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Research Article

Keywords: Glacial Lake Outburst Floods (GLOFs), Sentinel-1 SAR, Water-Area Detection, Himalayan Glacial Lakes, Remote Sensing, Digital Elevation Model (DEM), Sentinel-2 MNDWI, Terrain Effects

Posted Date: October 27th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11495245/v1

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Additional Declarations: The authors declare no competing interests.

SAR-Based Monitoring of Glacial Lake Dynamics at Chorabari Tal and Vasuki Tal, Uttarakhand Himalaya: Temporal Analysis and Anomaly Detection (2019–2024)

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***Abstract*—Glacial lake outburst floods (GLOFs) are an important hazard in the Himalayan region as the optical monitoring is limited by the continuous cloud cover, especially during the monsoon. This paper utilizes the Sentinel-1 data by applying Sentinel-1 VV water-area pipeline to Chorabari Tal and Vasuki Tal in the Kedarnath region using 154 acquisitions per lake. Quality control revealed two major issues in the initial processing: a wide region of interest (ROI) at Chorabari Tal included slope-aligned SAR shadow/layover artifacts and the coordinate initially used for the Vasuki Tal didn't correspond to the intended lake due to the steep terrain. After the reduction of the region of interest and DEM based slope masking, water detection at Chorabari Tal was 0.00–4.09 ha (mean 0.19 ha) with non-zero values concentrated in March–April when the wet snow may be misclassified as water. Vasuki Tal ranged from 0.27 to 10.34 ha (mean 4.01 ha). SAR areas differed by 8.0%, 122.4% and 16.0% while comparing with Sentinel 2 MNDWI on three dates. The July 2022 difference is in line with the wet-snow misclassification but was not verified. A manually traced Google Earth polygon imagery dated 1 November 2025 gives 7.8 ha which is larger than the 2019–2024 SAR mean, this discrepancy was not resolved. Anomaly counts for Vasuki Tal ($|z| > 2$) were four under a monthly baseline and seven under a four-season baseline, which shows that the count depends on the baseline choice. The strongest cross-correlation between the 14-day mean ERA5-Land temperature and lake area is seen at a lead of 17 days, however the statistical significance of this is not shown and it is probably driven by seasonality. It is also worth noting that no radiometric terrain normalization nor geometry-based layover or shadow masking was performed. This approach is probably not acceptable for operational hazard monitoring in the current state.**

***Index Terms*—glacial lake outburst flood (GLOF), Chorabari Tal, Vasuki Tal, Sentinel-1 SAR, water body mapping, terrain correction, DEM, terrain masking, anomaly detection, Kedarnath, Himalaya, remote sensing**

I. Introduction

The cryosphere of the Hindu Kush Himalayan region is made up of extensive glaciers and glacial lakes, whose changes have direct effects on water and hazards downstream. Based on the findings, it is believed that glaciers in some parts of the Himalaya have receded and made way for the development and expansion of proglacial and supraglacial lakes in some parts of the Himalaya, which increase the risk of GLOFs.

A GLOF occurred at Chorabari Tal in Uttarakhand following heavy rainfall and subsequent failure of a moraine dam in 2013 causing loss of life and large scale destruction of infrastructure downstream [1], [2]. The Chorabari Tal (also known as Gandhi Sarovar) was located upstream of the Kedarnath temple and probably contributed to the 2013 flood hydrograph.

Monitoring of high-elevation lakes in the Himalayas is difficult as these systems are frequently obscured by cloud cover, which prevents the operation of optical sensors during the monsoonal summer season when hydrometeorological threats are expected to intensify. Previous research indicates that the C-band synthetic aperture radar (SAR) data sets could provide a approach to obtain measurements under cloud cover. However, terrain geometry, including layover and shadow effects, and wet snow in mountain areas can be challenging factors that are similar to open water bodies. These effects may also pose a potential challenge for the interpretation of the data.

This paper evaluates a simple fixed-threshold processing chain and talks about two errors found during quality control: a terrain-induced artifact at Chorabari Tal and a coordinate error at Vasuki Tal.

