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Improving 3D Geostatistical temperature model of Germany for shallow geothermal development

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ABSTRACT

Shallow geothermal energy (<400 m) is readily accessible and can be rapidly scaled using heat pump technologies, offering a significant advantage over semi-deep and deep geothermal resources. In alignment with Germany's heat transition goals, the WärmeGut project aims to provide critical data to support the expansion of shallow geothermal energy systems. Accurate subsurface temperature data, particularly its lateral and vertical distribution, is essential for the assessment of potential for heat pumps. While the current 3D temperature model of Germany provides temperature profiles down to 5 km below sea level, its resolution in the near-surface range is insufficient for shallow geothermal applications. This study seeks to improve the model within the upper 500 m by integrating additional temperature data from both surface sources (satellite observations and weather stations) and subsurface measurements (groundwater wells and boreholes). Currently, shallow borehole data from Rhineland-Palatinate is corrected for temperature effects related to the drilling process and groundwater pumping. The integrated dataset will be interpolated in 3D space using universal kriging in the ISATIS® software, which accounts for trends in subsurface temperature distribution. This enhanced geostatistical approach will update and refine the Germany-wide 3D temperature model, improving its utility for shallow geothermal energy development. The improved 3D temperature model will be published in the web-based geothermal information system GeotIS after its finalization.

1. INTRODUCTION

Germany's transition to low-carbon heating requires the deployment of technologies that are both sustainable and scalable. Among these, shallow geothermal energy – defined as the use of subsurface systems up to ~400 meters depth – offers a compelling solution due to its year-round availability, low emissions, and compatibility with electrified heat pump technologies (Lund et al 2022). Compared to semi-deep or deep geothermal reservoirs, shallow systems are easier to implement in both urban and rural settings, enabling distributed heating infrastructures that foster local energy resilience.

However, the effective development of such systems depends critically on reliable subsurface temperature data, particularly within the upper few hundred meters. The current 3D geostatistical temperature model of Germany (Agemar et al 2012; Agemar et al 2014), which provides temperature distributions down to 5 km, has been significantly improved through bottom-hole temperature (BHT) corrections (Agemar, 2022), the inclusion of new borehole datasets and applying specific measurement uncertainties in a universal kriging process. While these enhancements improve model predictability at greater depths, the vertical and lateral resolution in the top 500 meters remains insufficient for site-specific geothermal assessments. Additionally, the near-surface thermal regime is influenced by complex and highly variable surface conditions – such as seasonal temperature fluctuations, rainfall, groundwater variability, and anthropogenic structures – that further reduce modeling reliability in this critical zone.

To address these limitations, the WärmeGut project directly targets the improvement of Germany's temperature model for shallow geothermal applications. One of its key objectives is to enhance the geostatistical temperature representation within the 0–500 m depth range. This will be achieved by integrating diverse temperature datasets from satellite land surface temperatures (LST), weather stations, and shallow borehole temperature logs. The borehole logs will be corrected to remove drilling-induced effects and after which, 3D interpolation will be carried out to incorporate spatial correlation and large-scale geological and topographic trends.

The updated model aims not only to improve predictive accuracy, but also to serve as a publicly accessible planning tool. By reducing technical uncertainty and investment risk, this effort supports the accelerated deployment of shallow geothermal systems, aligning with Germany's national heat transition goals (Heim et al 2022).

2. EXISTING TEMPERATURE MODEL

GeotIS (Geothermal Information System), operated by the Leibniz Institute for Applied Geophysics (LIAG) since 2007, is one of Europe's most comprehensive geothermal databases. Initially launched as a web-based GIS platform for visualizing major geothermal facilities in Germany, it provided key parameters such as reservoir temperatures and installed geothermal capacity. Over time, GeotIS expanded to include geological and geophysical data, including 3D temperature models and geologic formations for critical regions like the eastern part of the North German Basin and the central Molasse Basin. By 2010, the 3D temperature model was extended to encompass the entire German territory.

