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Implementation of Database-Supported Analysis for Spatio-Temporal Digital Terrain Models

Ruiqi Liu[1], Paul Vincent Kuper[1], and Martin Breunig [1]

[1] Geodetic Institute, Karlsruhe Institute of Technology, Karlsruhe, Germany

Correspondence: Ruiqi Liu (ruiqi.liu@kit.edu)

ABSTRACT. Digital Terrain Models (DTMs) have consistently been a focus of research in a wide range of fields that require observation and analysis of Earth's surface elevation. However, spatio-temporal changes of DTMs are particularly important as they can provide critical insights into phenomena such as natural hazards and urban development. Analysing these spatio-temporal changes in DTMs usually involves large volumes of data. Therefore, a geodatabase is essential for organizing and managing theses DTM datasets, enabling spatio-temporal retrieval for subsequent analysis. The exemplary implementation of analytical methods for spatio-temporal DTM datasets is the key focus of this paper. We present an event-based time-stamping data model for the management of spatio-temporal DTMs. We also conduct regional statistical analysis across different regions as well as elevation change analysis within the same region over time. Various resampling algorithms are described to harmonize different resolutions of DTMs for elevation change analysis. Finally, we visualize the results of our spatio-temporal analysis in the web-based environment. In the future, further research will also integrate AI methods to enhance spatio-temporal analysis of big DTM datasets.

Submission Type. Model, Analysis, Case Study.

BoK Concepts. AM(AM2, AM6), DM(DM1, DM5), GD.

Keywords. Geospatial Data Modelling, Geospatial Data Management, Spatio-Temporal Data Management, Big Geospatial Data Analysis, Digital Terrain Models.

1 Introduction and Related Work

The Digital Terrain Model (DTM) is a numerical representation of the continuous earth's surface by a large number of discrete points with known xyz coordinates (Miller 1958; Miller et al., 1958), which can contribute to a wide range of applications (Weibel and Heller, 1990). They are especially used to monitor changes over time such as environmental planning, hazard risk management, and digital city twins development. However, it is difficult to observe and represent these changes continuously. A commonly used mathematical approach is to transform continuous space changes into the sum of changes sampled at a set of temporal units (Peuquet 2001; Zhang et al., 2020). Such a series of DTM datasets, being acquired at different timestamps for reflecting space changes over time, we call "spatio-temporal DTM" in this paper.

Similar to other spatio-temporal data, which contain spatial and temporal information (Atluri et al., 2019), spatio-temporal DTM datasets can reflect huge volume of data. In our research, one of the most popular methods for obtaining medium-scale DTM datasets is used: Airborne Laser Scanning (ALS) (Kraus and Pfeifer, 2001).

Due to the large volume of spatio-temporal DTM datasets, it is essential to manage them in a geodatabase. For the evaluation of open source big geospatial raster data storage, (Hu et al., 2018) classified databases supporting the management of raster data into Object-Relational Database Management Systems such as PostgreSQL/PostGIS (*https://postgis.net*), Array-based DBMSs such as RasDaMan (Baumann et al., 1997), and NoSQL DBMSs such as MongoDB (*https://www.mongodb.com*). Based on these geodatabases, further DTM analysis can be conducted. For example, (Breunig et al., 2010) developed a prototype 3D/4D geodatabase to support the analysis of landslides. (Elmqvist et al., 2001) created a symbolic structure to detect terrain features such as ditches or ridges. However, several challenges still remain in effectively managing and analysing spatio-temporal DTM raster data. Firstly, to the knowledge of the authors, there is no appropriate model designed specifically for the management of spatio-temporal DTM datasets. Furthermore, it is still an issue to compare DTM datasets of the same region with different resolutions. Finally, in existing geodatabases, analysis results cannot be directly visualized on a map, as part of the graphical use interface. In the following, these gaps are addressed by describing the implementation of methods for spatio-temporal analysis to:

- Manage spatio-temporal DTM datasets in an appropriate geodatabase.
- Compare the elevation of DTM datasets of the same region at different timestamps with different resolutions (Haunert and Sester, 2005).
- Visualize elevation change results on a map.

We aim to develop a geodatabase to close these gaps, which can provide a more efficient and effective approach to spatio-temporal DTM analysis. Preliminary work has been carried out under (Liu, 2024).

