accurate elevation data [10], including sea surface heights. Unlike traditional radar altimeter sensors, which face challenges in measuring water levels of small lakes and reservoirs (<1 km^2) due to land interference, ICESat-2 overcomes this limitation. With smaller footprints and high vertical accuracy, ICESat-2, with a 17-m diameter footprint at a 50 Hz pulse-repetition frequency (PRF), provides laser shots spaced at 140 m along track, making it well-suited for calculating water levels in small water bodies [15]. However, due to limited temporal coverage and sparse along-track footprints (with a 0.7-m interval), most small water bodies have only a few observations.

Larger bodies of water tend to have higher observation rates because the number of satellites passes over a water body increases with its size. Therefore, reservoirs of greater expanse receive more frequent coverage, resulting in a higher density of observational data. In 2019, researchers conducted a study in

China, validating their findings across 30 reservoirs and lakes. Several reservoirs had limited data in this research, with only a few observations available. For instance, Lake Hulun, spanning 2303 km², had just 15 observations recorded. This scarcity of data highlights the challenges faced in collecting information, even for large bodies of water. The relative error in this research was found to be 0.06 meters, with an uncertainty range between 0.02 and 0.07 meters. Furthermore, the correlation coefficient varied from 0.5 to 1, with an average of 0.99.Cloud cover and sensor malfunctions are some reasons contributing to this limitation [16].

Previous research has extensively explored large reservoirs in China, USA, and Australia[17]. Lakes such as Lake Mead, Lake Eildon, Whitney Lake, Fleming Gorge, Lake Hume, and Lake Mulwala have been the focus of multiple studies. In this research, they achieved a correlation coefficient of 0.999, and the RMSE was 0.08 meters. These investigations aimed to understand these reservoirs' hydrological dynamics and ecological implications. Building upon this existing research, our study further contributes to understanding reservoir systems, particularly in estimating water levels using satellite data for small reservoirs. By examining multiple regions and water bodies, we aim to provide comprehensive insights into the challenges and opportunities associated with using satellite data for reservoir monitoring.

3. Methodology

3.1 Study Area

Nine reservoirs in Sri Lanka, as shown in Figure 1, were selected for this study considering data availability to align with the aim of the study.

Data for five years, from December 2018 to 2023, was considered for the study. Daily water level data from these 9 reservoirs was collected through the Division of Major Dams and Reservoir Operations of the Mahaweli Authority, Sri Lanka, and the Irrigation Department. These authorities maintain near real-time water level records for most reservoirs in Sri Lanka. The reservoir area and the number of ICESat-2 observations during the five years are shown in Table 1. The reservoir areas range from 1.3 km² to 35 km² and the number of ICESat-2 observations varies from 3 to 8 during the 5 years. Only a limited number of satellite observations are available due to the limitations mentioned in the previous section. To ensure data quality, we thoroughly examined each reservoir's time series of water levels for any data errors. The collected gauge data was used to evaluate the altimetric accuracy of ICESat-2.

Figure 1 - Locations of Nine Selected Reservoirs in Sri Lanka

Table 1 - Surface Area and Number of Observations for each Reservoir in the Study Area

Reservoir	Surface area (km²)	No. of observations
Udawalawe	35	8
Parakrama Samudraya	22.6	8
Kala Wewa	18.1	8
Victoria	22.7	5
Randenigala	13.5	7
Nachchaduwa	12	6
Nuwara Wewa	12	7
Kotmale	6.5	6
Rantambe	1.3	3

