QUANTIFYING THE RELATIONSHIP BETWEEN SPATIAL RESOLUTION AND SPATIAL UNCERTAINTY IN SPATIAL ANALYSIS

Subtitle

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Preface

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Abstract

Spatial analysis helps us understand how different features are distributed across space, but the results often depend on the level of detail in the data and how much uncertainty they contain. Spatial resolution decides the level of detail we can see, while spatial uncertainty reflects the inaccuracy caused by data collection, processing, or simplification. In many studies, higher resolution is assumed to give better results, but in practice, it can also increase noise or errors. This study focuses on understanding how these two factors interact and influence the quality of spatial analysis. The main goal is to investigate how spatial resolution affects spatial uncertainty and to see whether there is a balance between them. The hypothesis is that more detailed data do not always mean more accurate results. The research will address two questions: (1) How does spatial resolution change spatial uncertainty? (2) At what level does increasing resolution stop improving the outcome? The analysis will use raster datasets with various resolutions, together with a digital elevation model (DEM) as reference. The data will be processed in QGIS, and statistical calculations will be done in Python to measure and compare uncertainty levels. A watershed area is used as the case study. The results are presented as maps and graphs showing how uncertainty changes with resolution. These findings helps GIS users, environmental researchers choose suitable data and improve reliability of spatial analysis.

Keywords: Data precision; Scale dependency; Error propagation; Geospatial modeling; Analytical reliability;

Abbreviations

DEM..Digital Elevation Model
DROF... Dynamic Resolution Optimization Framework
RMSE.. Root Mean Square Error
URR... Uncertainty Reduction Ratio
MAE...Mean Absolute Error
OLS.. Ordinary Least Squares

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1 Introduction

Optimizing spatial resolution is central to enhancing the reliability of geoscientific analysis. It profoundly impacts the accuracy of resource monitoring, environmental assessment (Siouti et al., 2025), and carbon neutrality decision-making, proving particularly critical in terrain-driven fields such as hydrology, geomorphology (Adeniyi & Maerker, 2024; Le et al., 2025), and watershed modeling. Advances in sensing technology—from drone-based LiDAR to high-resolution satellite systems (Li et al., 2025)—have vastly expanded our capacity to capture surface heterogeneity, achieving unprecedented levels of detail. However, resolution enhancement does not yield linear gains. While improving local detail characterization, it may introduce random noise (Fang et al., 2025), increase data volume, elevate computational demands, and significantly inflate computational costs (Cassetti et al., 2025; Xu et al., 2025). This further complicates the longstanding core balancing challenge in geospatial science: the "resolution-accuracy trade-off."

A growing body of research indicates that topographic and hydrological features exhibit scale sensitivity. Parameters derived from Digital Elevation Models (DEMs), such as slope, curvature, and catchment area, often demonstrate nonlinear responses to changes in grid size. This leads to significant biases in analyses like watershed delineation, erosion modeling, and runoff estimation (Ferchichi et al., 2025; Harroud et al., 2025; Manocha, Kumar, & Kumar, 2025; Şandric et al., 2025). Despite these empirical advances, the quantitative relationship between spatial resolution and uncertainty propagation in DEM-derived topographic attributes remains poorly standardized. Many studies still rely on case-specific calibrations (S. Wang et al., 2025; Z. Wang et al., 2025; Wei et al., 2025) or employ advanced deep learning uncertainty frameworks (Gao et al., 2025; He et al., 2025)—powerful tools that exceed the practical scope of standard geomorphological analysis.

At the watershed scale, recent applied research further highlights this gap. Tools like PyLandslide (Basheer & Oommen, 2024) and the residual random forest framework for soil layer thickness mapping (Abebe et al., 2025) demonstrate growing attention to spatial uncertainty, yet few studies provide systematic, resolution-dependent quantitative analyses explicitly linking measurement scale to the robustness of extracted topographic features. Similarly, while hydrological calibration frameworks like CEASA (Tefera et al., 2025) incorporate spatially adaptive constraints to improve evapotranspiration modeling, the theoretical definition of a "resolution-uncertainty response function" remains unclear in terrain analysis. This limitation persists in other environmental domains—such as drought monitoring (Abebe et al., 2025) and groundwater quality prediction(Tefera et al., 2025)—where scale and uncertainty jointly determine model performance. These issues prevent the objective determination of "optimal resolution," making it difficult to simultaneously maximize analytical accuracy and computational efficiency.