In contrast to the software libraries of the University Corporation for Atmospheric Research (UCAR), we do not access large volume DTMs by netCDF files (Network Common Data Forms) in main memory, but directly in a geodatabase to integrate advanced analysis functions and retrieval methods. NetCDF may then be used as an import and export format, if needed, to transfer DTMs from the geodatabase to other geo-software.

2 Data and Implementation

2.1 Study area and data

The study area in this paper is located in Baden-Württemberg, a state in Southwest Germany, showing the complexity of terrain such as mountains, forests, and river valleys. Multiple test DTM datasets in the GeoTIFF format have been provided by the State Office for Geoinformation and Land Development (LGL) through three ALS flight campaigns held at different timestamps. Figure 1 shows the resolution difference of these campaigns. All three campaigns cover the same area, but the DTM datasets resolution changes, with ALS_1 (2000-2005) providing 1x1m resolution, and ALS_2 (2016-2021) and ALS_3 (since 2022) providing 0.25x0.25m resolution.

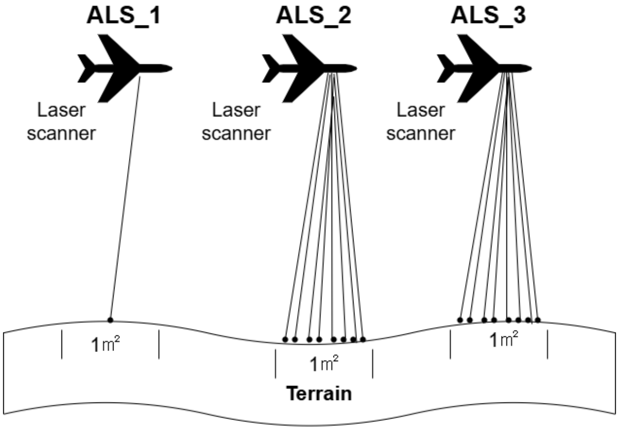


Figure 1. The acquisition of DTM datasets.

2.2 Implementation of DTM datasets Management

For the efficient management of spatio-temporal DTM datasets, we apply a model named the "Event-Based Time-Stamping Data Model (ETSDM)", which integrates the strengths of both the snapshot-based model (Armstrong, 1988) and the event-based model (Peuquet and Duan, 1995). Similar to the snapshot model, ETSDM organizes the DTM datasets into different time-stamping layers. ETSDM also integrates the principles of the event-based model that focuses on dynamic changes. It considers an event as a collection of actions that are related to the elevation changes of DTM datasets being realized in the geodatabase as *generation*, *import*, and *update*.

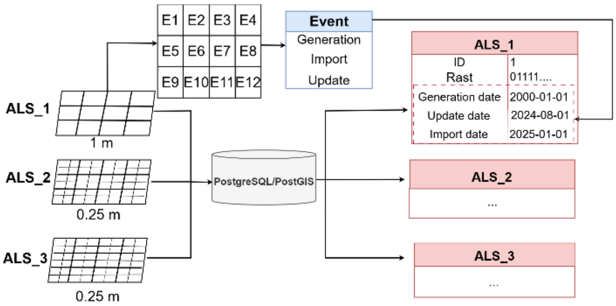


Figure 2. The model based on PostgreSQL/PostGIS.

As Figure 2 shows, this model is developed based on PostGIS. From the perspective of layers, in this case, 36 DTM datasets acquired from three campaigns will be respectively stored into corresponding tables: ALS_1, ALS_2 and ALS_3, with each table storing 12 DTM datasets. From an event perspective, DTM datasets at each timestamp can be represented as events E1, E2, …, and E12, with actions in the event such as *generation, import*, and *update* being recorded as dates in the table.

2.3 Implementation of Analysis Services

2.3.1 Resampling algorithms

Resampling is an important step for spatio-temporal analysis, which can be applied for reducing data size while preserving key regional characteristics or for harmonizing the resolution of different DTMs. We have evaluated various resampling algorithms: the *nearest neighbour interpolation*, the *bilinear interpolation* and the *specific value interpolation* respectively in QGIS.

The *nearest neighbour interpolation* assigns each new pixel value as the value of the original pixel which is the closest to it (Parker et.al, 1983). In the down-sampling process, the value of the bottom-right pixel of each block is used as the value for the corresponding region after resampling. In the up-sampling process, the value for each block in the original dataset remains unchanged to fill the corresponding area in the up-sampled dataset.

