Mapping surface area changes in three reservoirs on the island of Trinidad between 2017 and 2023 using Sentinel-1 SAR imagery

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Abstract

Rapid urbanization and climate change have the potential to negatively affect water availability in the coming decades. The Caribbean region is particularly at risk since, among other factors, large water storage facilities are not as abundant as in larger nations. It is imperative therefore, that water resources in the small island nations of this region are efficiently monitored and managed. Recent open-source, satellite earth-observation data and processing capabilities have presented additional tools for managers to better regulate water and water infrastructure. In this study, we use Synthetic Aperture Radar (SAR) data from the Sentinel-1 satellite to map surface area changes in three reservoirs on the island of Trinidad using a Google Earth Engine (GEE) framework. Sentinel-1 data was processed using GEE to produce average reservoir surface area calculations for each season (wet and dry) of each year for the period 2017-2023. The resultant reservoir surface area values were cross referenced against average seasonal precipitation values obtained from the CHIRPS (Climate Hazards Group Infra-Red Precipitation with Station data) database. The SAR-derived reservoir surface area values were also compared against reservoir surface area values and reservoir 'lake level' values for 2017 – 2023 obtained from the Water Resources Agency (WRA) of Trinidad and Tobago. Results showed that the approach used in this study can be integrated into existing water resource monitoring frameworks, particularly for the larger reservoirs, to improve efficiency at little to no additional cost.

1. Introduction

Global urbanization is rapidly increasing with the population in urban cities projected to grow by more than 3 billion between 2010 and 2050 (Cividino et al., 2020). Together with socioeconomic development and population growth, global urban water scarcity is projected to affect 1.693–2.373 billion people by the year 2050 (He et al., 2021). The effects of climate change will affect both the quality and availability of this commodity on large spatial and temporal scales (He and Rosa, 2023, Aversa et al., 2023). Increased reservoir construction has been touted as one possible solution, amongst others, that can be implemented to alleviate future water availability and distribution issues (Mao, 2024). The implementation of a series of large reservoirs began during the 1960's and 70's in North America with approximately 61,988 now existing worldwide (ICOLD, 2023). Reservoirs serve a multitude of functions from agricultural irrigation, aquaculture, and flood control to hydroelectric energy and navigation (Breznik et al., 2023, Macharia and Jori, 2023, Schmitt et al., 2022). In the Caribbean region, there are very few reservoirs, as the cost associated with establishing the required infrastructure is high and the topography of many islands does not favour construction (Scalley, 2012). However, there are still some medium to large capacity dams existing in countries such as Jamaica, St Lucia, Cuba and Trinidad and Tobago (Becher et al., 2022, Beharry and Clarke, 2023).

Assessment and monitoring of reservoir water levels is imperative in predicting water availability for the future (He et al., 2024, Tran et al., 2024). Changes in reservoir surface area is often directly proportional to changes in water levels and is one metric that can be used in monitoring and planning for sustainable systems (Francis et al., 2021). This is critical for the development of conservation frameworks to help combat the effects of climate change and is in alignment with Sustainable Development Goal 6 (SDG 6), (UN-Water, 2020). Additionally, poor oversight of reservoir infrastructure and water level changes have the potential to threaten natural ecosystems and hydrological balance (Eekhout et al., 2020).

Trinidad and Tobago, situated in the Eastern Caribbean (EC) region is considered to be developed with over 99% of the population having access to potable water (Ministry of Public Utilities & WASA, 2022). Despite this, however, operational issues and seasonality (wet and dry) have resulted in less than 40% of WASA's clients receiving a reliable and continual supply (Roopnarine et al., 2023). This deficit is further intensified during the dry season when precipitation and reservoir levels are low (Rajballie et al., 2022). Increased urbanization as well as the effects of climate change were expected to escalate the demand for water in urban towns in Trinidad and Tobago by 60 – 70% between 2020 and 2025 (Leon et al., 2020). Therefore, there is a critical need for effective and cost-efficient tools to support the continuous assessment and monitoring of reservoirs and other water resources, enabling improved conservation and management while meeting growing demand.