The principal contributions are:

- A SAR-based water-area extraction pipeline applied to two Himalayan lake sites with explicit region checking.
- Identification of a shadow/layover artifact at Chorabari Tal and its mitigation with a DEM slope mask.
- Identification and correction of the Vasuki Tal coordinate error using Sentinel-2.
- A three-date comparison with optical data and an anomaly sensitivity analysis showing that anomaly counts strongly depends on the seasonal baseline.

II. Study Area

A. Chorabari Tal (Gandhi Sarovar)

Chorabari Tal is a proglacial lake basin connected to the Chorabari Glacier (approximately 30.748° N, 79.067° E, at $\sim$3900 m a.s.l., Rudraprayag, Uttarakhand). The basin

drains southward into the Mandakini River, a tributary of the Alaknanda–Ganges system. Here, we provide information of the Chorabari Tal GLOF that occurred on 16–17 June 2013, but the present study focuses on the quantification of surface-water conditions from the time duration of 2019 to 2024.

B. Vasuki Tal

Vasuki Tal represents a lake basin created by glacial activity with coordinates $\sim 30.726^\circ$ N and $\sim 79.037^\circ$ E at an elevation of ~ 4135 meters. Review of Sentinel-2 imagery and Google Earth Pro found out that a clear lake basin may exist at this coordinate in Google Earth Pro data on 1 November 2025. A manual lake boundary polygon on Google Earth Pro shows the lake may have an approximate perimeter of 1.19 km and a surface area of 7.8 ha, which is less than the initial estimate based on quick screen captures while defining this mask, which suggested a 400–500 m width at the first rough validation point. This represents an updated coordinate set from the earlier versions of this data set which were validated as not being a lake.

The Rudraprayag District Administration reports Vasuki Tal at about 8 km from the Kedarnath by trail and at an altitude of 4,135 m [3]. The distance in a straight line from the pinpointed area to the location of Kedarnath is approximately 3.3 km. Although the distance over a trail may be greater than straight line, this was not confirmed with the source. Therefore, the lake was identified based on the imagery of the lake that was bounded at the specified height.

III. Data and Methodology

A. Sentinel-1 SAR Data

The primary data used in the study were the Sentinel-1A and Sentinel-1B C-band (5.4 GHz) intensity data, acquired in the Interferometric Wide (IW) mode, and provided as Level-1 Ground Range Detected (GRD) products [4]. Data availability was made accessible through the Google Earth Engine (GEE) platform via the data set ID `COPERNICUS/S1_GRD`. Data for each of the lakes was available through GEE from January 2019 to December 2024, with the number of Sentinel-1 acquisitions being 154 for each, and the average acquisition frequency ranging between 12 and 24 days, and longer intervals post the termination of Sentinel-1B in December 2021.

B. Region-of-Interest Definition and Correction

A circular range of interest of a fixed radius was drawn around the center coordinate of each site. Validation revealed two issues.

Chorabari Tal: The original ROI of this site was too wide, as it included the hillside and catchment of the known lake basin. Following this, the ROI was further truncated to an area of 300m radius from the site, as confirmed by the interpretation of optical images.

Vasuki Tal: There were no lakes at 30.934° N, 79.161° E as the area is quite steep. During false color analysis through Sentinel-2, lakes near Kedarnath were observed (30.726° N, 79.037° E). A 300 m radius ROI (comprising 28 hectares) around this site is used for all Vasuki Tal observations. All further area estimation is done on the scaled version of the ROI around the lake.

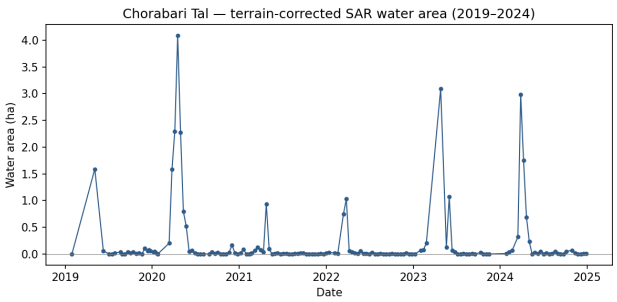


Fig. 1. SAR-derived water-surface area after DEM-based slope masking at Chorabari Tal, January 2019 to December 2024.