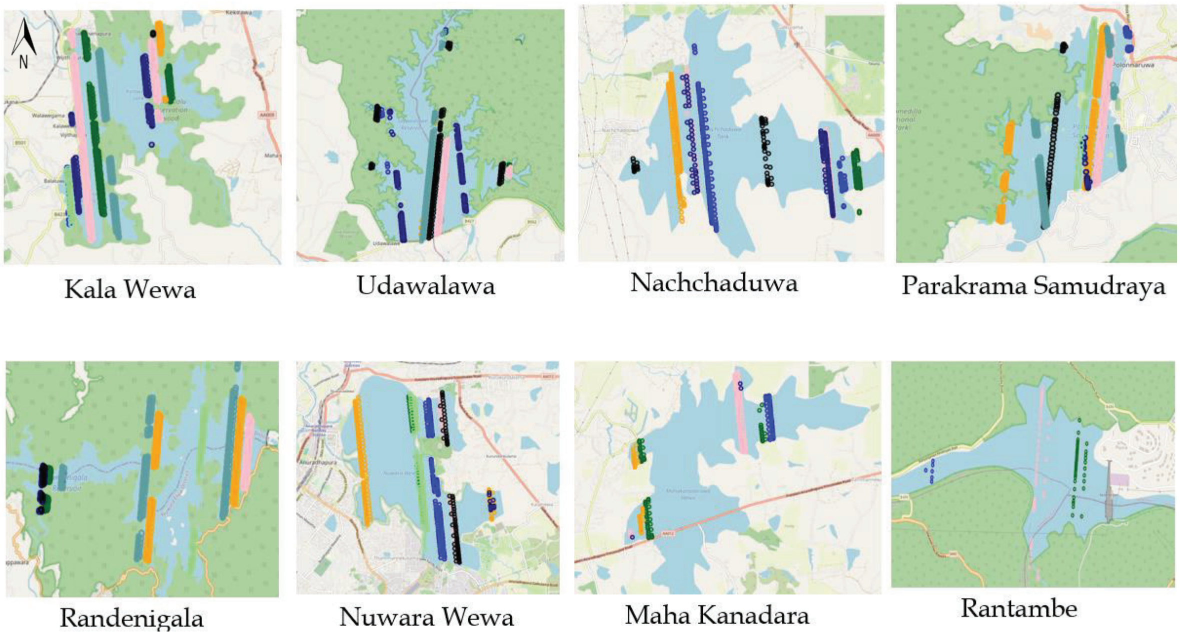

Figure 2 - Altimeter Footprints of the ICESat-2 Satellite over the Studied Reservoirs, with Distinct Colors Representing Various Observation Dates

Figure 2 illustrates the altimeter footprints of the ICESat-2 satellite over the studied reservoirs. Each footprint represents the location where the ICESat-2 ATL13 data was collected, with distinct colors corresponding to different observation dates, showing the temporal distribution of satellite passes. However, despite the high accuracy of ICESat-2, the dataset is limited for these reservoirs. Since 2018, over a 5-year span, only 6 to 8 readings were captured on average, covering less than 40% of the potential data points. The satellite's 91-day revisit cycle results in significant temporal gaps, making it difficult to fully capture seasonal variations in water levels [18]. As shown in Table 2, these temporal gaps often prevent the determination of lake seasonality using ICESat-2 data alone. While the spatial distribution of footprints reflects extensive coverage and resolution, the limited temporal frequency reduces the ability to monitor water-level changes comprehensively.

A comprehensive review of previous studies was conducted to address these challenges and ensure accurate data selection. ICESat-2 was chosen due to its superior accuracy in water level estimation, even though its 91-day revisit interval limits the capture of seasonal variations. All available ICESat-2 ATL13 products [19] were collected from the National Snow and Ice Data Center(https://n5eil01u.ecs.nsidc.org/ATLAS/) to obtain reservoir water elevations. To validate the reliability of these datasets, they were compared with water levels from nine major reservoirs spanning the past five years.

An initial filtering process was implemented to ensure data reliability, focusing on four key quality flags in the ICESat-2 ATL13 products. First, data points with "qf_bckgrd" equal to 6, indicating the largest background photon density and typically captured at midday with a low signal-to-noise ratio, were removed to mitigate outliers. This step helps in eliminating data influenced by excessive background noise, ensuring more accurate measurements[17].

Second, entries with "qf_bias_em" greater than 2 or less than -2, representing the highest electromagnetic bias and potential elevation errors, were discarded. This filtering helps remove data that might be skewed due to electromagnetic interference, which can lead to significant inaccuracies in elevation reading.

Third, data flagged with "qf_bias_fit" greater than 2 or less than -2, associated with significant elevation bias, were eliminated. By excluding these data points, we ensure that only measurements with minimal elevation bias are considered, enhancing the overall precision of the dataset.