Traditional methods of monitoring reservoir surface area and water levels include the use of sonar and onsite water level gauges (Abileah et al., 2011, Mainville and Craymer, 2005). Both of these methods can be difficult to implement due to the typical remote locations of reservoirs (Tortini et al., 2020). In recent years, advances in satellite remote sensing technology and the availability of open-source satellite imagery have enhanced the monitoring aspect of large reservoirs from space (Chen et al., 2024, Park et al., 2020). Satellite derived Synthetic Aperture Radar (SAR) imagery can be used for high-frequency mapping of surface water (Yang et al., 2024). The Sentinel-1 SAR satellite which forms part of the European Space Agency's (ESA) Copernicus program offers 6-day repeat coverage at no cost to users (Beriaux et al., 2021). While optical satellites such as Sentinel-2, Landsat-8 and Planet have a higher accuracy for surface water detection than SAR (Alatalo et al., 2023, Cristea et al., 2020), their field of view is often limited by clouds, particularly in tropical regions such as Trinidad (Wang et al., 2021).

The goal of this study was to demonstrate the utility of using Sentinel-1 SAR imagery for mapping and monitoring reservoir surface area and extent on the island of Trinidad. The surface area of three specific reservoirs were calculated across a 7-year period for both the dry and wet seasons using Sentinel-1 imagery. Surface area changes of the three main reservoirs in Trinidad, namely, the Arena, Navet and Hollis reservoirs were calculated from SAR imagery for both wet and dry seasons for 2017 to 2023. The Arena dam is the largest reservoir ever built in Trinidad spanning over 680 hectares. With a storage capacity of 46.6 million m^3 it supplies potable water to the central regions of the island. The Navet reservoir covers approximately 324 hectares with the potential to store 19.1 million m^3 of water for serving the southern areas, while the Hollis reservoir is the smallest of all three dams only holding about 4.75 million m^3 for distribution to northern areas of the island (WASA, 2015).

2. Methodology

In this study, we utilized Sentinel-1 SAR images from January 2017 - December 2023. The SAR images were first aggregated into dry and wet averages for each year before any further processing. The aggregated seasonal products were then clipped by geographic bounding coordinates encompassing each reservoir. The aggregated and clipped images were then processed using the Google Earth Engine (GEE) HYDRAfloods package. Areas representing the water coverage of each reservoir in their respective years and seasons were then extracted by using the Otsu method for edge detection (Tiwari et al., 2020). Figure 1 shows sample extracted surface area boundaries of each reservoir overlain on Google Earth imagery to demonstrate the relative differences in sizes among them. The average surface area values per season for each year between 2017 and 2023 were then plotted in bar charts for each reservoir (Figure 3A & 3B).

Daily lake level and corresponding reservoir surface area data for 2017–2023 were obtained from the WRA. From these data, the average surface area per season for each year between 2017 and 2023 was extracted for each reservoir. The SAR-derived seasonal reservoir surface area values, the WRA-derived seasonal surface area values, and the WRA-derived lake level values were then plotted for trend comparison (Figure 4). WRA-derived seasonal surface area values, originally provided in square metres, were converted to hectares to ensure consistency with the SAR-derived surface area estimates. These datasets were then plotted for both wet and dry seasons across all three reservoirs; Arena, Navet, and Hollis, to evaluate agreement, trends, and statistical relationships. Pearson correlation coefficients (r) were then calculated to quantify the relationships between (i) SAR-derived surface area and WRA-derived surface area, and (ii) surface area and lake levels. Correlation strength was interpreted using standard thresholds, where values above 0.80 indicated very strong relationships. A flowchart depicting a summary of the methodology is given in Figure 2.

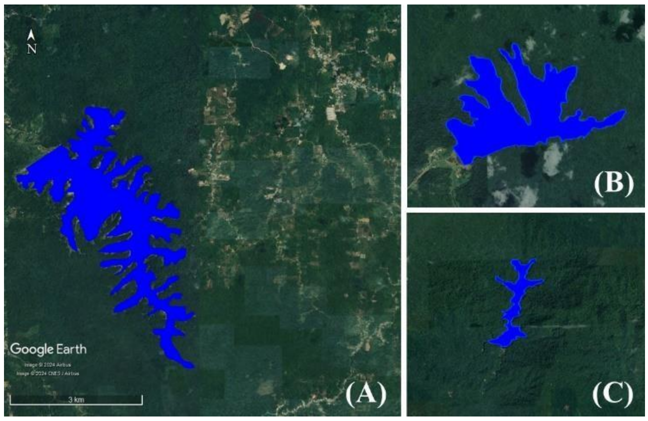


Fig 1. Showing (A) Arena Reservoir, (B) Navet Reservoir and (C) Hollis Reservoir.