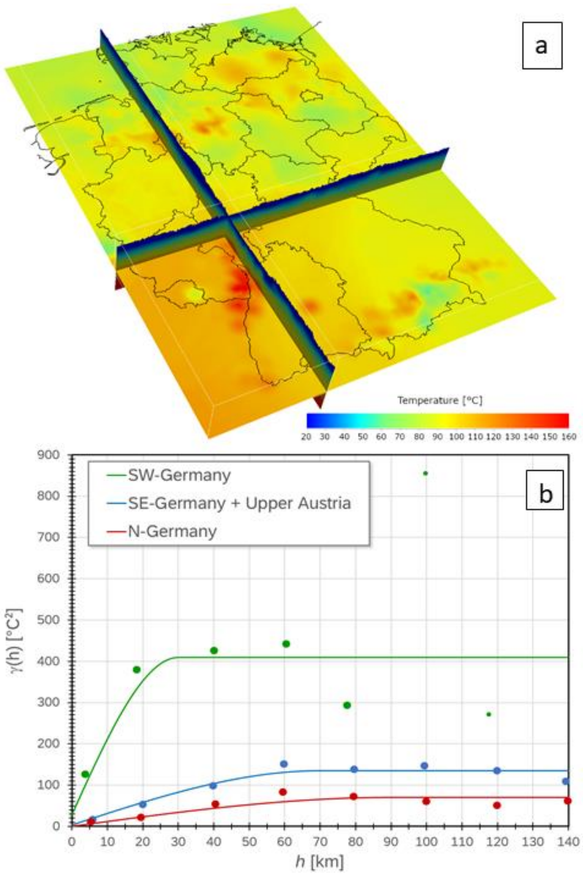

Figure 1: (a) 3d model representing the temperature estimate of the subsurface in Germany and Upper Austria upto 5 km below sea level (b) Semi-variogramme models (spherical) for different areas: South Western Germany, South Eastern Germany + Upper Austria and Northern Germany.

2.1 Data Sources and Quality Classification

The core of the GeotIS temperature model is built upon subsurface temperature measurements sourced primarily from the FIS-GP (Fachinformationssystem Geophysik) database (FIS-GP) (Kühne et al 2003), which served as one of the primary data repositories for it. This system consists of multiple subsystems, with the geothermal subsystem (Schulz and Werner 1989) containing subsurface temperature records from 10,559 wells across Germany.

The quality and reliability of these temperature logs vary considerably based on the measurement technique and well conditions:

- Equilibrium Temperature Logs (ETL) and Reservoir Temperatures, often recorded during steady-state conditions, require minimal correction and were considered ideal for geostatistical modeling. Due to routine monitoring of production wells, reservoir temperatures were available in time series, typically with fluctuations under 1 K.
- Bottom-hole Temperature (BHT) Data, which are recorded immediately after drilling ceases, with measurements at multiple depths, resulting in two or more BHT values per well. However, the temperature around the borehole is frequently disturbed by mud circulation, leading to deviations from true geothermal gradients. To approximate the undisturbed temperature, several correction methods were applied, taking into account parameters such as circulation time, elapsed time after drilling, and well radius (Hermanrud et al 1990). Despite these corrections, residual errors of ±8 to 10 K often persisted (Hermanrud et al 1990; Förster 2001).

2.2 Geostatistical Modeling and Variogram Analysis

The 3D temperature model in GeotIS was obtained by universal kriging on a 1 km × 1 km grid, with prior variogram analysis for three distinct sub-regions (Fig. 1; Table 1):

- Northern Germany (N-Germany): Characterized by conductive heat flow with low spatial variability.
- Southwestern Germany (SW-Germany): Marked by convective influences, particularly in the Upper Rhine Graben.
- Southeastern Germany + Upper Austria (SE-Germany): Displaying mixed conductive and convective heat transfer.

2.3 Model Limitations and Uncertainty

While the kriging estimator effectively managed uncertainty, it tended to overestimate error margins in some areas, like for instance in the Saarland where subsurface temperature uncertainty estimates were based on the variogram of Upper Rhine Graben temperatures.

To solve this problem, we can subdivide the subsurface into sub-models along geothermal play types in order to fulfil the condition of stationarity even more comprehensively. Since the spatial variability of temperature is depth-dependent, the subsurface will also be subdivided vertically into different depth ranges. In the end, all sub-models will be merged into one model. This will result in a major improvement because current geostatistical 3d temperature model is based on three box shaped sub-models, only.

Table 1: Kriging parameters derived from semi-variogrammes for three regions.