To address these gaps, this paper proposes the Dynamic Resolution Optimization Framework (DROF), designed to model and evaluate the "resolution-uncertainty response" relationship of DEM-derived topographic features in watershed scenarios. This framework integrates mature geospatial tools (QGIS, Python) with quantitative metrics such as Root Mean Square Error (RMSE) and Uncertainty Reduction Ratio (URR) to construct an objective function for determining optimal operational resolution. Unlike heuristic or case-specific approaches, it prioritizes reproducibility, statistical robustness, and practical applicability. Formalizing the "resolution-uncertainty" relationship it provides a transparent, data-driven resolution optimization approach for terrain-driven environmental modeling. This research not only enhances methodological rigor but also improves the reproducibility and interpretability of watershed-scale geoscience spatial analysis.
This is a cross-reference to figure 1.

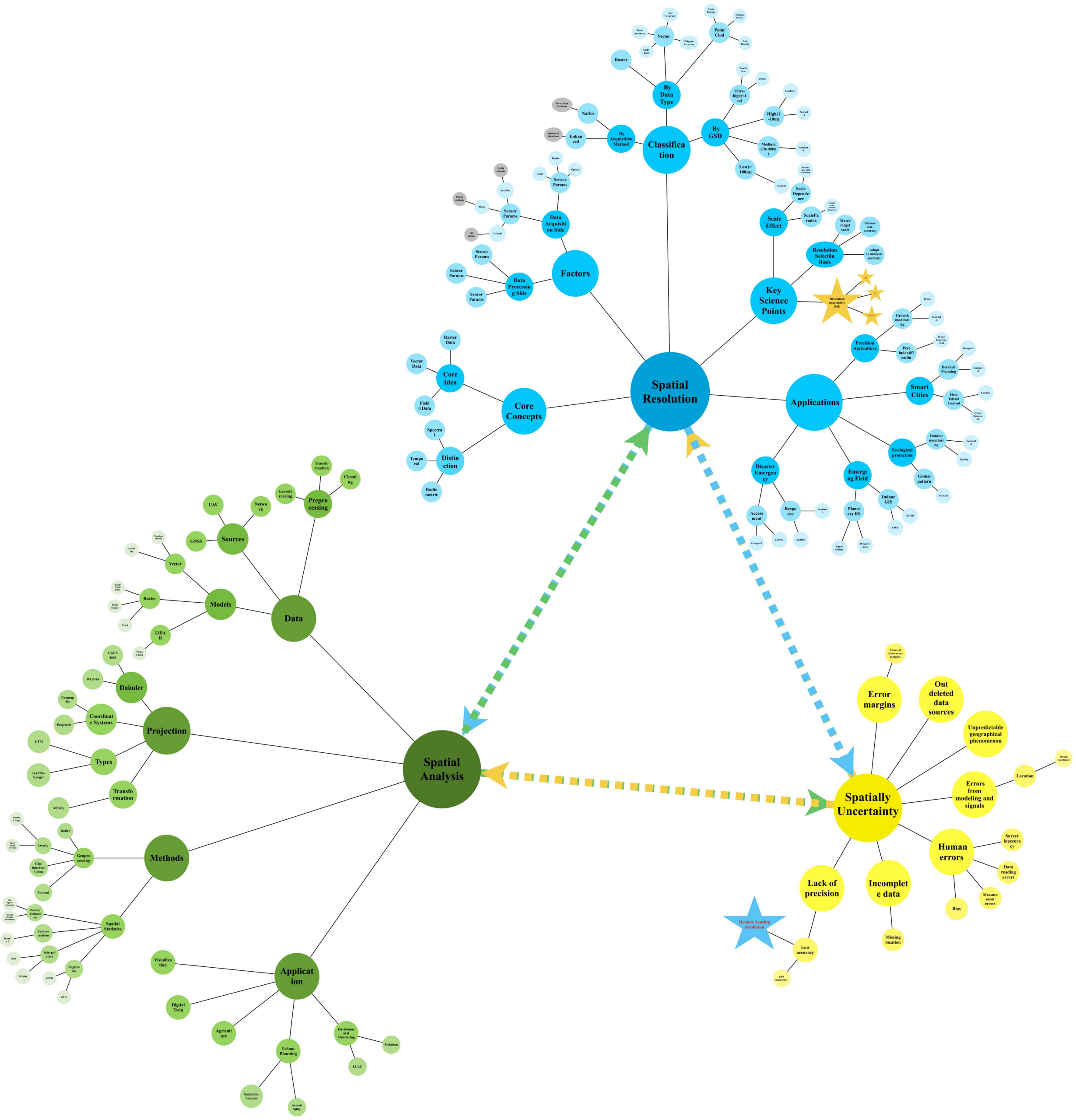

Figure 1: Mind Map of this work

2 Materials and Methodes

2.1 Pilot-site

The study area is the entire Weser River Basin in Germany, chosen for its high terrain diversity from uplands to flat plains. The base dataset is a basin-wide 10 meter (10m) DEM (R_{ref}), sourced from authoritative German or European data programs. This 10m DEM is treated as the ground truth. To ensure computational feasibility, all data processing, including resampling R_{ref} down to resolutions up to 1000 m, is executed using high-performance computing tools (e.g., Python with GDAL or GEE).