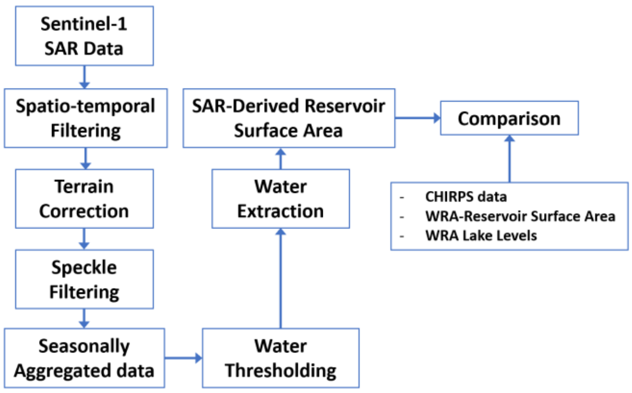
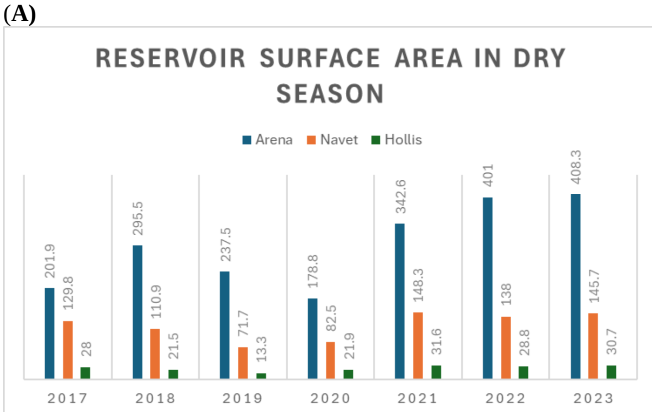


Fig 2. Methodological workflow.

3. Results and Analysis

(A)



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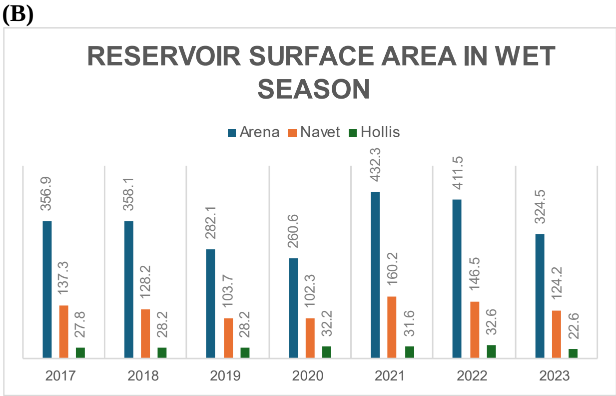
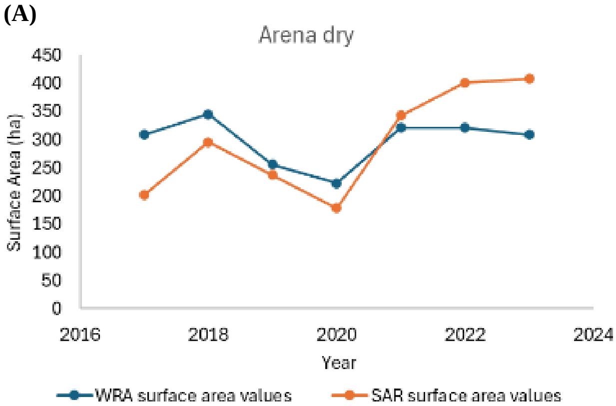
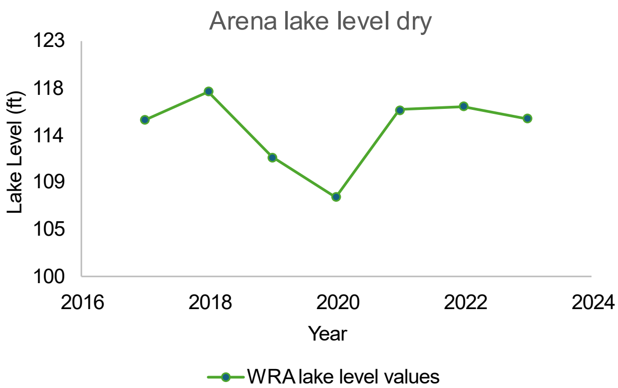


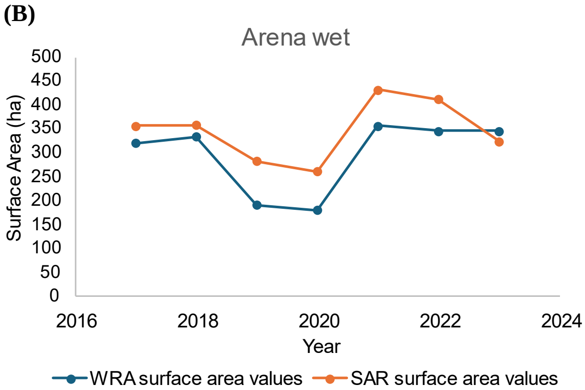
Fig 3. Average reservoir surface area derived from SAR imagery for Arena, Navet, and Hollis reservoirs (2017–2023): (A) dry season and (B) wet season.

