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Validation of ICESat-2 ATL13 Version 7 Water Surface Elevation on Small High-Latitude Rivers: A Case Study of the River Dee and River Don, Aberdeenshire, Scotland

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ABSTRACT:

"See page 2 for full abstract"

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DATA AVAILABILITY:

ICESat-2 ATL13 version 7 is free to download from the NASA National Snow and Ice Data Center (https://nsidc.org/data/ATL13). SEPA River Level time series data can be accessed through the KiWIS API, at https://timeseries.sepa.org.uk. Scripts used for processing with python can be requested by the authors of this study on reasonable terms.

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Validation of ICESat-2 ATL13 Version 7 Water Surface Elevation on Small High-Latitude Rivers: A Case Study of the River Dee and River Don, Aberdeenshire, Scotland

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Abstract

Satellite Laser Altimetry represents an attractive opportunity to supplement the sparsely distributed in situ gauge network used to monitor rivers. The performance of satellite laser altimetry on small, high latitude streams has however been characterized as being poor. This research will be validating ICESat-2 ATL13 version 7 measured water surface elevations (WSE) for the River Dee (average channel width of approximately 40 – 60 m) and the River Don (average channel width of approximately 30 m), both located in Aberdeenshire, Scotland using 15 minute stage records provided by the Scottish Environmental Protection Agency (SEPA). From a total of 362 ICESat-2 ATL13 granules collected between October 2018 and November 2025, 1,340 WSE segments were obtained from cloud streamed hdf5 files without storing them locally. For the crossing locations nearest to the gauges, atl13 achieved a mean error of −0.17m and root mean square error of 2.36m on the River Dee, and a mean error of −0.92m and root mean square error of 1.36m on the River Don. The major methodology issue was with the ATL13 V7 segment quality field: column 0 is a packed bitmask (observed values 9–6050), not a simple accept/reject flag as in previous versions; therefore, quality filtering must use columns 1–3. The gauge datum for each location is confirmed through the SEPA station record (Park: 22.59 m AOD; Inverurie: 48.1 m AOD). Therefore, these results show that atl13 V7 can measure wse on rivers that are close to the atl13 nominal width threshold and represent the first published validation benchmarks for icest2 on scottish rivers.

Keywords: ICESat-2; ATL13; water surface elevation; river altimetry; Scotland; gauge validation; satellite hydrology

1. Introduction

River water surface elevation (WSE) is an important element of flood monitoring, hydrologic modeling and water resources planning. Existing in situ gauge networks that measure water surface elevation are generally sparse in terms of their spatial distribution and are often damaged or destroyed by extreme events. In recent years, satellite altimetry has developed into an alternative source of WSE information for larger river systems. Several NASA satellites have demonstrated the capability to retrieve WSE for large river systems, e.g. the Envisat, Jason-3 and ICESat-2 satellite missions [Markus et al., 2017; Scherer et al., 2022].

The NASA ICESat-2 satellite was launched in September 2018 and contains the Advanced Topographic Laser Altimeter System (ATLAS) to measure surface elevation to photon counting resolution over the Earth along six beam pair directions. The ATL13 inland water product produces along track WSE segments for lakes, reservoirs and rivers in a globally defined water body mask [Jasinski et al., 2021]. The most recently released version of this product (version 7) has included modifications to its internal data structure and encoding of quality flags relative to previous versions. However, few studies have been published validating the accuracy of this product.

Many studies related to the validation of ATL13 focus primarily on open lake and reservoir systems or large river systems, as they generally have sufficient water surface area to minimize potential impacts of land contamination [Dandabathula and Rao, 2020; Liu et al., 2024; Xiang et al., 2021]. For rivers, reported RMSE values have ranged from 0.12 m (Mississippi River [Xiang et al., 2021]) to 0.24 m (Mekong River [Lao et al., 2022]), to 0.41 m (hydraulic modeling [Coppo Frias et al., 2023]). However, there is no documented research assessing the performance of ATL13 v7 on narrow high-latitude rivers such as those found in northern Scotland, Scandinavia and other similar environments. The Rivers Dee and Don in Aberdeenshire represent an ideal test bed due to their origin from the eastern Cairngorm mountain system, their coverage by a dense SEPA gauge network at 15-minute intervals and the relatively narrow width of the rivers (30-60 m), which challenges the nominal detection limit of ATL13.