The *bilinear interpolation* is to determine the output pixel value by the weighted average of the values of the four nearest pixels from the original pixel (Dasgupta and Kumar, 2022). The bilinear interpolation formula (Smith, 1981) for a point (x, y) inside the unit square defined by points (i, j), $(i + 1, j)$, $(i, j + 1)$, and $(i + 1, j + 1)$ with weighted values (a, b), and corresponding pixel values $F\ (i + 1)$, $F\ (i + 1, j)$, $F\ (i, j + 1)$, and $F\ (i + 1, j + 1)$ is given by Eq. (1):

$$f\ (x,y) = (1 - a)(1 - b)F\ (i,j) + a(1 - b)F\ (i + 1,j) + (1 - a)bF\ (i,j + 1) + abF\ (i + 1,j + 1) \qquad (1)$$

In the down-sampling process, each new pixel value after resampling will be at the centre of the right-bottom value of each block. For the up-resampling, the four corner points will be consistent with previous values. The remaining pixels will be calculated by the weighted average of four surrounding points.

The *specific value interpolation* is to assign the resampled pixel values a specific value, such as the minimum, mean, or maximum value of the corresponding region. In each block, the corresponding min or mean value will be chosen as the resampled result.

2.3.2 Workflow of Spatio-Temporal Analysis

The spatio-temporal analysis is composed of two parts: regional statistical analysis and elevation change analysis. Regional statistical analysis aims to retrieve all DTM datasets within a specific spatial or temporal range to extract basic terrain statistical characteristics. Elevation change analysis focuses on the computation of the elevation change at each terrain point by comparing DTM datasets in the same spatial region at different timestamps. This approach provides historical insights into the detailed changes. Figure 3 shows the workflow of the spatio-temporal analysis. Before the analysis, it is essential to handle spatio-temporal queries to retrieve the region of interest. The query results are transferred to PostgreSQL\PostGIS through Node.js, which serves as the connection of the front-end client and the database. We also conducted experiments with the management of DTMs in RasDaMan (Baumann et al., 1997).

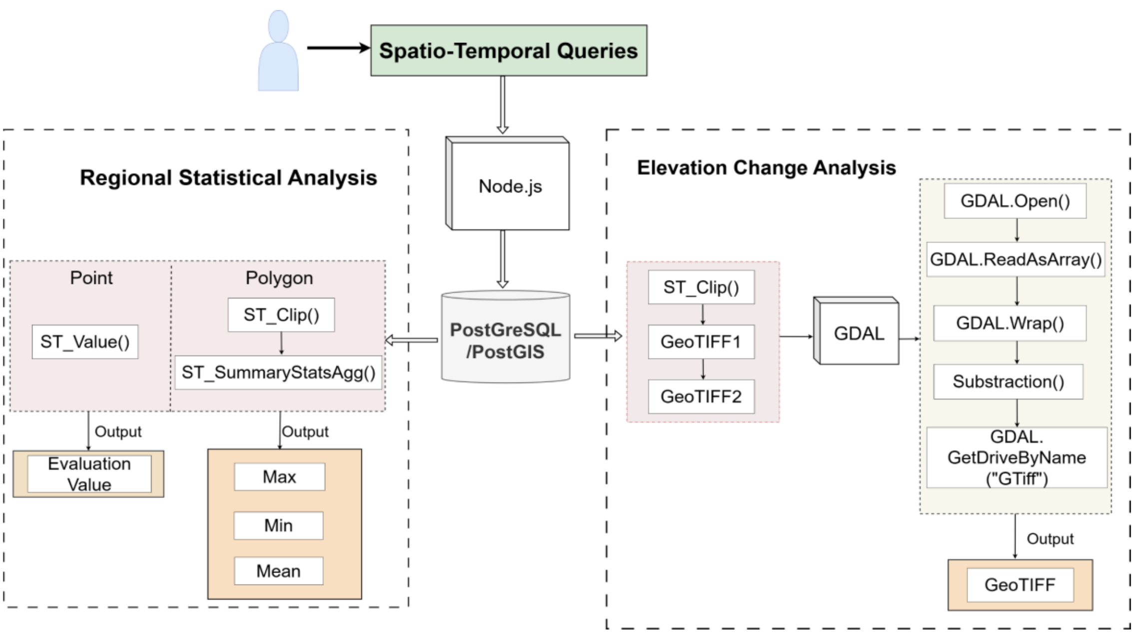


Figure 3. Workflow of spatio-temporal analysis.