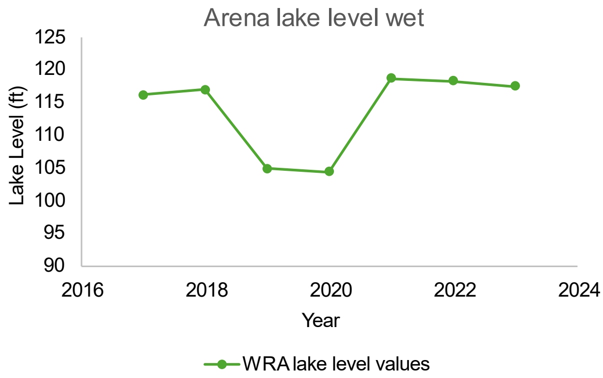
(A)



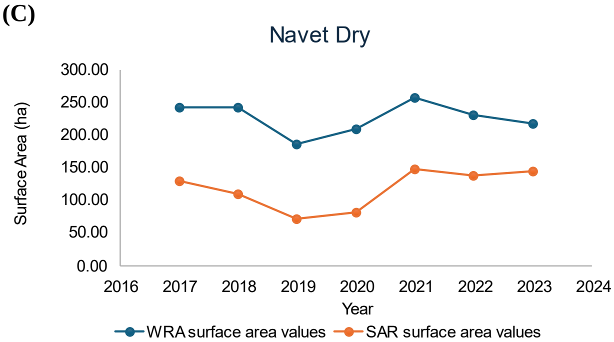


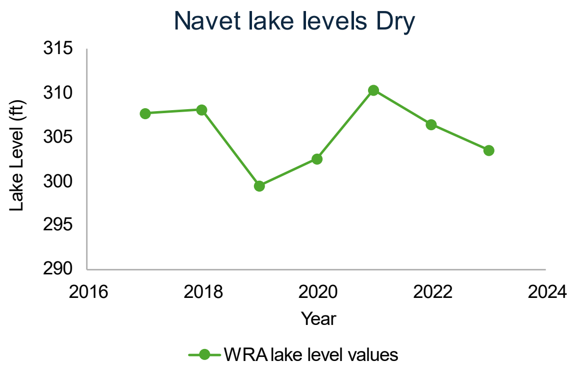
(B)



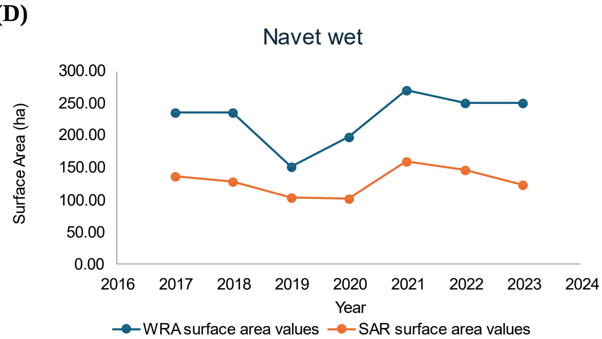


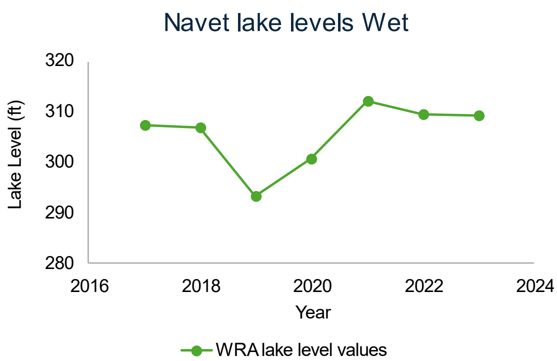
(C)