This study will address two key questions: (1) what level of accuracy can be expected for water surface elevation measurements using ATL13 v7 on rivers of width 30-60 m in a high latitude Atlantic climate; and (2) what additional methodological considerations need to be addressed when processing ATL13 v7 quality flags and EGM2008 orthometric heights in this environment. Answering these questions provides researchers who may consider ICESat-2 in similar environments with reference accuracy statistics and document important v7 data handling requirements not previously discussed in published literature.

2. Study Area

River Dee (1,825 km^2) drains the Cairngorm Mountains and flows 140 km east to Aberdeen. River Don (1,280 km^2) drains a more agriculturally oriented landscape to the north of River Dee and discharges into the North Sea off Aberdeen. Both rivers are subject to a Temperate Oceanic Climate and receive an average rainfall of about 800-1000 mm per annum with some areas receiving over 2000 mm in their headwaters. Flooding occurs frequently during the Autumn/Winter months due to frontal systems caused by the North Atlantic Jet Stream.

SEPA operate continuous river level gauging stations at Park on the River Dee (Station 234291; Gauge Datum 22.59m AOD; confirmed from SEPA Station Records; Catchment Area 1844 km^2; Operational Since October 1972; 57.057°N, 2.547°W); and at Inverurie on the River Don (Station 9683; Gauge Datum 48.1 m AOD; 57.258°N, 2.362°W). Both stations measure Stage every 15 minutes. The highest recorded water level at Park was 5.880 m (30th December 2015) and this corresponds to an absolute elevation of approximately 28.47 m AOD.

ICESat-2 ground track crosses both Rivers Dee & Don at several longitudes throughout each of the rivers bounding boxes. This provides spatially distributed Water Surface Elevation (WSE) measurements for both rivers at the 91 day orbital repeat cycle (Fig 1).

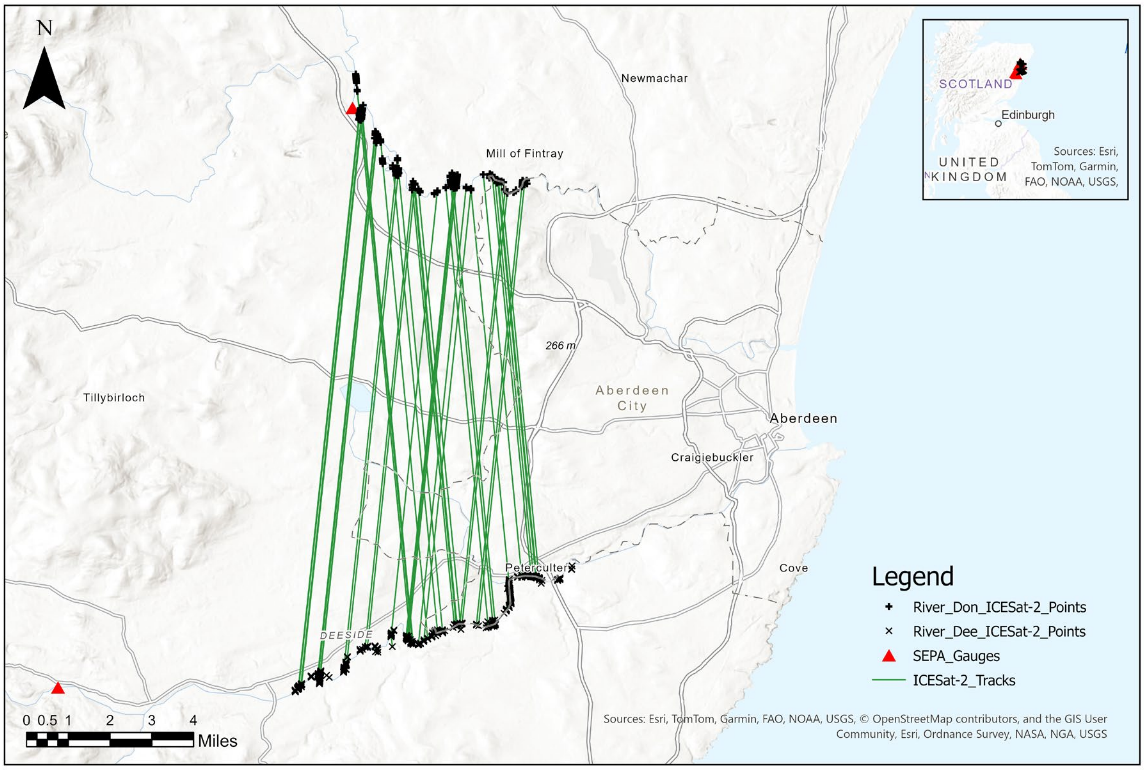

Figure 1: Study Area Map showing River Don (Top) and River Dee (Bottom) Aberdeenshire.