However, we chose PostGIS as our main geodatabase, because the better support of vector data. For the regional statistical analysis, the specific value of a point or statistics of a region can be acquired. For the elevation change analysis, firstly, the two related DTM datasets are queried in PostGIS and exported as GeoTIFF files. Then the two GeoTIFF files are imported into GDAL to compute the elevation change. If the resolution of the two GeoTIFF files is different, the GeoTIFF file with the lower resolution will be up-sampled to the same resolution as the other one. If they have the same resolution, their pixel values can be subtracted directly to compute the elevation difference. Finally, the result is exported as a new GeoTIFF file.

2.4 Implementation of Analysis Result Visualization

After calculating elevation changes, it is important to visualize the analysis results on a map. Depending on the size of the results, there are two visualization methods shown in Figure 4. For smaller datasets, the results are directly exported as GeoTIFF files and saved locally. For larger datasets, the results are stored in PostGIS and connected to Geoserver (Geoserver, 2025), which provides OGC web services such as WMS (Web Map Service) and WCS (Web Coverage Service). As well known, WMS defines an HTTP interface to request map images (Scharl and Tochtermann, 2009), while the WCS standard interface enables access to coverage data (Baumann, 2010).

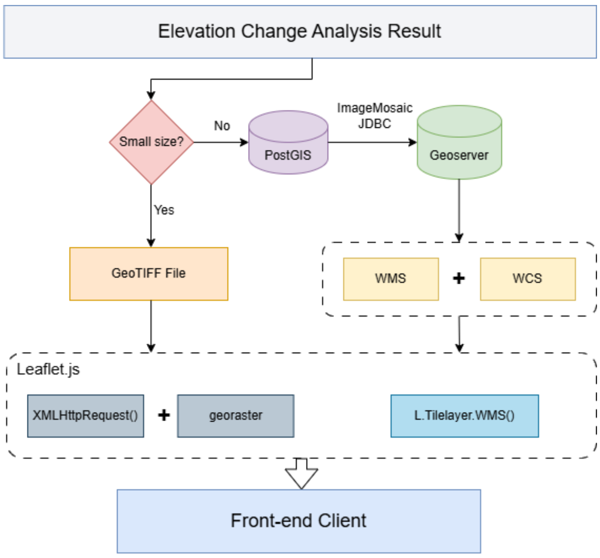
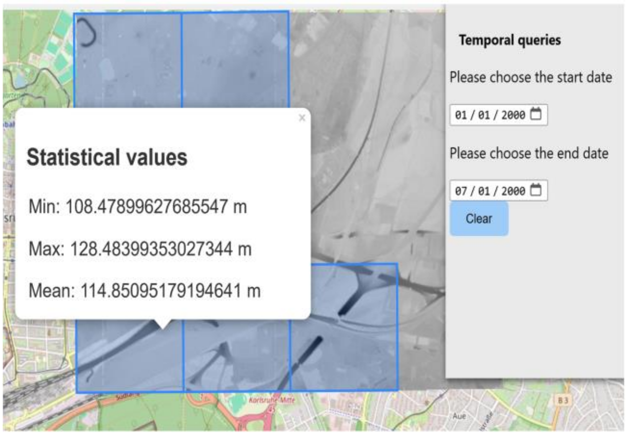
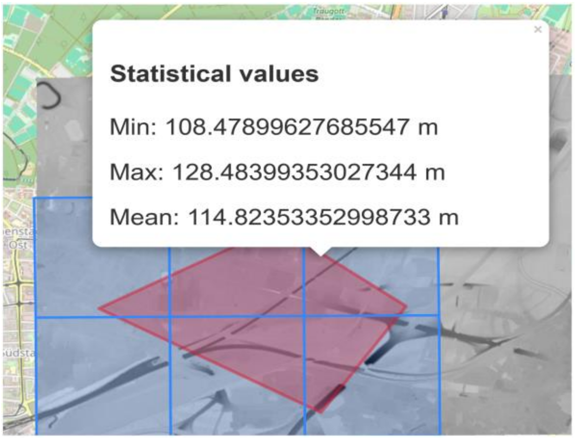


Figure 4. Workflow of elevation change analysis result visualization.