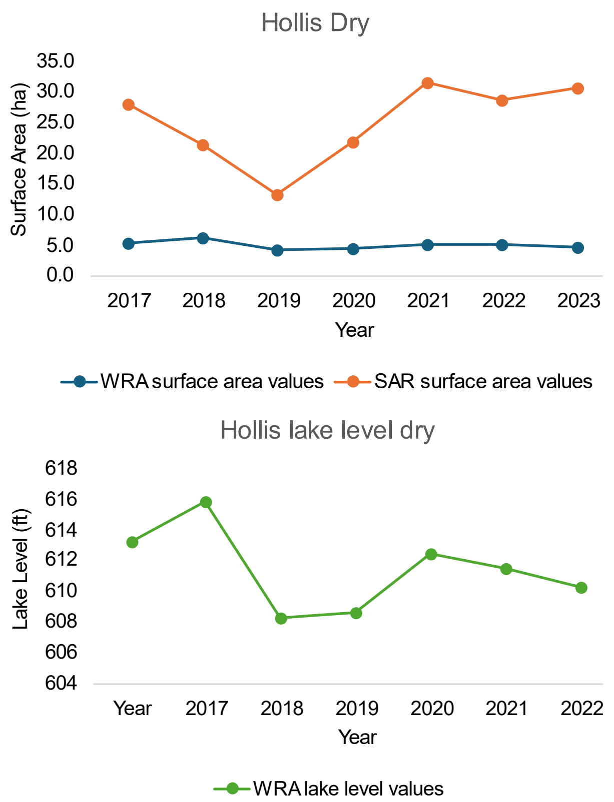


(D)





(E)



(F)

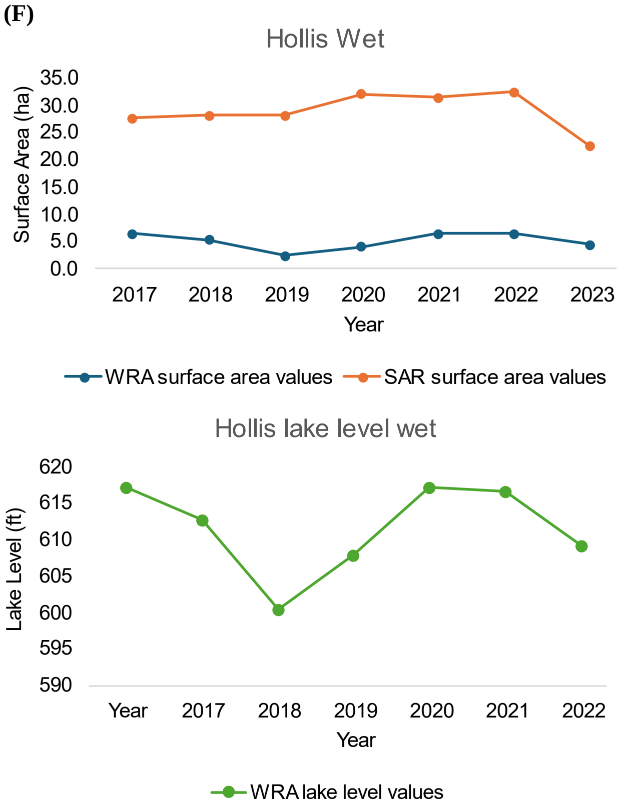


Fig 4. Comparison of trends in WRA and SAR-derived reservoir surface area (ha) and WRA-measured lake levels (ft) for the Arena, Navet, and Hollis reservoirs between 2017 and 2023: (A) Arena (dry season), (B) Arena (wet season), (C) Navet (dry season), (D) Navet (wet season), (E) Hollis (dry season), and (F) Hollis (wet season).

Figure 4 shows a comparison of reservoir surface area estimates derived from Sentinel-1 SAR imagery and those obtained from the WRA of Trinidad and Tobago, together with corresponding lake level data

3.1 Arena Reservoir

The Arena reservoir exhibited very strong correlations across all datasets. In the dry season, SAR-derived surface area showed a strong correlation with WRA surface area ($r = 0.63$) and a strong relationship with lake levels ($r = 0.65$). In the wet season, these relationships strengthened significantly, with SAR vs WRA area showing a very strong correlation ($r = 0.86$), and both surface area datasets demonstrating near-perfect correlations with lake levels ($r \approx 0.99$).

These results indicate that SAR-derived estimates reliably capture reservoir dynamics for larger systems such as Arena. The strong agreement between datasets also supports the assumption that surface area is directly related to water level, validating the use of SAR as a proxy for reservoir monitoring.