Finally, entries with "stdev_water_surf" larger than 2, indicative of an extremely large significant wave height, were excluded. This criterion ensures that data affected by unusually high waves, which could distort surface height readings, are removed [17].

By applying these stringent filtering criteria, we significantly improved the quality and reliability of the dataset, ensuring that the subsequent analysis is based on the most accurate and dependable data available.

Then, water elevations for the study were selected. For this, shape files were created for the specific water bodies under study, allowing the masking of ICESat-2 ATL13 products to obtain elevation data only for the selected reservoir areas. The study employed WGS84 ellipsoidal heights (h), EGM2008 orthometric heights (H), and geoid heights (N) along the track. Opting for orthometric heights concerning the EGM2008 geoid addressed the instability issue associated with ellipsoidal heights, providing a more reliable measure of water levels. Due to the gravity effect, the water level of large lakes/reservoirs is not a stable value when ellipsoidal heights are used. In this study, the orthometric heights (H) concerning the EGM2008 geoid were used, and the results for all reservoirs were based on this chosen vertical datum, ensuring a consistent and accurate assessment across the study [20].

$$H = h_{alt} - h_{range} - N \quad \ldots(1)$$

where H is the water body height, h_{alt} is the distance from the satellite to the reference ellipsoid, h_{range} is the distance between the altimeter and water body and N is the geoid height from reference ellipsoid (Figure 3).

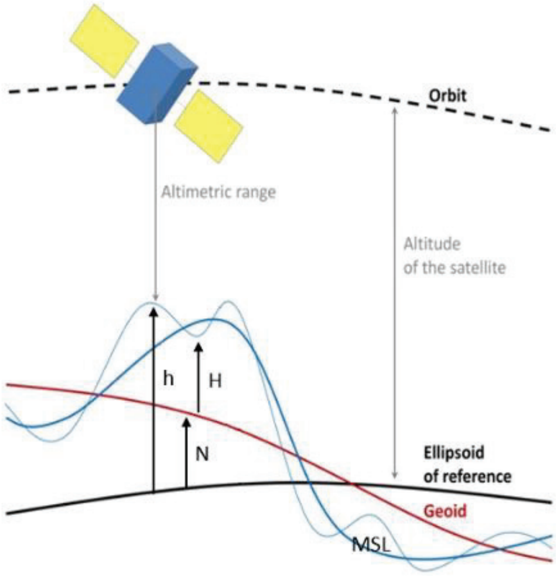

Figure 3 - Schematic Diagram of Elevations between Satellite and the Earth Used for Calculation (Source: Lam, 2022, https://www.bing.com/images/blob?bcid=s2jmBalxCpsHkQ)

Finally, an outlier removal process was conducted for elevation data. Therefore, the interquartile range (IQR) method was adopted to remove the outliers of each ground track for each observation time. Data was processed using the IQR method to isolate the middle 50% of data. The mean value of this subset was then calculated to represent the data for that day.