	SW-Germany	SE-Germany + Upper Austria	N-Germany
Nugget	30 K^2	4 K^2	1 K^2
Sill	410 K^2	135 K^2	70 K^2
Range horizontal	30 km	70 km	90 km
Range vertical	1000 m	2000 m	2000 m
Type	Spherical	Spherical	Spherical

Additionally, at the near-surface, local deviations between modeled surface temperatures and meteorological data arise due to site-specific conditions, including; soil moisture and groundwater depth, vegetation cover and land use, and topographic relief. These factors introduce variability, raising the statistical error to approximately ±1 K at shallow depths.

The WärmeGut Project specifically addresses surface and near-surface heterogeneities by integrating additional high-resolution datasets from satellite observations, weather stations, and enhanced borehole measurements. This initiative aims to significantly improve the vertical and lateral resolution of the current 3D temperature model.

3. DATA

To address resolution limitations in the upper 500 meters, the WärmeGut project utilizes a composite dataset that includes:

- Satellite-derived land surface temperatures (LST) from MODIS and LANDSAT-8, offering broad spatial coverage and seasonal variability insights.
- Meteorological station data from the German Weather Service (DWD), which provides long-term records for soil temperatures between 5 to 100 cm of depth.
- Borehole temperature profiles from groundwater wells, representing direct subsurface measurements. Where necessary, these are corrected for drilling-induced anomalies.

3.1 Remote sensing data

LANDSAT-8 (LC08) satellite dataset was downloaded from the USGS Earthexplorer website. To cover whole Germany, images from 6 paths and 5-6 rows were used, resulting in a number of over 9000 individual images between time periods of 2013 to 2024.

The LC08 data only has daytime coverage and lacked nighttime data. In order to calculate the average annual LST product for complete day (24 hours), MODIS satellite from the Google Earth Engine (GEE) is used. The MODIS LST products available on GEE are processed using a generalized Split-Window algorithm (Wan et al 1996) with a pair of MODIS daytime and nighttime in seven TIR bands, atmospheric temperature and water vapor. The LSTs used in this study is the daily MODIS LST product， at 1-km spatial resolution. MOD21C1 is the TERRA MODIS LST product, which provide day and nighttime LST at 10:30 a.m. and 10:30 p.m., respectively. Similarly, MYD21C1 is the AQUA MODIS LST product, which provide day and nighttime LST at 01:30 p.m. and 01:30 a.m., respectively.

3.2 In-situ data

The German weather service (DWD) provide derived soil temperature ranging from 5 to 100 cm depth for 487 locations across Germany. These temperatures are calculated by the model AMBETI developed at the agrometeorological research center in Braunschweig (Braden, 1995). Daily temperatures (2013 - 2024) approximated from 11 years of soil temperatures at 5 cm below ground were used.

A total of approximately 620 temperature logs from 330 boreholes across Rhineland-Palatinate were provided by the State Geological Survey (LGB-RLP). The dataset is characterized by a high degree of heterogeneity, with densely logged areas, particularly in the southern part of the region, contrasting with sparsely covered zones. The quality of the logs also varies, as the measurements were collected over a wide timespan between 1971 and 2013 during various measurement campaigns. Additionally, the data are influenced by external factors such as drilling activities, prior groundwater extraction, and seasonal variations, especially in the upper tens of meters of the subsurface.

4. METHODS

4.1 Average Land Surface Temperature

<u>*Landsat-8*</u>

The LST is calculated using the Landsat 8 thermal bands with 100 m spatial resolution. It requires applying a set of equations through a raster image calculator (ArcMap, ArcGIS Pro, QGIS). Here the bands B4 (RED), B5 (near IR) and B10 (IR) were used. The processing steps for LST were carried are shown in Fig. 3.

To minimise the time required for processing, the batch processing of the ArcGIS model builder was used. This made it possible to process all up to 450 individual images of a scene with all individual steps in a single pass. For a reliable surface temperature calculation, it is necessary to ensure that only cloud-free areas are included in the calculation. To do this, the USGS Earth explorer can be configurated that only scenes with cloud-free days are used. However, this method has the consequence that the number of usable images per Landsat scene is very limited. Overall, the number of usable images would be reduced by 95%, which would drastically reduce the reliability of the temperature averages in a scene.

Therefore, a different approach was chosen, which increases the computational effort, but allows the use of all images from a scene in a selected time period: with the tool reclassify in ArcGIS and the QA file, which is available for each scene, a clipping mask can be created, which removes all areas with cloud cover from the resulting LST files. In order to utilise as much cloud-free area as possible in each scene, cloud free shadow areas were also included.