3.2 Navet Reservoir

The Navet reservoir also demonstrated strong to very strong correlations. During the dry season, SAR-derived surface area correlated strongly with WRA surface area ($r = 0.75$) and lake levels ($r = 0.73$). In the wet season, these relationships improved further, with SAR vs WRA area reaching very strong correlation ($r = 0.86$), and near-perfect correlation observed between WRA surface area and lake levels ($r \approx 0.999$).

Although slightly weaker than Arena, these results still indicate a high level of reliability in SAR-derived estimates for medium-sized reservoirs. The consistent trends between datasets suggest that SAR is capable of capturing seasonal variability effectively.

3.3 Hollis Reservoir

In contrast, the Hollis reservoir displayed markedly weaker correlations between SAR-derived and WRA surface area estimates. In the dry season, the correlation between SAR and WRA area was weak ($r = 0.28$), and similarly weak relationships were observed with lake levels ($r \approx 0.34$). Wet season correlations showed only marginal improvement ($r \approx 0.31$).

Despite this, WRA surface area and lake level data maintained very strong correlations ($r \approx 0.99$), indicating that the underlying hydrological relationship remains robust. The discrepancies observed in SAR-derived estimates are therefore likely attributable to limitations in spatial resolution (10 m Sentinel-1 data) and increased digitization uncertainty for smaller reservoirs. These factors reduce the precision of boundary delineation and contribute to error propagation in surface area calculations.

3.4 General Trends

Across all reservoirs, a clear pattern emerges whereby the accuracy and reliability of SAR-derived surface area estimates decrease with reservoir size. Larger reservoirs such as Arena show strong agreement between SAR and in-situ datasets, while smaller reservoirs such as Hollis exhibit greater discrepancies. This trend highlights the importance of scale when applying SAR-based monitoring approaches.

Overall, the results confirm that SAR-derived surface area estimates align closely with both WRA-derived surface area and lake level data for larger reservoirs, and that surface area can serve as a reliable proxy for water level dynamics in these systems.

Figure 4 integrates SAR-derived surface area, WRA surface area, and WRA lake level datasets to further examine their relationships. The analysis confirms that strong correlations exist between water height (lake levels) and surface area for Arena and Navet reservoirs, particularly during the wet season. However, this relationship is less clearly resolved for the Hollis reservoir due to the limitations associated with smaller spatial extents and SAR resolution.

4. Discussion

The results of the analysis provide strong evidence supporting the utility of Sentinel-1 SAR imagery for monitoring reservoir surface area and, by extension, water level dynamics in Trinidad and Tobago. The integration of SAR-derived data with WRA surface area and lake level datasets demonstrates that remote sensing approaches can reliably support in-situ observations for larger reservoirs.

The very strong correlations observed for the Arena reservoir, particularly during the wet season ($r > 0.85$ for SAR vs WRA area and $r \approx 0.99$ for relationships with lake levels), highlight the robustness of SAR-based monitoring in larger water bodies. Similar, though slightly reduced, performance was observed for the Navet reservoir, indicating that SAR remains effective for medium-sized systems. These findings are consistent with established understanding that SAR performs well in detecting water bodies due to its sensitivity to surface roughness and ability to penetrate cloud cover, an important advantage in tropical environments.

In contrast, the relatively weak correlations observed for the Hollis reservoir underscore a key limitation of SAR-based approaches which is spatial resolution. At 10 m resolution, Sentinel-1 imagery may not adequately capture the fine-scale boundaries of smaller reservoirs, leading to increased uncertainty in surface area delineation. This limitation is compounded by potential interference and error propagation from vegetation overhang along the reservoir boundary as well as classification processes, particularly where shoreline complexity is high.

Importantly, the consistently strong correlations between the SAR-surface area, WRA surface area and lake level data across large and medium reservoirs confirm that surface area remains a reliable proxy for water level. This reinforces the validity of using remotely sensed surface area as a surrogate for hydrological monitoring, particularly in contexts where in-situ measurements are limited or unavailable.

From an applied perspective, these findings demonstrate that SAR-based monitoring can be effectively integrated into national water resource management frameworks. For larger reservoirs, SAR provides a cost-effective, scalable, and high-frequency monitoring solution that can support decision-making, early warning systems, and long-term planning. However, for smaller reservoirs, supplementary approaches such as higher-resolution optical imagery, drone surveys, or in-situ calibration may be required to improve accuracy.