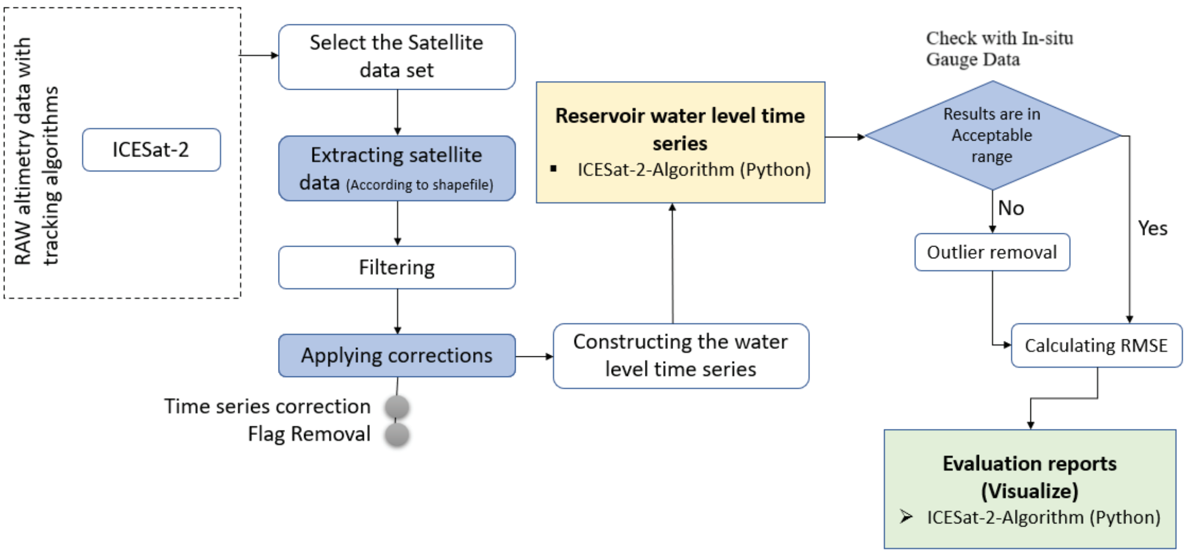

Figure 4 - Workflow of Lake Surface Height Extraction from Data Acquired by the ICESat-2 Satellite

Next, for the data validation process, in situ gauge data of reservoirs obtained from the Mahaweli Authority and Irrigation Department were used. Comparisons between daily averaged water levels derived from ATL13 products and in situ data of the nine reservoirs were performed to validate our produced water level results (Figure 4). The accuracy and correlation of the water level estimation were verified using calculations of Relative RootMean Square Error (RRMSE), Kling-Gupta Efficiency (KGE), bias, and the correlation coefficient (r), demonstrating strong validation between observed and gauge values. A histogram was produced for the Kotmale Reservoir on a specified date, providing a detailed visualization of the data distribution for that particular date.

4. Results and Discussion

Table 2 presents a comparison of water levels derived from ICESat-2 data with observed gauge data for the respective reservoirs. The ICESat-2 data accurately captured the reservoir levels, although it consistently overestimated the gauge data across all reservoirs. The average bias was 0.37 m. Among the reservoirs, the Victoria reservoir data showed the lowest average difference of 0.16 m, while the Udawalawe reservoir had the highest average difference of 0.43 m. Figure 5 provides a graphical representation of the results, illustrating the time series variations. The comparison between ICESat-2 water elevation data and in-situ gauge data indicates that deviations are independent of the time of year.

Table 3 presents the number of observations for each reservoir and the RRMSE and correlation coefficient. The RRMSE values range from 0.0006 (Kotmale reservoir)to 0.006(Parakrama Samudraya), while the correlation coefficient was always above 0.99 across all results. KGE values were close to 1 in most of the reservoirs.

These findings indicate that the observed data closely aligns with the gauge data values, reflecting the high accuracy of results obtained from the ICESat-2 satellite. Further studies can investigate the potential for bias correction, as all the values exhibit a positive bias.

Table 2 - Summary of the water level time series of validated reservoirs with their gauge data