MODIS LST Processing and Co-Kriging with DWD Data

MODIS LST products were processed in GEE for the period 2013–2024 (Gorelick et al 2017). The analysis focused on two primary bands: LST_Day_1km and LST_Night_1km, representing daytime and nighttime temperatures, respectively. Raw pixel values were scaled by 0.02 and converted to Celsius by subtracting 273.15 K. Both layers were clipped to Germany's national boundaries and averaged to compute a 24-hour Mean LST. Finally, the processed LST layer was exported as a GeoTIFF in UTM Zone 32N at 1 km resolution.

To improve the accuracy of surface temperature estimates, the MODIS-derived LST was compared with DWD soil temperature measurements. The comparison yielded a positive linear correlation with an R^2 value of 0.56, indicating reasonable alignment despite differing spatial resolutions. Given MODIS's high coverage but lower accuracy, and DWD's higher accuracy with sparse distribution, the two datasets were integrated using co-kriging. This geostatistical method allowed for spatially continuous temperature fields that reflect realistic boundary conditions and smoothing of local anomalies while preserving large-scale trends in surface temperature distribution. Fig. 2 shows the complete methodology workflow adopted for this study.

4.2 Temperature correction for shallow boreholes

One important factor considered in the data processing of the shallow logs is the effect of previous groundwater extraction. The upward-flowing water is typically warmer and can artificially increase temperature readings in the upper sections of the well, leading to potential overestimations. To account for this effect, a correction based on an advective heat transport approach is applied, compensating for the influence of mixing between deeper and shallower groundwater. Although evaluations are generally based on logs acquired under shut-in conditions, this correction methodology also enables the incorporation of production-time data. This is feasible when the inflow distribution along the well is known — a condition met in approximately 20% of the wells. This methodology was applied to about 5% of the boreholes in the dataset.

The 3D point cloud of temperature measurements is created by integrating boreholes and LST points in ISATIS®.neo software. Trend removal is carried out before semi-variogram fitting. The downward geothermal gradient is calculated though a trend inferred from the data. The Universal Kriging interpolation is carried out with the residual temperature. The interpolation grid with 500 x 500m horizontal, and 20m vertical spacing is used.