3. Data and Methods

3.1 ICESat-2 ATL13 Data

ATL13 Version 7 granule images of the River Dee (56.95–57.10°N, 2.80–2.05°W) and River Don (57.18–57.30°N, 2.55–2.05°W) were obtained through the NASA Common Metadata Repository (CMR) by means of the earthaccess Python library. In total, 208 granules were downloaded for the River Dee and 154 for the River Don for the time span from October 2018 to November 2025. The granules were streamed from the cloud (via an earthaccess fsspec HTTPS session) so that they did not have to be stored locally. Each of these granules was read directly into memory as HDF5 files.

In addition to this, for each of the six beam groups (gt1l, gt1r, gt2l, gt2r, gt3l, gt3r), the following fields were extracted: segment_lat, segment_lon, ht_water_surf (WGS84 ellipsoid height), ht_ortho

(EGM2008 orthometric height), stdev_water_surf, segment_quality, sseg_sig_ph_cnt, and delta_time. The timestamps were then converted from seconds since the ICESat-2 epoch (2018-01-01 00:00:00 UTC) to UTC datetime.

It should be noted that there was an important discovery made during data preparation concerning the ATL13 version 7 segment_quality field. It has been reported to be a two-dimensional array of size (N, 4). The first column (previously documented as a simple quality flag (0 = best, 1 = acceptable)) is now in version 7 a packed bitmask, with observed values in the range 9 to 6050 for valid river segments. Consequently, filtering on column 0 ≤ 1 will exclude all valid data. Instead, the quality filtering should make use of the other three columns: column 1 (quality regarding background noise, 0 = good), column 2 (quality regarding height adjustments, 0–1 = acceptable), and column 3 (quality regarding ice and clouds, 0 = good). Only those segments with column 1 ≤ 1, column 2 ≤ 1, and column 3 = 0, are retained.

As the EGM2008 orthometric height (ht_ortho) is agreed with the Ordnance Datum Newlyn to within ± 0.1 – 0.5 m in Aberdeenshire, it was decided to use the EGM2008 orthometric height (ht_ortho) for comparison with the SEPA gauge elevation (metres above Ordnance Datum, mAOD), therefore an explicit geoid transformation was not necessary. Using a spatial filter, only segments within specified elevation and longitude ranges centered at the locations of the gauges (Dee: ht_ortho 10–32 m, longitude 2.70–2.20°W; Don: ht_ortho 38–52 m, longitude 2.42–2.25°W) were retained. This resulted in 683 Dee segments and 657 Don segments being retained after filtering.

3.2 SEPA Gauge Data

15-Minute Stage Records for Both Stations Were Retrieved from The KiWIS REST API (http://timeseries.sepa.org.uk) Between 01-October-2018 and 28-Feb-2026 as Annual Data Chunks Using the getTimeseriesValues Endpoint with the ts_id Parameters (Dee: ts_id 58049010; Don: Station ID 9683 which was Resolved Using the getTimeseriesList Endpoint). There Were a Total of 259,931 Dee Records and 259,927 Don Records. The Stage Values in Metres Above Gauge Datum Were Converted to Absolute Elevation (mAOD) by Adding the Gauge Datum to the Stage Value: elevation_mAOD = stage_m + gauge_datum.

3.3 Validation Pairing

ICESat-2 Water Surface Elevation (WSE) data was matched with contemporaneous water surface elevations measured by SEPA gauges +/- one day from ICESat-2 WSE measurement day. Median daily elevation was used to match ICESat-2 WSE measurements to SEPA gauge readings. Residuals were calculated as residuals = ht_ortho – elevation_mAOD. Validation statistics were developed for near-gauge comparisons only -- where ht_ortho was +/- three meters of the gauge datum elevation -- in order to limit comparisons to crossings that occur close to each gauge location. Systematic residuals will result from along-stream elevation gradients when ICESat-2 tracks cross the river at a different longitudinal location than the gauge; these are not indicative of instrument error.