Reservoir	Date	Satellite Data(m)	Gauge Data(m)
Kotmale	03/01/19	699.19	698.76
	04/04/19	682.28	681.89
	01/04/20	687.18	686.68
	29/09/20	697.69	697.66
	19/12/21	697.33	696.63
	27/03/23	677.68	677.45
Rantambe	24/12/19	152.20	151.83
	20/06/21	150.70	150.45
	18/10/21	150.19	149.89
Randenigala	26/03/19	230.10	229.74
	24/12/19	231.14	230.75
	20/06/21	229.47	229.04
	19/09/21	230.28	229.98
	20/03/22	223.64	223.13
	19/06/22	222.60	222.22
	18/09/22	226.26	225.86
Nuwara Wewa	02/10/19	83.77	83.40
	01/04/20	86.83	86.39
	30/03/21	87.20	86.88
	28/12/21	87.59	87.21
	28/03/22	86.93	86.50
	27/06/22	86.72	86.39
	26/12/22	85.02	84.61
Nachchaduwa	04/04/19	101.23	100.84
	01/04/20	101.00	100.56
	29/09/20	99.96	99.55
	30/03/21	101.55	101.12
	27/06/22	100.73	100.36
	27/03/23	101.37	100.94
Kala Wewa	03/01/19	129.14	128.78
	04/04/19	127.68	127.28
	01/04/20	127.51	127.05
	01/07/20	129.00	128.61
	29/09/20	125.78	125.24
	29/06/21	128.63	128.20
	27/06/22	128.42	128.03
	27/03/23	129.14	128.80
Udawalawe	23/10/19	86.02	85.71
	24/12/19	88.83	88.46
	01/01/20	88.83	88.42
	22/06/20	84.65	84.25
	29/12/20	83.81	83.22
	20/06/21	88.43	88.05
	18/10/21	87.47	86.95
	18/09/22	83.54	83.07
Victoria	25/12/18	432.95	432.81
	23/03/20	428.85	428.60
	29/12/20	430.69	430.49
	22/03/21	429.73	429.67
	19/09/21	430.79	430.64
Parakrama Samudraya	23/10/19	56.96	56.67
	24/12/19	59.40	59.08
	29/05/20	58.90	58.50
	20/06/21	58.12	57.71
	25/05/22	58.89	58.68
	19/06/22	59.04	58.62
	18/09/22	58.39	58.04
	22/02/23	59.26	58.96