C. Water Body Mapping

Initially, water pixels were identified through a fixed backscatter threshold of -18 dB in the σ^0_{VV} channel, and subsequent morphological filtering to eliminate clutter pixels. The fixed thresholding and morphological filtering approach is a common baseline in SAR-based water classification studies. Adaptive approaches, like the method of Twele et al. (2016) [5], using a scene-specific identification of the threshold, were not used in this study.

The estimated area was estimated based on the number of classified pixels multiplied by an estimated detection ground range (GRD pixel area of 100 m^2 was used). Radiometric terrain normalization or modeling of the effect of incidence-angle was not performed.

Meanwhile, for optical comparison, the cloudfree Sentinel-2 scenes were used to compute Modified NDWI (MNDWI). The MNDWI was generated using the traditional green-SWIR variation proposed by Xu (2006) [6], using MNDWI > 0.0 to delineate the water bodies.

$$\text{MNDWI} = \frac{\rho_{Green} - \rho_{SWIR}}{\rho_{Green} + \rho_{SWIR}}. \tag{1}$$

D. Terrain-Based Artifact Mitigation

The first (2nd overall, more extensive) ROI was used over the scenes of Chorabari Tal; water detected varied from 50.4 ha to 506.3 ha. The classification mask was visually inspected, the pixels detected did not display a typical "lake shape" but were strings of pixels conforming to the underlying terrain. These patterns are potentially terrain-related SAR layovers and shadows, not open water.

To compensate for this, a terrain mask was created using SRTM 30m digital elevation model, removing all pixels that had a slope $> 15^\circ$. This process is based on the assumption that water exists in low angle terrain, while more steeper areas would be more likely to contain layover and shadow effects. It must be noted that slope is only an approximation of these effects, as it does not account for radar look direction or

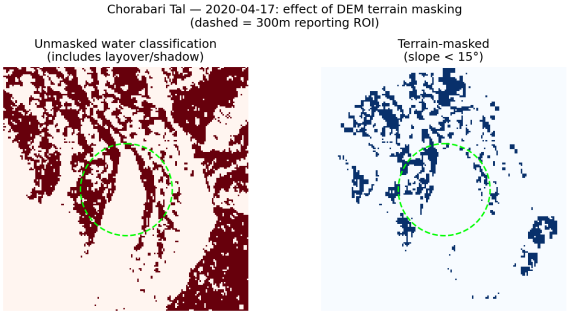


Fig. 2. Unmasked and terrain-masked water-pixel classification at Chorabari Tal on 17 April 2020, the single highest-area date in the corrected record. The dashed green circle shows the 300 m reporting range. A manual count of pixels within this circular overlay in the masked panel sums to 403 (≈4.03 ha), close to the pipeline-reported value of 4.09 ha for this date (≈1.5% difference). The cause of this small difference was not checked; boundary-pixel discretisation is one possible explanation. The unmasked panel shows slope-aligned bands of SAR layover/shadow that obscure the shape of the lake.

incidence angle, and thus even relatively flat areas may contain shadow effects if they are on the lee side of a mountain ridge.

Combine terrain mask, smaller 300-m ROI and -18dB threshold to arrive at the final estimations for Chorabari Tal. ROI reduction and terrain mask enabled are run together; it was not evaluated as separate operations. Results before and after ROI reduction and terrain masking are compared in Fig. 2.

E. Threshold Check Against MNDWI

To estimate the effectiveness and limitations of the fixed -18 dB classifier, the water area obtained at the corrected Vasuki Tal coordinate using SAR was compared to the area obtained by cloud-free Sentinel-2 image with the MNDWI. The results, listed in Table I, show relative differences of 8.0%, 122.4%, 16.0% for the three acquisition dates. These values were obtained by applying the given formula: $|A_{\mathrm{SAR}} - A_{\mathrm{MNDWI}}|/A_{\mathrm{MNDWI}}$, and rounding the A_{MNDWI} value to the reported value in the table. The very high discrepancy observed for July 2022 indicates potential misclassification of water, wet snow, or slush, but this could not be verified and three dates are too few to estimate the overall accuracy of the classifier. As such, this comparison can be considered a stress test rather than an accuracy test.