Efficient water resource management is necessary for ensuring the survivability of small island developing states like those of the Caribbean region. Projected high rates of urbanization coupled with the effects of climate change pose significant risks to water availability in the coming years. Water demand and water pollution are both exacerbated by urbanization, whereas droughts, floods and seasonal water variability can all be intensified by climate change. The geographic and financial constraints of Caribbean SIDS further compound this situation; therefore, the efficient management of water resources and infrastructure should be of high priority in these high-risk regions.

Current water resource monitoring practices rely heavily on conventional in-situ methods which are often time, labour and fiscally restrictive. The use of drones has helped to alleviate these restrictions to some degree but even this technology has many drawbacks. The approach applied in this study offers increased accessibility, affordability and relevance particularly for resource limited environments. SAR technology has the ability to penetrate clouds which is especially useful for tropical regions that are persistently hampered by clouds, while GEE provides a seamless environment for efficient data processing and analysis.

The WRA surface area and lake level data and CHIRPS database allowed for further analysis and played a functional role in validating and contextualizing the reservoir surface area changes observed. In this regard, it is important to combine hydrological and meteorological data for a more holistic understanding of water resource dynamics.

The results of this study demonstrate the utility of SAR data for reservoir monitoring on small islands to enhance water resource monitoring and management strategies. Data would be better calibrated against periodic, in-situ measurements for e.g., from higher-resolution surface area measurements from drones. There is a need for innovative and low-cost solutions for water resource management in an environment of increased urbanization and pending climate change.

5. Conclusion

In conclusion, the framework used in this study can be integrated into early warning systems for identifying water resource availability risk and adaptive water management strategies. Its cost- effective approach and accessibility make it a viable option for resource constrained governments such as those of the Caribbean region.

Further, this study highlights both the strengths and limitations of SAR-based reservoir monitoring in small island developing states. While highly effective for larger systems, careful consideration of spatial scale and methodological refinement is necessary to ensure reliable application across varying reservoir types.

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References

Abileah, R., Vignudelli, S., Scozzari, A., 2011: A completely remote sensing approach to monitoring reservoir water volume. Proc. IWTC, 15.

Alatalo, J., Sipola, T., Rantonen, M., 2023: Improved difference images for change detection classifiers in SAR imagery using deep learning. IEEE Trans. Geosci. Remote Sens., 61. https://doi.org/10.1109/TGRS.2023.3324994

Aversa, D., Adamashvili, N., Fiore, M., Spada, A., 2023: Scoping review via text data mining on water scarcity and climate change. Sustainability, 15(1). https://doi.org/10.3390/su15010070

Becher, O., Pant, R., Verschuur, J., Mandal, A., Paltan, H., Lawless, M., Raven, E., Hall, J., 2023: A multi-hazard risk framework to stress-test water supply systems to climate-related disruptions. Earth’s Future, 11(1). https://doi.org/10.1029/2022EF002946

Beharry, S.L., Clarke, R.M., 2023: Estimations of future reservoir volumes under different climate scenarios for a tropical reservoir in Trinidad. Environ. Monit. Assess., 195(5). https://doi.org/10.1007/s10661-023-11207-8

Beriaux, E., Jago, A., Lucau-Danila, C., Planchon, V., Defourny, P., 2021: Sentinel-1 time series for crop identification in future CAP monitoring. Remote Sens., 13(14). https://doi.org/10.3390/rs13142785

Breznik, J., Oštir, K., Ivačič, M., Rak, G., 2023: Water dynamics analysis in karst flood areas using Sentinel-1 time series. Remote Sens., 15(15). https://doi.org/10.3390/rs15153861

Chen, Y., Wang, Y., Li, L., Cui, Y., Duan, X., Long, D., 2024: Monthly monitoring of inundated areas and water storage dynamics in large reservoirs using multisource remote sensing. Water Resour. Res., 60(8). https://doi.org/10.1029/2023WR036450

Cividino, S., Halbac-Cotoara-Zamfir, R., Salvati, L., 2020: Revisiting the “city life cycle”: Global urbanization and implications for regional development. Sustainability, 12(3). https://doi.org/10.3390/su12031151

Eekhout, J.P., Boix-Fayos, C., Pérez-Cutillas, P., de Vente, J., 2020: Impact of reservoir construction, land use and climate on ecosystem services. J. Hydrol., 590, 125208. https://doi.org/10.1016/j.jhydrol.2020.125208

Francis, O.I., Anornu, G.K., Adjei, K.A., Martin, E.O., 2021: Development of water surface area–storage capacity relationship for Gurara reservoir. Model. Earth Syst. Environ., 7(3), 2047–2058. https://doi.org/10.1007/s40808-020-00949-w