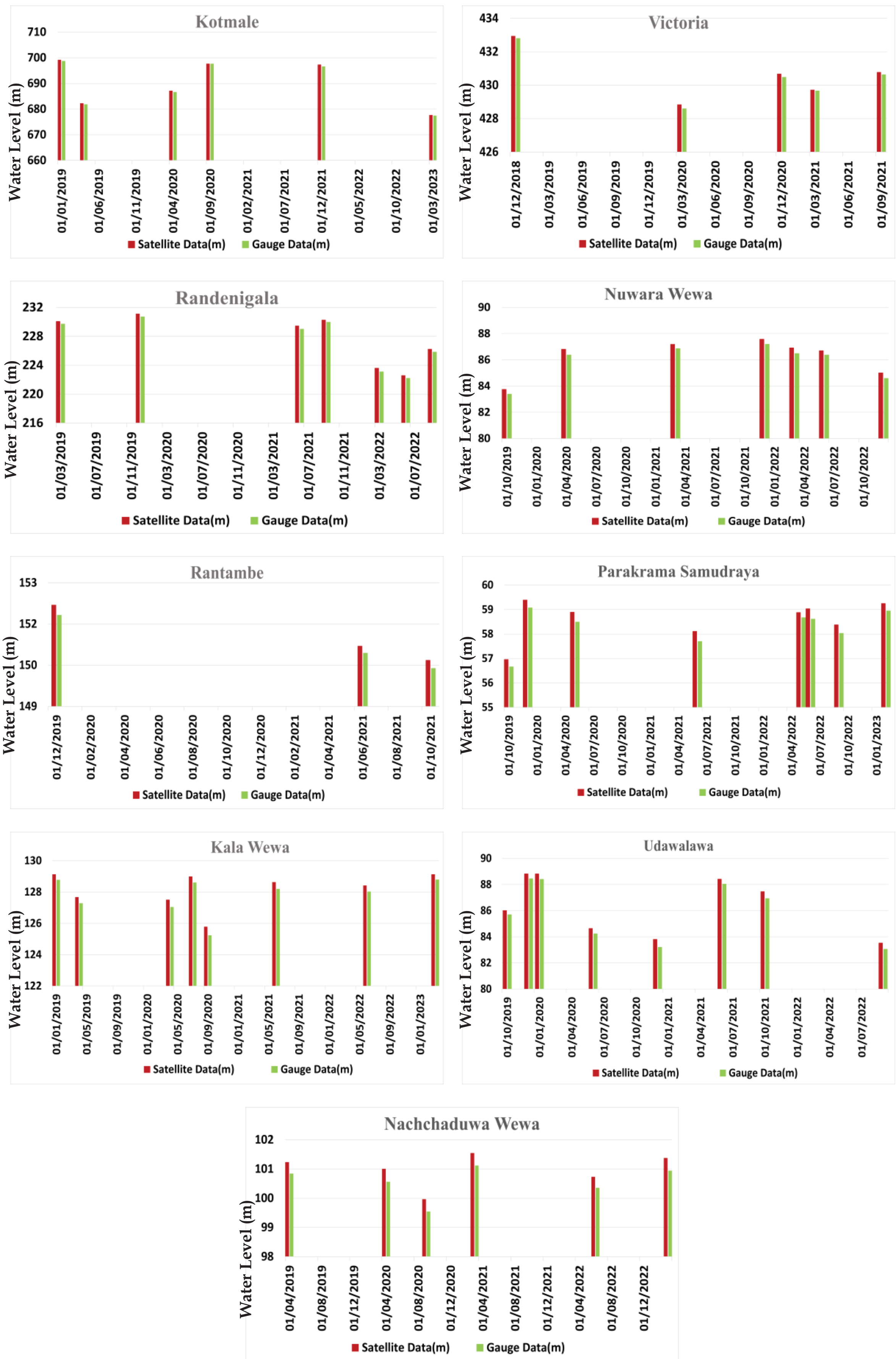

Figure 5 - Reservoirs Water Elevation Data Obtained from ICESat-2 and in-Situ Gauge Data

Table 3 - Comparison of Observations, KGE, RRMSE, and Correlation Coefficient among Studied Reservoirs

Reservoir	Kling Gupta Efficiency (KGE)	RRMSE	Correlation coefficient
Kotmale	0.99	0.0006	0.99
Victoria	0.98	0.0004	0.99
Randenigala	0.99	0.002	0.99
Rantambe	0.95	0.002	0.99
Kala Wewa	0.95	0.003	0.99
Parakrama Samudraya	0.99	0.006	0.99
Nuwara Wewa	0.99	0.004	0.99
Nachchaduwa	6	0.004	0.99
Udawalawe	0.98	0.005	0.99

The data for the Kotmale reservoir was further analyzed to understand the satellite's performance. Figure 6 shows the locations of ICESat-2 altimeter footprints, with distinct colors representing data collected on various dates. This provides a visual representation of the spatial and temporal distribution of water levels. Figure 7 compares the derived water levels from ICESat-2 with the water level variation over the entire period. This comparison demonstrates that the satellite accurately captured the reservoir's fluctuations.

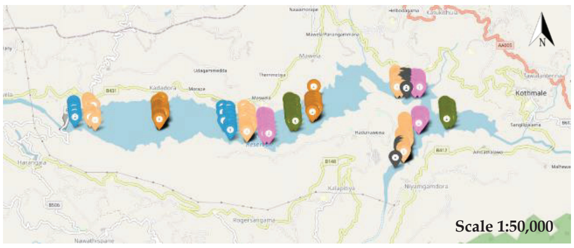

Figure 6 - Kotmale Reservoir Water Elevation Data Obtained from ICESat-2 and Location of Altimeter Footprints

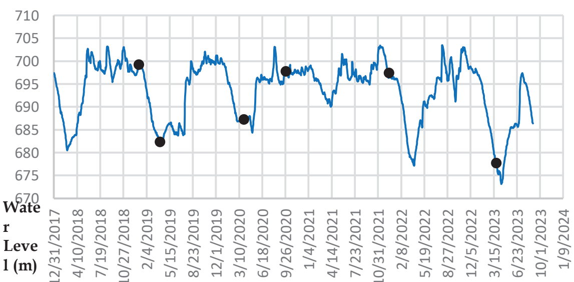

Figure 7 - Gauge Water Level (Blue Line) and Altimetric Water Level (Black dots) of the Kotmale Reservoir

ICESat-2 provides extensive data for a particular reservoir on specific dates, resulting in substantial datasets. For example, on March 27, 2023, a total of 94 data points were collected for the Kotmale Reservoir. Remarkably, all these data points were recorded within just 0.434 seconds. Figure 8 shows the histogram of these data points. The highest number of observations is between 677.64 and 677.65 m, while the gauge observation is 677.45 m, and the average of the satellite data is 677.68 m. This indicates that further screening may be able to provide a better representation of the satellite data.