In addition, MNDWI is an approximation in itself, not a ground-truth. For this size lake, boundary-pixel uncertainty alone will probably be a significant percentage of the estimated area, since the lake's perimeter is only around 1.2 km and the MNDWI area is in the 4–5 ha range.

TABLE I
THRESHOLD CHECK AGAINST MNDWI AT VASUKI TAL

Optical date	SAR date	MNDWI (ha)	SAR (ha)	Rel. diff. (%)
2019-10-27	2019-10-26	4.87	5.26	8.0
2022-07-05	2022-06-30	1.74	3.87	122.4
2023-10-06	2023-10-11	4.26	4.94	16.0

F. Temperature Data

Surface air temperature records were acquired from ERA5 reanalysis [7] for Chorabari Tal, using the grid cell containing the lake coordinate (30.748° N, 79.067° E; cell centre 30.75° N, 79.00° E), with a spatial resolution of $0.25° \times 0.25°$ and daily time steps in degrees Celsius. For Vasuki Tal, temperature was taken from the ERA5-Land reanalysis [8] at the corrected lake coordinate (30.726° N, 79.037° E), which has a spatial resolution of around 9 km. A 14-day trailing mean was applied to both temperature series.

Note, that neither of these datasets considers the spatial variation of the temperature lapse rate with elevation throughout the entire catchment. Thus, the temperatures should be seen as spatial averages for the given grid cells. Additionally, for Vasuki Tal the elevation of the ERA5-Land grid cell may be far away from the actual elevation of the lake (around 4135 m a.s.l.), potentially leading to some elevation difference in the comparison.

G. Anomaly Detection

Seasonal standardisation was only applied to the corrected Vasuki Tal record. Two baselines were tested: (i) a monthly baseline, with the standard deviation and the mean computed separately for each of the twelve months, and (ii) a four-season baseline. For observation A_t, the standardised anomaly is

$$z_t = \frac{A_t - \bar{A}_{b(t)}}{\sigma_{b(t)}}, \tag{2}$$

where $b(t)$ denotes the applicable month or season. Observations with $|z_t| > 2$ were flagged. With roughly 13 observations per month, the monthly means and standard deviations are poorly constrained, and the series is autocorrelated. Furthermore, the Gaussian tail probability of 4.55% for the event $|z| > 2$, is just an approximation to an upper bound, and should not be taken as an exact false positive rate.

The Chorabari Tal series was not standardized as 54/154 (35.1%) of the observations were 0.00 ha. The zero-dominated nature of the distribution means that the month-wise means and standard deviations are unlikely to have a meaningful interpretation.

H. Temperature–Area Cross-Correlation

Cross-correlation between the 14-day trailing mean temperature and Vasuki Tal area was calculated using lags of ± 60 days. The positive lag value infers that the temperature is prior to the lake area. The lag value with the highest magnitude of correlation was interpreted. Because both series are autocorrelated and share an annual cycle, and because the maximum was selected over many lags, the Pearson p-value is not meaningful. No significance test was performed and no causal relationship is implied.

IV. RESULTS

A. Chorabari Tal: Corrected Water Area

After ROI reduction and terrain masking the water detection analysis at Chorabari Tal from 2019-2024 yields between 0.00

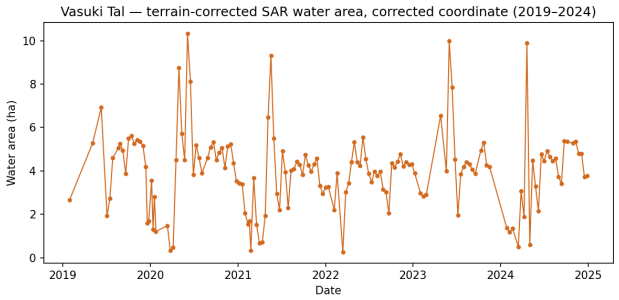


Fig. 3. Corrected SAR-derived water-surface area of Vasuki Tal from January 2019 to December 2024.

ha to 4.09 ha, with a mean value of 0.19 ha (Fig. 1; both lakes are compared in Fig. 4). There were 54 (35.1%) scenes where water was not present out of the 154 total observations. The five largest non-zero water bodies (Table II) were observed from March to April. Wet snow is anticipated to resemble water at this time of year and that is consistent with the water classification here, and in fact no persistent open water was detected by the classifier in this study.