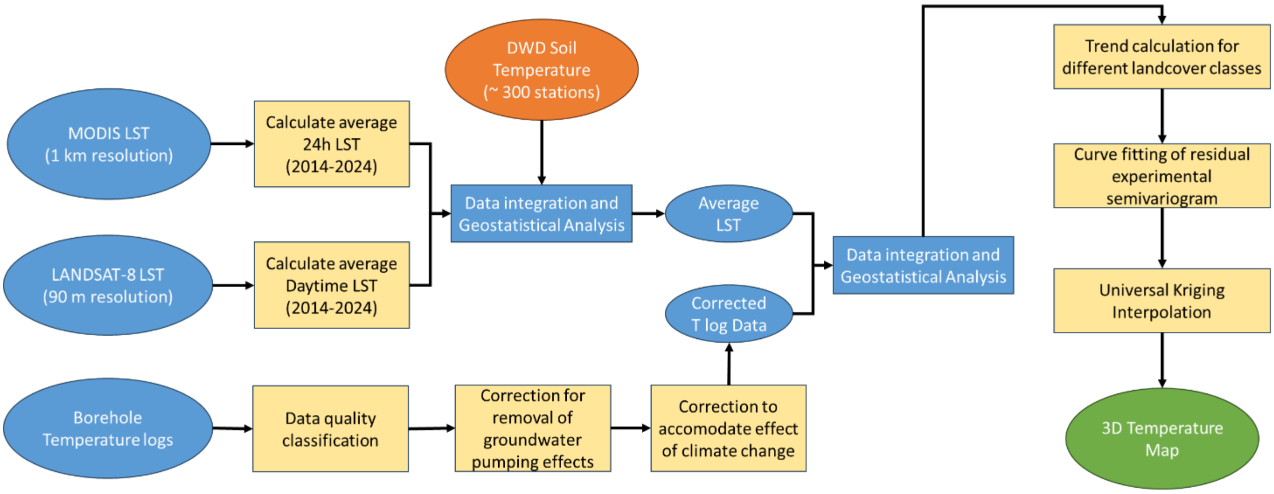

Figure 2: Schematic workflow of the methodology

5. RESULTS AND DISCUSSION

5.1 Land Surface Temperature Models

The average LST derived from Landsat-8 (2013–2024) reveals distinct thermal patterns strongly influenced by land cover types (Fig. 3). Water bodies and high-altitude regions (e.g., Harz Mountains, the Alps) display notably lower LST values, typically below 5°C. In contrast, urbanized zones such as Frankfurt Airport and major industrial areas exhibit elevated LSTs, often exceeding 14°C. Forested regions and agricultural lands present intermediate LST ranges of 6–12°C, with cultivated areas generally registering slightly warmer temperatures than forested zones.

The spatial resolution of Landsat-8 (100 m) provides high-detail surface temperature mapping; however, a significant limitation arises from its reliance solely on daytime thermal measurements. Consequently, the LST obtained from Landsat-8 represents only the average daytime surface temperature, which neglects nighttime cooling effects. Since nighttime thermal data from Landsat-8 is unavailable for the observed period (2013–

2024), complementary datasets are necessary to estimate the 24-hour mean LST.