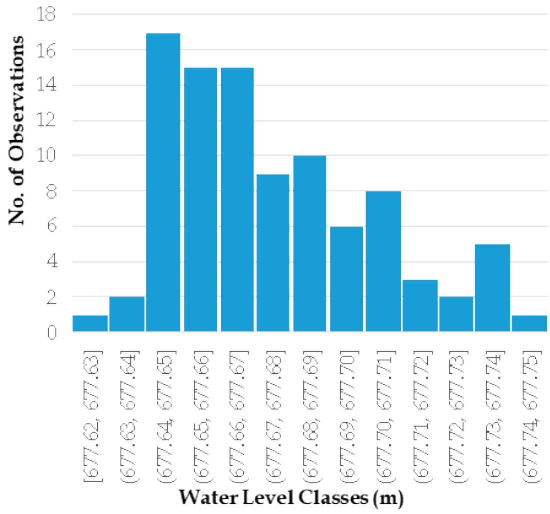

Figure 8 – Histogram of Data Collected from Kotmale Reservoir on 27 March 2023

This analysis examined the bias between satellite-estimated water levels and in-situ gauge measurements for selected reservoirs, as presented in Table 4.

Table 4 - Comparison of Bias and Average In-Situ Gauge Water Level

Reservoir	Average Water Surface Level (m)	Bias (m)
Udawalawe	86.0	0.431
Kala Wewa	127.8	0.413
Parakrama Samudraya	58.3	0.336
Rantambe	150.7	0.303
Nuwara Wewa	85.9	0.382
Randenigala	227.3	0.395
Victoria	430.4	0.158
Kotmale	689.8	0.38
Nachchaduwa	100.6	0.415

No clear pattern or correlation emerged when examining the relationship between bias and average water levels. The variation in bias values does not appear to be related to the average water levels at each reservoir.

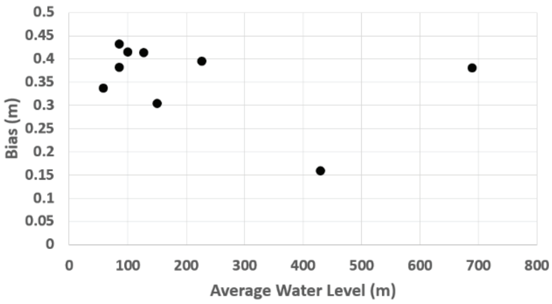

Figure 9 – Relationship between Bias and the Average Water Surface Level

To assess the uncertainty associated with elevation readings derived from satellite data, the photon returns were analyzed to construct a graph depicting the uncertainty in these elevation values. Even when providing an average elevation, it is essential to consider the potential range of values. For instance, if the average elevation is 55.62 m with an uncertainty of 0.04 m, the actual elevation could range from 55.58 m to 55.66 m. This approach helps in understanding and managing the variability in satellite-derived data. The number of photons that returned to the satellite was used to create a graph showing the uncertainty in the elevation values. The return of a higher number of photons indicates lower uncertainty, implying greater confidence in the elevation readings. Conversely, fewer returns indicate higher uncertainty, suggesting that the elevation readings may vary more. By examining the number of photons returns, the reliability of the satellite-derived elevation data can be understood.

Figure 10 shows the uncertainty graph for Kotmale Reservoir. For instance, on September 29, 2020, the observed water level at Kotmale Reservoir was recorded as 697.69 m. By analyzing the reflected photons, an uncertainty of 68 mm was determined for that day. Consequently, the observed value could fluctuate between 697.622 m and 697.758 m. However, despite accounting for this uncertainty, a consistent bias remains across all results. Thus, even after adjusting for the uncertainty in the observed reading, aligning the satellite data with the gauge data value remains challenging.

Figure 11 presents a comparative analysis between satellite-observed water levels obtained from ICESat-2 and traditional gauge measurements for all nine reservoirs. The correlation coefficient is 0.99, indicating a solid alignment between the satellite and gauge measurements. This high correlation demonstrates the reliability of ICESat-2 in accurately monitoring water levels.