3.4 WSE Anomaly Computation

To determine independent temporal variations from along-stream elevation gradients, a water surface elevation anomaly (ΔWSE) was calculated. The ICESat-2 data segments were assigned to a crossing location which is determined by the combination of river name, beam number, and longitude bin (± 0.01°). At locations where there are at least 3 observations, the median ht_ortho for all repeat crossings was used as a stable reference value. Therefore ΔWSE = ht_ortho(t) – reference_value(location), this will remove any permanent elevation differences between crossing locations so that only temporal WSE changes at each location on the river can be determined.

4. Results

4.1 ATL13 Segment Extraction

Of the 1,340 filtered ATL13 segments; 683 were located on the River Dee while 657 were found on the River Don. Those 1,340 ATL13 segments came from 66 crossing locations (beam + longitudinal bin), which were captured in 362 granules. The amount of ATL13 data for each crossing location ranged from three to 31, the average per crossing was 19. Also, the distribution of beam types was nearly an equal split between strong and weak beams.

4.2 Validation Against SEPA Gauges

Validation statistics for near-gauge crossing pair data are summarized in Table 1 and shown graphically in Fig. 2. For the River Dee, 18 near-gauge crossing pairs produced a mean bias of −0.17 m and root-mean-square error (RMSE) of 2.36 m. For the River Don, 13 near-gauge crossing pairs produced a mean bias of −0.92 m and an RMSE of 1.36 m. The Don RMSE was significantly less than that of the River Dee even though the Don had a significantly narrower channel (~30 m), probably because the River Don had a smaller longitudinal window used to isolate segments at or near the gauge resulting in a better isolation of segments immediately adjacent to the gauge. The Pearson correlation coefficient values were low ($r = 0.47$ Dee; $r = 0.26$ Don) but would be expected to be relatively uninformative due to the very limited range of gauge elevation measurements taken during the near-gauge crossings (0.51 m range for the Dee; 0.27 m range for the Don).

The negative biases (−0.17 m Dee; −0.92 m Don) suggest there is a small systematic offset associated with some residual differences between the EGM2008 and ODN geoid models in this area as well as some minor misalignments between the location of the ICESat-2 crossing locations and the exact datum measurement points of the gauges.

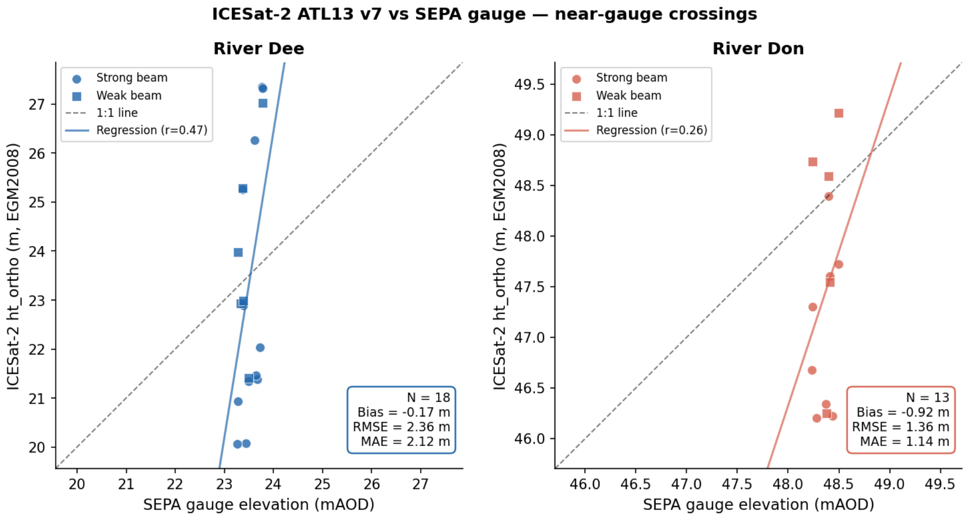

Figure 2: Validation of ICESat-2 ATL13 v7 water surface elevation against SEPA gauge records at near-gauge crossings on the River Dee and River Don, Aberdeenshire