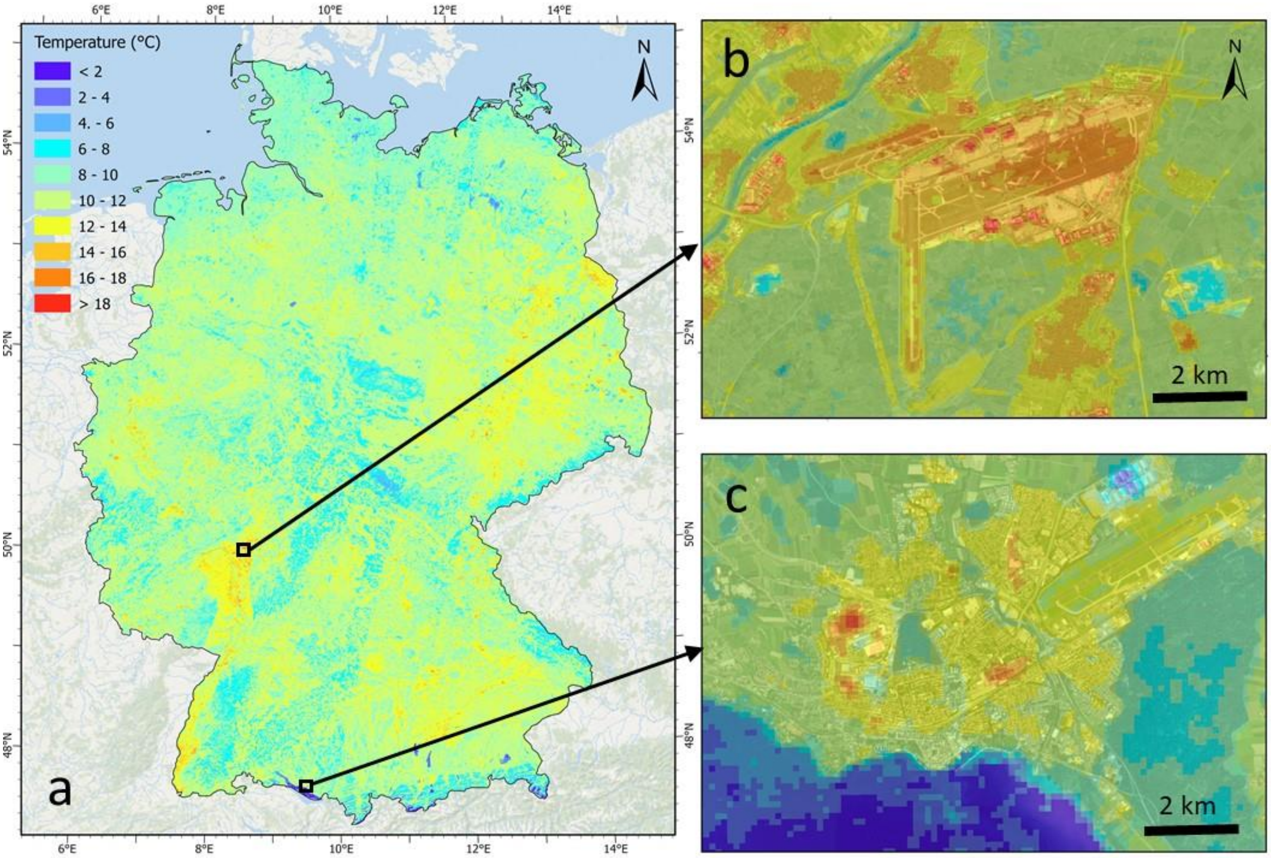

Figure 3: (a) Average LST calculated from Landsat 8 (2013 – 2024) (b) Average LST around Frankfurt airport showing high LST over terminals (c) LST of Friedrichshafen city on the northern shore of Lake Constance.

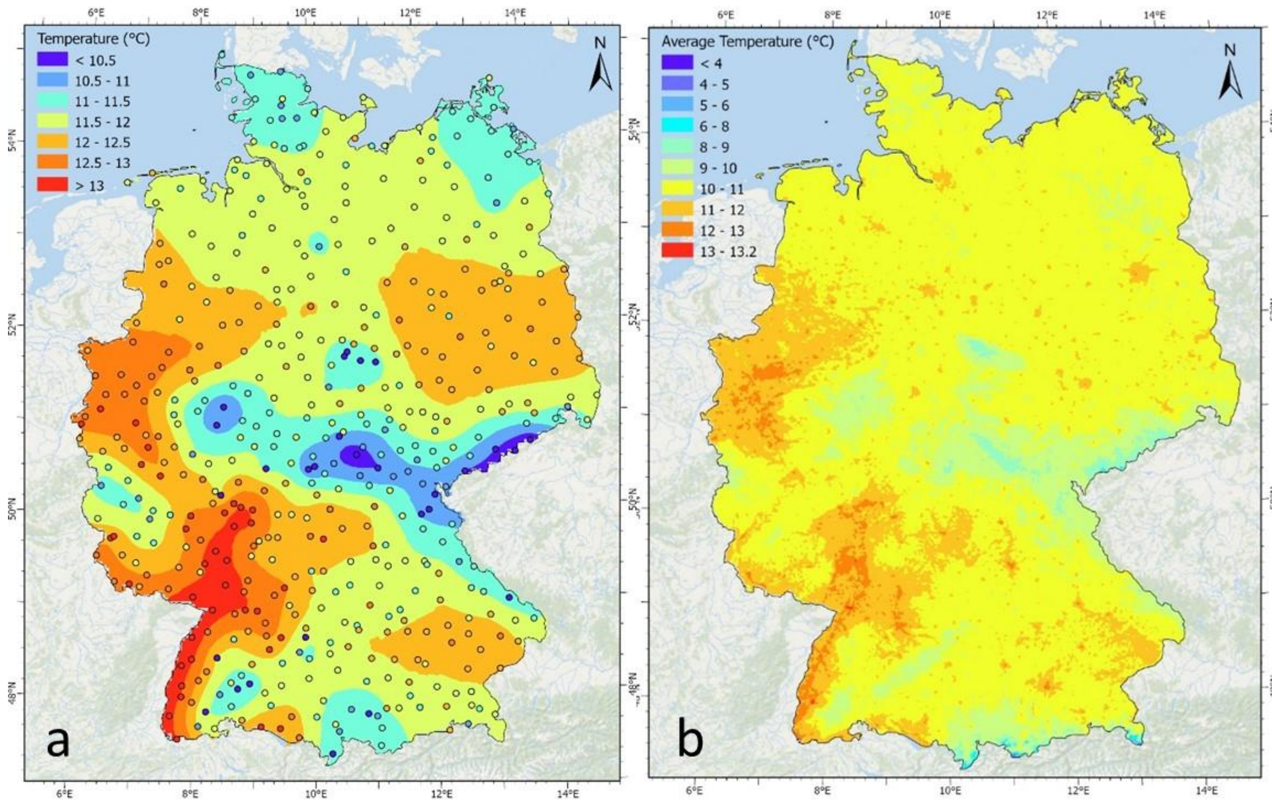

Figure 4: (a) Interpolated (ordinary kriging) average soil temperature at 5 cm below surface from DWD data for the time period 2014-2024 (b) Co-Kriging of DWD soil temperature with MODIS LST.