He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J., Bryan, B.A., 2021: Future global urban water scarcity and potential solutions. Nat. Commun., 12(1). https://doi.org/10.1038/s41467-021-25026-3

He, L., Rosa, L., 2023: Solutions to agricultural green water scarcity under climate change. PNAS Nexus, 2(4). https://doi.org/10.1093/pnasnexus/pgad117

He, S., Wang, D., Sang, X., Niu, G., 2024: Water resource regulation based on drought-limited water level optimization. Sustainability, 16(16). https://doi.org/10.3390/su16167015

ICOLD, 2023: General synthesis. https://www.icoldcigb.org/GB/world_register/general_synthesis.asp

Leon, L.P., Chaplot, B., Solomon, A., 2020: Water consumption forecasting using soft computing: Trinidad and Tobago case study. Water Sci. Technol. Water Supply, 20(8), 3576–3584. https://doi.org/10.2166/ws.2020.273

Macharia, R., Jori, E., 2023: Aquaculture in hydropower reservoirs. Tanz. J. Eng. Technol., 42(3), 1–15. https://doi.org/10.52339/tjet.v42i3.951

Mainville, A., Craymer, M.R., 2005: Present-day tilting of the Great Lakes region. Geol. Soc. Am. Bull., 117(7–8), 1070–1080. https://doi.org/10.1130/B25392.1

Mao, K., 2024: Role of reservoir management in mitigating water scarcity. Ukr. J. Ecol., 14(1), 43–46. https://doi.org/10.15421/2024_535

Ministry of Public Utilities & WASA 2022: Water Sector Master Data Bank.

Park, E., Merino, E., Lewis, Q.W., Lindsey, E.O., Yang, X., 2020: Automated global assessment of reservoir water level using SAR. Remote Sens., 12(8). https://doi.org/10.3390/rs12081353

Rajballie, A., Tripathi, V., Chinchamee, A., 2022: Water consumption forecasting models in Trinidad. Water Supply, 22(5), 5434–5447. https://doi.org/10.2166/ws.2022.147

Roopnarine, R., Cashman, A., Eudoxie, G., Govia, S.J., Davis-Rostant, C., Jackson, R., Crichlow, A., 2023: Impact of COVID-19 and natural disasters on water consumption. H2Open J., 6(1), 15–28. https://doi.org/10.2166/h2oj.2023.059

Scalley, T.H., 2012: Freshwater resources in the insular Caribbean: An environmental perspective. Caribb. Stud., 40(2), 63–93. https://doi.org/10.1353/crb.2012.0030

Schmitt, R.J.P., Rosa, L., Daily, G.C., 2022: Global expansion of sustainable irrigation limited by water storage. Proc. Natl. Acad. Sci. https://doi.org/10.1073/pnas

Tiwari, V., Kumar, V., Matin, M.A., Thapa, A., Ellenburg, W.L., Gupta, N., Thapa, S., 2020: Flood inundation mapping (Kerala 2018) using SAR and Google Earth Engine. PLoS ONE, 15(8).

Tran, H.P., Ha, T.C., Nguyen, T.T.H., Nguyen, N.T., Duong, B.M., Danh, M., Tran, P.D., Pham, T.N., 2024: Mapping water body area using Sentinel-1 SAR. E3S Web Conf., 496. https://doi.org/10.1051/e3sconf/202449603001

Tortini, R., Noujdina, N., Yeo, S., Ricko, M., Birkett, C.M., Khandelwal, A., Kumar, V., Marlier, M.E., Lettenmaier, D.P., 2020: Global surface water storage change dataset. Earth Syst. Sci. Data, 12(2), 1141–1151. https://doi.org/10.5194/essd-12-1141-2020

UN-Water, 2020: Summary progress update 2021—SDG 6: Water and sanitation for all.

Wang, J., Yang, D., Chen, S., Zhu, X., Wu, S., Bogonovich, M., Guo, Z., Zhu, Z., Wu, J., 2021: Automatic cloud and shadow detection for PlanetScope imagery. Remote Sens. Environ., 264, 112604. https://doi.org/10.1016/j.rse.2021.112604

WASA, 2015: Water and Sewerage Authority website.

Yang, S., Wang, L., Yuan, Y., Fan, L., Wu, Y., Sun, W., Yang, G., 2024: Recognition of small water bodies using SAR-optical fusion. Sci. Total Environ., 946, 174329. https://doi.org/10.1016/j.scitotenv.2024.174329