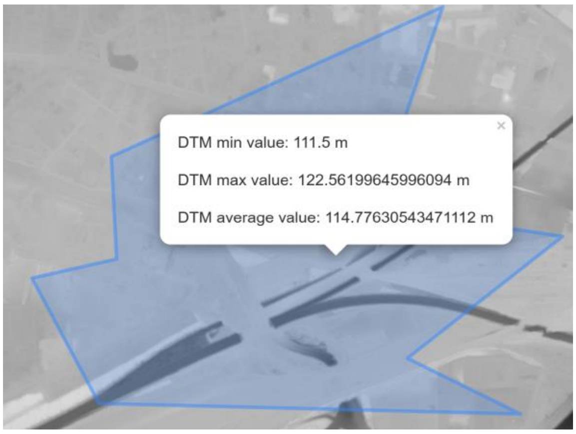


(a) Regional statistics by temporal database queries.



(b) Regional statistics by spatial database queries.

(c) Regional point database query.



(d) Regional polygon shape database query.

Figure 5. Workflow of spatio-temporal analysis.

Leaflet.js, the lightweight Javascript library for interactive maps (Leaflet, 2025), can visualize GeoTIFF files via the *georaster* package, and visualize WMS layers through the interface *L.Tilelayer.WMS()*.

2.5 Data and Software Availability

Scripts to set up the geodatabase are available at https://github.com/Ruiqi627/GeoDBMS-for-DTM-data.