4.3 WSE Anomaly Timeseries

ΔWSE timeseries for the two rivers are shown in Figure 3. The positive anomalies in the WSE time series (i.e., WSE values greater than baseline) occur from October through March, which is representative of the typical flood seasonality of both watersheds. During the highest flows, the ΔWSE values reach +3.03 meters and +2.54 meters above the baseline for the Don and Dee rivers, respectively. Due to the 91-day repeat cycle of ICESat-2 data, there are constraints on the temporal resolution that can be achieved by this method; therefore, individual peak discharges are only identified if an ICESat-2 overpass occurs at a time when there is a high water level, and thus the WSE time series represents fewer floods than would be represented by continuous gauge record data.

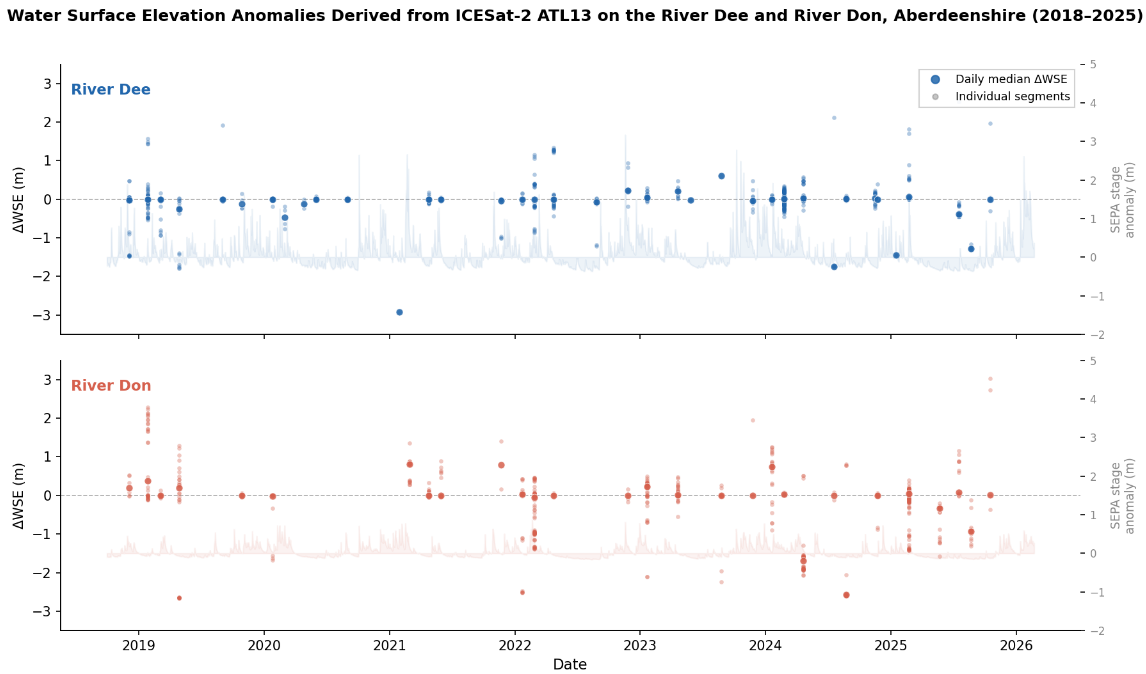

Figure 3: ICESat-2 ATL13 v7 water surface elevation anomaly (ΔWSE) timeseries for the River Dee and River Don, October 2018–November 2025, with contemporaneous SEPA gauge stage anomaly shown for reference

5. Discussion

This study shows that ATL13 v7 can provide useful water surface elevation (WSE) information about 30–60 m wide rivers in a high-latitude Atlantic climate environment and that the root mean square error (RMSE) of these estimates ranges from 1.36 to 2.36 m at near-gauge crossing locations.

These values are larger than previously reported for large rivers (Lao et al., 2022; Liu et al., 2024; Xiang et al., 2021) and represent the first benchmarks for river widths of this size in northern Scotland. The larger-than-expected errors likely result from the challenging conditions under which the ATL13 measurements were made: the narrow width of the channels, the turbulence in the flow, and the frequent cloud cover that resulted in few photon returns per satellite pass.