To address this, MODIS LST products, which include both daytime and nighttime measurements at 1 km resolution, were integrated with Landsat-8 data. Despite its lower spatial resolution, MODIS provides critical nighttime surface data, allowing for the calculation of a 24-hour average LST. However, merging MODIS and Landsat-8 datasets for complete diurnal coverage results in a final resolution of 1 km, sacrificing the fine spatial detail inherent to Landsat-8.

5.2 Co-Kriged Surface Temperature Model

The co-kriged surface temperature model—a fusion of MODIS LST and DWD station data—demonstrates substantial improvements in spatial coherence and surface realism (Fig. 4). This integration leverages the broad spatial coverage of MODIS with the high temporal accuracy of DWD, producing a statistically smoothed temperature field that better represents land-surface heterogeneities.

Significant enhancements were observed in urban regions such as Berlin, Frankfurt, and Munich, where fine-scale thermal patterns were more accurately resolved compared to DWD data alone (Fig. 4a). The fused model more effectively captures urban heat islands (in densely populated areas), vegetation-driven cooling effects in forested zones, and topographical influences in mountainous regions. The enhanced LST model serves as a robust boundary layer condition for subsurface temperature interpolation.

5.3 Shallow Temperature Distribution in Rhineland-Palatinate

In order to derive the shallow subsurface temperature distribution, a detailed analysis of more than 600 temperature logs was conducted. The evaluation of shallow borehole data—corrected for the effects of groundwater extraction—enabled site-specific thermal gradient estimation in Rhineland-Palatinate. Fig. 5 displays the spatial distribution of subsurface temperatures data points over different geological regions. Elevated temperatures are observed in the regions of the Upper Rhine Graben, Mainz Basin, Middle Rhine Graben along with the Moselle and Lahn rivers, while lower temperatures dominate in the Hunsrück and Westerwald (Fig. 5). The temperature in the subsurface is significantly influenced by topography and show a negative trend with increasing elevation above sea level.

Figure 6 shows a preliminary interpolated temperature model obtained by combining LST with the borehole temperature logs. The average deviation is 0.2 K with a standard deviation of 1.2 K, demonstrating the suitability of the approach. Areas previously interpolated using sparsely distributed deep data now show localized thermal patterns, which would help in more accurate geothermal potential assessments at shallow scale. For the extension towards all of Germany, a streamlined data processing workflow will be followed in future (Fig. 2).

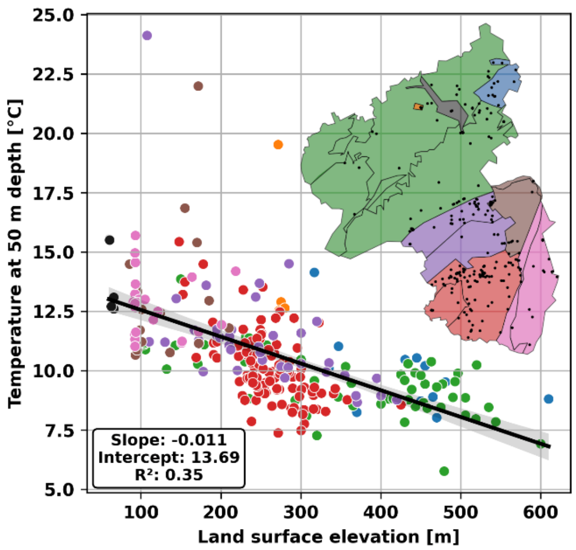

Figure 5: Corrected temperature logs grouped by different geological regions of Rhineland-Palatinate showing distribution and effect of elevation on temperatures at 50m below surface. The higher temperatures are at Upper Rhine Graben (pink & orchid), Mainz basin (grey), Middle Rhine Basin (black), and lower temperatures at Hunsrück (slate), and Westerwald (blue)

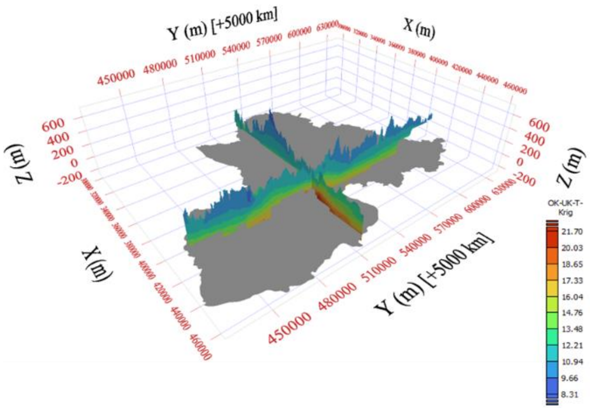

Figure 6: Preliminary 3D interpolated shallow subsurface temperature model of Rhineland-Palatinate