TABLE II
FIVE LARGEST NON-ZERO CHORABARI TAL READINGS, 2019–2024

Date	Area (ha)
2020-04-17	4.09
2023-04-26	3.09
2024-03-27	2.99
2020-04-05	2.30
2020-04-29	2.27

The uncorrected region produced water areas up to 506.3 ha, dominated by slope-aligned shadow/layover bands (Fig. 2); the corrected maximum is 4.09 ha. Because the ROI reduction and the terrain mask were introduced together, their individual contributions were not separated.

B. Vasuki Tal: Corrected Water Area

After ROI and coordinate correction, Vasuki Tal water area ranged from 0.27 to 10.34 ha (mean 4.01 ha, $n = 154$; Fig. 3, Table III). The Google Earth Pro polygon (7.8 ha) is 1.95 times larger than the SAR mean, and the SAR mean falls between the three MNDWI estimates (1.74, 4.26, and 4.87 ha) in Table I. Difference from the manually traced polygon cannot, then, be explained by SAR alone, at least from the limited comparisons.

TABLE III
SUMMARY STATISTICS OF CORRECTED AREA ESTIMATES (2019–2024)

Lake	n	Min (ha)	Max (ha)	Mean (ha)
Chorabari Tal	154	0.00	4.09	0.19
Vasuki Tal	154	0.27	10.34	4.01

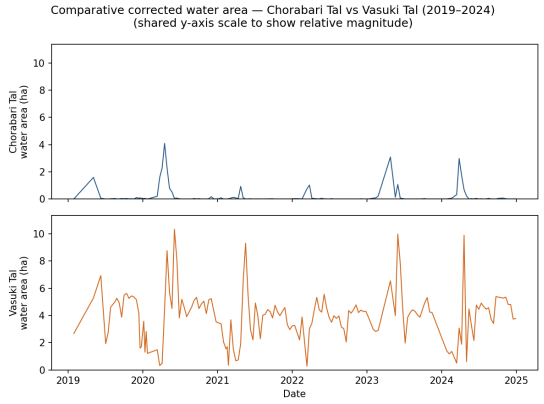


Fig. 4. Corrected lake-area time series for Chorabari Tal and Vasuki Tal, 2019–2024, in two panels with the same vertical range (0–10 ha).

C. Anomaly Detection Results

Vasuki Tal observations with $|z| > 2$ numbered four under the monthly baseline and seven under the four-season baseline. Similarly, the flagged dates are not the same for the two baselines in nine instances. This indicates the number of flagged instances is sensitive to the baseline used. Note: It should be emphasized that, for all cases, $|z| > 2$ counts are not treated as detections. Additionally, the dates considered for flagging were not corroborated with wet-snow conditions, suggesting some of them could be classifier artifacts and not lake changes.

D. Temperature–Lake Area Relationship

For the ERA5-land temperature, the 14-day trailing mean analysis showed the strongest relationship with the Vasuki Tal lake area was at a lag of 17 days, with the change in temperature preceded that of the lake area by 17 days ($r = 0.356$) - descriptive relationship. Statistical significance was not checked nor is this relationship to be used for prediction and the variables is unlikely to give any kind of predictive capability, it is expected to give a similar seasonal variation. 35.1% of the Chorabari Tal series was zeros and has no correlation.

V. DISCUSSION

A. Hazard Implications

Chorabari Tal series indicates absence of permanent surface water during 2019-2024 (based on classification method followed in our study). However, this is a semi-quantitative classification of surface water at the site, and does not mean there is a risk of GLOF. GLOF risk depends on moraine and ice dam stability, glacier mass balance and drainage, and hydrometeorological conditions, none of which were studied in this paper.

Mapped extents at Vasuki Tal varied between 0.27 and 10.34 ha. The Vasuki Tal anomalies should not be taken as GLOFs, alerts or predictive alarms.