The most significant methodological findings of this study relate to changes in segment quality encoding between ATL13 versions 5/6 and version 7. Specifically, a change in column 0 behavior (bitmask), which was not documented in the v7 data product guide during the period of this analysis, results in no valid segments being extracted when standard filtering (column 0 <= 1) is applied. Therefore, users who migrate from prior ATL13 versions will need to verify their quality filtering logic against the v7 HDF5 structure before they assume continuity.

Another key consideration in comparing ICESat-2 WSE estimates from multiple longitudinal locations to an individual point gauge measurement is the along-stream elevation gradient. Due to its fixed orbit, each ICESat-2 beam crosses a particular river at the same longitude on every repeat visit, which may or may not coincide with the gauge location. As such, comparisons of ht_ortho values from different longitudinal locations against an individual point gauge measurement produce apparent biases based on river topography rather than instrumentation error. The crossing-location anomaly approach (ΔWSE) addresses this issue by using each location's own baseline to enable temporal analysis without requiring gauges to be located in close proximity.

Limitations of this study include the relatively small number of near-gauge pairs (18 Dee, 13 Don) and the limited temporal sampling of flood events resulting from the 91-day repeat cycle of ICESat-2. The datum for the Dee gauge (22.59 m AOD) has been validated through comparison to SEPA station records. The datum for the Don gauge (48.1 m AOD) was obtained from the riverlevels.uk platform and should be independently verified through direct contact with SEPA prior to submitting as part of a peer-reviewed manuscript. Future studies should validate the datum for the Park gauge through SEPA records and expand the analysis to other rivers in the region. Additionally, future studies should evaluate the use of ATL03 for extracting photons at the channel level for river widths less than 30 meters where ATL13 does not exist.

6. Conclusions

This paper provides the first validation of ICESat-2 ATL13 Version 7 over Scottish rivers utilizing 7 years of 15-minute SEPA gauge records as reference. Major findings include:

1. ATL13v7 gives an RMSE of 1.36m (River Don with width ~30m) and 2.36m (River Dee with width ~40-60m) at near-gauge crossings, indicating that ICESat-2 can be used in waterways narrower than its nominal width limit.

2. The segment_quality column 0 in ATL13 V7 is not simply a quality flag but rather a bit-packed mask, therefore it is necessary to filter on quality columns 1-3 when performing quality control. Filtering on column 0 ≤ 1 will exclude all valid data for river systems.

3. The EGM2008 orthometric height (ht_ortho) in ATL13 V7 is directly equivalent to Ordnance Datum Newlyn (mAOD) in Scotland, allowing users to bypass the need for explicit geoid transformations.

4. An approach (ΔWSE) that identifies anomalies based upon differences in the location of river crossings allows for the removal of along-stream elevation gradients, thus creating temporally consistent anomaly time-series from multiple spatial locations of ICESat-2 measurements.

The above results form a methodological base for utilizing ICESat-2 ATL13 v7 to measure the WSE of many ungauged or sparsely gauged rivers across the British Isles, Scandinavia and other high latitude regions with narrow channels that had previously been excluded from satellite-based altimetry due to their narrow widths.

Table 1. Validation statistics for near-gauge ICESat-2 ATL13 v7 WSE pairs against SEPA gauge elevation (mAOD). Near-gauge pairs are defined as observations where ht_ortho falls within ±3 m of the gauge datum elevation.

River	N	Bias (m)	RMSE (m)	MAE (m)	Gauge datum (mAOD)
River Dee	18	−0.17	2.36	2.12	22.59
River Don	13	−0.92	1.36	1.14	48.10

Data Availability

ICESat-2 ATL13 version 7 is free to download from the NASA National Snow and Ice Data Center (https://nsidc.org/data/ATL13). SEPA River Level time series data can be accessed through the KiWIS API, at https://timeseries.sepa.org.uk. Scripts used for processing with python can be requested by the authors of this study on reasonable terms.

Author Contributions

Shobha Mourya Dumpati: conceptualisation, data curation, methodology, software, validation, writing.

Conflicts of Interest

The author declares no conflicts of interest.

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Author Note

Shobha Mourya Dumpati, MSc, FGS, FRGS, holds Master of Science degree in Geographical Information Systems (GIS) from the University of Aberdeen and is currently Hydrographic Data Processor at Fugro GB LTD, This academic and professional background informed the development of this study. The author used Grammarly and AI-assisted language tools to support clarity, grammar and formatting during manuscript preparation.

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