6. CONCLUSION AND OUTLOOK

This study demonstrates a scalable methodology to improve the 3D geostatistical temperature model of Germany for the shallow subsurface (0–500 m). The surface and subsurface temperature datasets including satellite-derived LST, weather station records, and corrected borehole measurements are integrated to achieve higher spatial resolution and to improve local accuracy.

The use of co-kriging to merge the high spatial detail of MODIS LST with the more accurate yet spatially sparse DWD soil temperatures has proven particularly effective in enhancing surface temperature modeling. The resulting fused LST field accurately captures surface heterogeneities caused by urban heat islands, vegetation cover, and topographical variations. This integrated model now provides a more consistent and realistic thermal boundary layer for interpolating shallow subsurface temperatures.

In the Rhineland-Palatinate region, shallow borehole temperature data is corrected for groundwater extraction effects which have facilitated precise thermal gradient estimation at shallow depths. This methodology would serve as vital guide for correcting new borehole data.

Upcoming work will focus on acquisition and integration of borehole and hydrogeological data from all remaining federal states of Germany. Once finalized and validated, the enhanced 3D temperature model will be integrated into GeotIS.

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REFERENCES

Agemar, T., Alten, J.-A., Ganz, B., Kuder, J., Kühne, K., Schumacher, S., and Schulz, R.: The Geothermal Information System for Germany GeotIS, Z. Dt. Ges. Geowiss., 165(2), (2014), 129–144.

Agemar, T., Schellschmidt, R., and Schulz, R.: Subsurface Temperature Distribution of Germany, Geothermics, 44, (2012), 65–77. doi: 10.1016/j.geothermics.2012.07.002.

Agemar, T.: Bottom hole temperature correction based on empirical correlation, Geothermics, 99, (2022), 102296.

Avdan, U., and Jovanovska, G.: Algorithm for Automated Mapping of Land Surface Temperature Using LANDSAT 8 Satellite Data, Journal of Sensors, Volume 2016, (2016), 1–8.

Braden, H.: The model AMBETI - A detailed description of a soil-plant-atmosphere model, Berichte des Deutschen Wetterdienstes, Nr. 195, (1995).

Förster, A.: Analysis of borehole temperature data in the Northeast German Basin: continuous logs versus bottom-hole temperatures, Petroleum Geoscience, 7(3), (2001), 241–254.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., and Moore, R.: Google Earth Engine: Planetary-scale geospatial analysis for everyone, Remote Sensing of Environment, **202**, (2017), 18–27.

Heim, E., Laska, M., Becker, R., and Klitzsch, N.: Estimating the subsurface thermal conductivity and its uncertainty for shallow geothermal energy use—a workflow and geoportal based on publicly available data, Energies, 15(10), (2022), 3687.

Hermanrud, C., Cao, S., and Lerche, I.: Estimates of virgin rock temperature derived from BHT measurements; bias and error, Geophysics, 55(7), (1990), 924–931.

Kühne, K., Maul, A.-A., and Gorling, L.: Aufbau eines Fachinformationssystems Geophysik, Z. Angew. Geol., 2/2003, (2003), 48–53, Hannover.

Li, Z.-L., Wu, H., Duan, S.-B., Zhao, W., Ren, H., Liu, X., et al.: Satellite remote sensing of global land surface temperature: Definition, methods, products, and applications, Reviews of Geophysics, 61, (2023), 1–77.

Lund, J. W., Huttrer, G. W., and Toth, A. N.: Characteristics and trends in geothermal development and use, 1995 to 2020, Geothermics, 105, (2022), 102522.

Schulz, R., and Werner, K. H.: Geothermal resources and reserves: updating of temperature database, in: European Geothermal Update: Proceedings of the 4th International Seminar on Results of EC Geothermal Energy Research and Demonstration, Louwrier, K., Staroste, E., Garnish, J., and Karkoulias, D. (Eds.), 490–499, Kluwer Academic Publishers, Dordrecht, (1989).