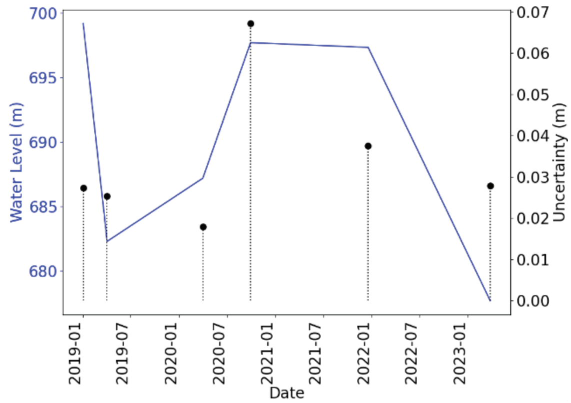

Figure 10 - Observed Water Level Variation from Kotmale Reservoir, Black Dots Represent the Uncertainty of the Corresponding Observed Elevation

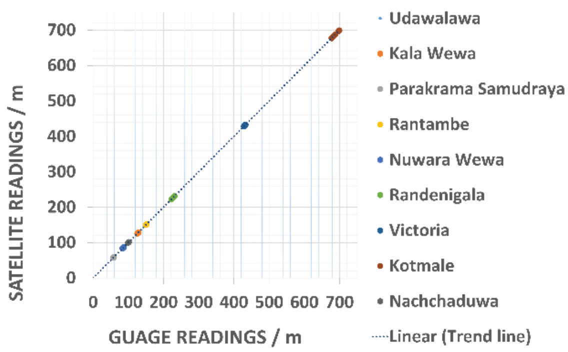

Figure 11 - Summary of Comparisons between Satellite-Observed Water Levels and Gauge Water Levels of 9 lakes/Reservoirs in Sri Lanka

5. Conclusions

This study aimed to assess the accuracy of satellite-derived elevation values compared to in-situ gauge data across nine reservoirs in Sri Lanka. The findings indicate that ICESat-2 data demonstrates remarkably high accuracy, despite slight deviations. The highest RRMSE was recorded at Parakrama Samudraya Reservoir, with a value of 0.006. The time difference between the gauge and satellite-retrieved water levels can be one potential reason for the slight deviations. Despite these variations, the correlation coefficient remained consistently high, above 0.99, across all reservoirs. This suggests a robust linear relationship between the satellite-derived and in-situ gauge data, underscoring the reliability of ICESat-2 in capturing elevation trends.

The investigation revealed a notably lower quantity of measurements in the reservoirs. Among the reservoirs studied, Kala Wewa Reservoir and Udawalawe Reservoir had the maximum number of readings, with only eight measurement data records. This limitation in data acquisition can be attributed to the smaller size of Sri Lankan reservoirs compared to other reservoirs previously investigated in the literature.

The outlier removal process proved effective in mitigating the impact of extreme values without introducing substantial alterations to the overall dataset, ensuring a more balanced and representative analysis. Additionally, the assessment of uncertainties associated with elevation readings provided further insights into the precision of the ICESat-2 data.

The methodology introduced in this study can be applied to estimate water levels in all reservoirs in the country. It would be helpful for seasonal analysis and identifying gauge malfunctions. These findings highlight the potential of ICESat-2 data in enhancing water resource management and monitoring efforts in Sri Lanka.

6. Recommendations

ICESat2 was launched in 2018, and data products have been available since then. Owing to the limited period of the data, approximately five years, it can be used in the future for longer-term analysis. Integrating ICESat-2 data with observations from other satellite missions like Sentinel-6, SWOTand CryoSat-2 can provide more frequent data, capturing rapid water level changes more effectively. Implementing advanced retracking algorithms will refine the ICESat-2 data by precisely locating the reflecting surface, enhancing the accuracy of water level measurements.

Additionally, utilizing machine learning algorithms to analyze the data can further improve accuracy and predictability by identifying patterns and trends in large datasets. Combining satellite data with ground-based measurements, such as gauge data, and integrating these with hydrological models will validate and improve the accuracy of satellite-derived water levels.

Expanding the studies to include more reservoirs and diverse geographical regions will validate the methodology across various environments, improving its robustness.

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