3 Results

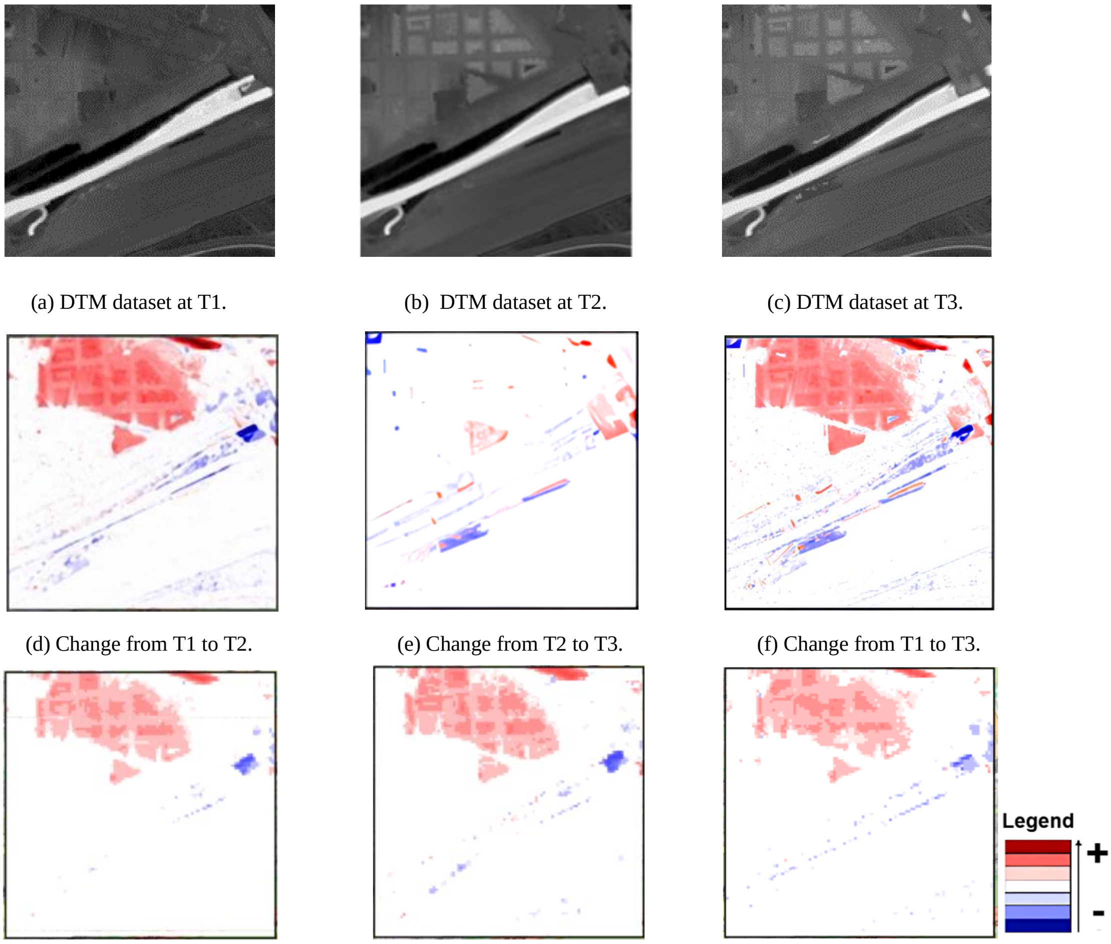
3.1 Regional Statistical Analysis

The regional statistical analysis is for users to better understand the elevation situation within the region of their interest. As Figure 5 shows, there are two approaches to ensure the analysis of a region. The first method is to retrieve regular DTM datasets based on temporal or spatial database queries. DTM datasets corresponding to the query conditions will be selected, and statistical values are then calculated for the region. The second method is for users to create any polygon shapes themselves or select specific points, rather than using regular DTM datasets as the smallest querying unit. Users can obtain the elevation value by clicking on a point or calculate statistical values by drawing an arbitrary polygon. The statistical analysis is then performed exclusively within the bounds of the drawn region.

3.2 Visualization of Elevation Change Analysis

For a single region, Figure 6 (a) - (f) is an example to generate the elevation change from T1 to T2, T2 to T3, and T1 to T3, where T represents the timestamp of the corresponding ALS. The deeper red areas reflect the increasing elevation, and the deeper blue areas show a decrease in the elevation value.

To better illustrate the differences among various resampling methods, we down-sampled the resolution from 0.25 m and 1 m to 10 m using the specific value resampling algorithms: max-resampling, mean-resampling, and min-resampling to calculate the elevation



(a) DTM dataset at T1. (b) DTM dataset at T2. (c) DTM dataset at T3.

(d) Change from T1 to T2. (e) Change from T2 to T3. (f) Change from T1 to T3.

(g) Mean-Resampling. (h) Max-Resampling. (i) Min-Resampling.

Figure 6. Elevation changes from T1 to T3 (Liu et al. 2025).

change from T1 to T2. As Figure 6(g) – (i) shows, the results indicate that max-resampling presents the most significant changes, suggesting that the maximum values within each pixel area change most significantly during the time. While min-resampling shows less changes in the corresponding region. Compared to max-resampling and min-resampling, mean-resampling involves fewer areas with changes, indicating that the elevation changes by mean-resampling are relatively stable. For multiple regions, Figure 7 demonstrates the elevation change of 12 DTM datasets from T1 to T2 queried via WMS.

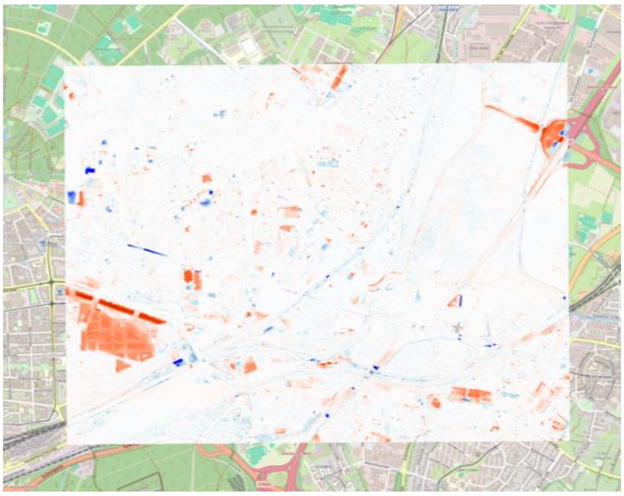


Figure 7. WMS query result of the elevation change from T1 to T2.

When the user wants to save a specific region, he can apply WCS to download the corresponding extent.

4 Conclusion and further research

This paper focused on the exemplary implementation of spatio-temporal DTM datasets analysis, discussing its management, analysis methods, and result visualization. For the management of spatio-temporal DTM datasets, we proposed an Event-based Time-Stamping Data Model and realized it based on PostGIS. Then we applied regional statistical analysis to extract key terrain characteristics and elevation change analysis to track detailed historical changes, and discussed the results of different resampling algorithms. For the visualization of database query results, when the data volume is relatively small, the results can be saved locally as GeoTIFF files. However, when the elevation change analysis involves multiple regions, Geoserver may be used.

Further research will incorporate AI methods for spatio-temporal analysis, such as the automatic detection of regions with the most significant changes, combined with land-use classification, to analyse the underlying drivers of these changes, and predict future trends using machine learning models.

Declaration of Generative AI in writing

The authors declare that they have not used Generative AI tools in the preparation of this manuscript. Specifically, the AI tools were utilized for language editing, improving grammar, and sentence structure, but not for generating scientific content, research data, or substantive conclusions. All intellectual and creative work, including the analysis and interpretation of data, is original and has been conducted by the authors without AI assistance.

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