This is a retrospective study. No operational alert system has been implemented or tested, and the Sentinel-1 revisit area,

with a revisit frequency of 12-24 days during the study period, will probably reduce sensitivity to episodic events.

B. Limitations

Two errors were found during the quality control procedure: (a) terrain artefact at Chorabari Tal, and (b) coordinate error at Vasuki Tal. These errors were detected only by visual comparison of the classification masks with the optical imagery, which emphasizes the importance of visual quality control in this analysis.

Important limitations: 1) use of a -18 dB VV threshold that can have potential misclassifications for wet snow/slush during melt period (July 2022: 122.4% relative area difference). 2) no radiometric terrain normalization and incidence-angle correction performed, 15° slope mask is only a rough proxy for layover and shadow effects. 3) no examination of slope-cutoff sensitivity. 4) only three dates of optical comparison for one lake, no pixel-by-pixel correspondence and no uncertainty estimates. 5) no independent validation of Vasuki Tal location with any in-situ or other ground-reference data. 6) Sentinel-1 revisit 12–24 days, with longer intervals after the Sentinel-1B operations ended so may miss short-lived events. 7) period from 2019 to 2024 is limited for evaluating interannual variability. 8) using ERA5/ERA5-land temperature which may not be representative of catchment temperature without an elevation-dependent lapse-rate correction.

In comparison to a human delineation of 7.8 ha from Google Earth Pro, the mean area of Vasuki Tal obtained via SAR was 4.01 ha. The three MNDWI areas (1.74 to 4.87 ha) lie within the SAR range. This disparity might result from variations in shoreline delineation and lake water levels, as well as the Google Earth Pro polygon being based on images from November 2025. As a result, rather than being the final ground truth, the Google Earth Pro measurement should be considered an extra manual measurement.

C. Comparison with Previous Studies

Bhambri et al. (2011) showed the variation in the areal extent of glaciers in the Garhwal Himalaya from 1968 to 2006 using areal extent data from the Corona, Landsat, and ASTER satellite data. In their study, they show evidence of negative glacier change in the Garhwal Himalaya as well as increasing recession rate after 1990 [9]. It is also important to mention that the definition of glacier change in Bhambri et al. (2011) was limited to glacier extent alone, whereas this paper aims at the surface area of lakes on this same line, and a different epoch. Terrain-flattened Sentinel-1 products, adaptive SAR water mapping [5], and glacier lake mapping with machine-learning algorithms are not investigated here but are also promising research directions.

VI. Conclusion

A fixed-threshold Sentinel-1 VV water-area pipeline was applied for both lakes. Optical quality control was used to identify a layover/shadow artefact at Chorabari Tal and correct the coordinate error at Vasuki Tal.

Chorabari Tal had a range of 0.00 to 4.09 ha, with a mean of 0.19 ha; non-zero values were principally observed in March and April, when wet-snow contamination may have occurred. Vasuki Tal had a range of 0.27 to 10.34 ha, with a mean of 4.01 ha; a polygon in the vicinity of Vasuki Tal (Google Earth Pro, 1 Nov 2025) gave an area of 7.8 ha, which is larger than the 2019 to 2024 SAR mean area of Vasuki Tal.

Compared to Sentinel-2 MNDWI on 3 dates, SAR differences were 8.0%, 122.4% and 16.0%, respectively. The inconsistency across the three dates, particularly the large discrepancy on one date, means that these comparisons are insufficient to establish classifier accuracy. Anomalies ranged from four to seven depending on the baseline and therefore should not be treated as detection thresholds. The 17-day temperature lead (Pearson correlation coefficient $r = 0.356$) is descriptive and may reflect shared seasonality rather than a causal relationship.

Future work should evaluate terrain-flattened γ^0, geometry-based layover/shadow masking, adaptive thresholds, a minimum of 20 date-pair comparisons, slope-cutoff sensitivity, and deseasonalised/prewhitened temperature.

Acknowledgments

The author acknowledges the European Space Agency (ESA) for providing Sentinel-1 SAR data through the Copernicus programme and the European Centre for Medium-Range Weather Forecasts (ECMWF) for the ERA5 and ERA5-Land reanalysis products.

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