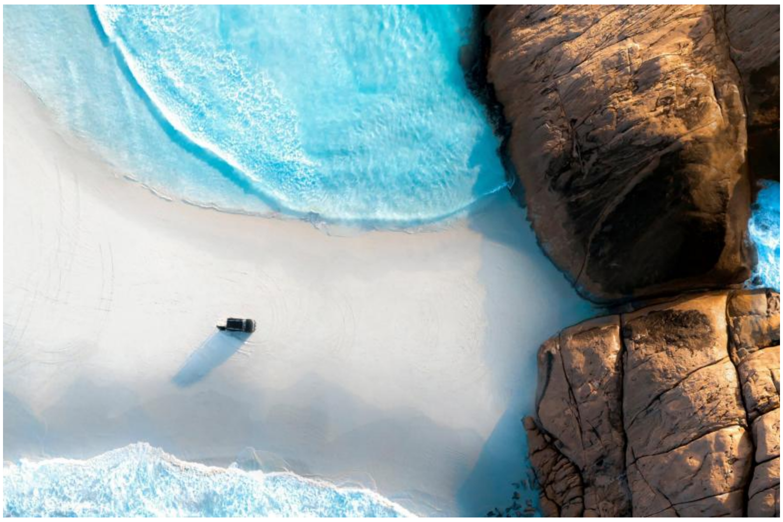

Figure 2: The Weser River Basin

2.2 Hardware, Software, Date

The selection of appropriate software and the definition of the input data hierarchy were crucial for managing the computational demands of the basin-wide analysis. Table 1 details the computational environment, the primary data source, and the specific suite of resolutions used for the systematic uncertainty assessment.

Table 1: Hardware, Software, Dates

No.	Component	Detail	Notes
1	GIS Platform	Google Earth Engine (GEE)	Necessary for basin-wide processing (46,300 km^2).
2	Statistical Software	Python (≥3.10)	Libraries: NumPy, Pandas, SciPy, Matplotlib.
3	Reference Resolution (R_{ref})	10 m	Ground truth resolution for comparison.
4	Analyzed Resolutions (R_i)	10 m,25 m,50 m,100 m,250 m,500 m,1000 m	Resampled via Bilinear Interpolation.

2.3 Methodologies

This study applies the Systematic Resolution Optimization Framework (SROF) to the entire Weser River Basin (46,300 km^2), utilizing a 10 meter DEM (R_{ref}) processed on a high-performance platform (GEE/Python). We generated seven coarser DEMs (25 m to 1000 m) via Bilinear Interpolation. The methodology extracts the Slope Angle from all resolutions, quantifies the uncertainty using the Root Mean Square Error (RMSE) against the reference data, and then fits a logarithmic response function. The goal is to determine the Optimal Operational Resolution (R_{opt}) by identifying the peak diminishing returns point using the Uncertainty Reduction Rate (URR), balancing accuracy and computational efficiency across the basin.

Fig3 is the workflow of this work.

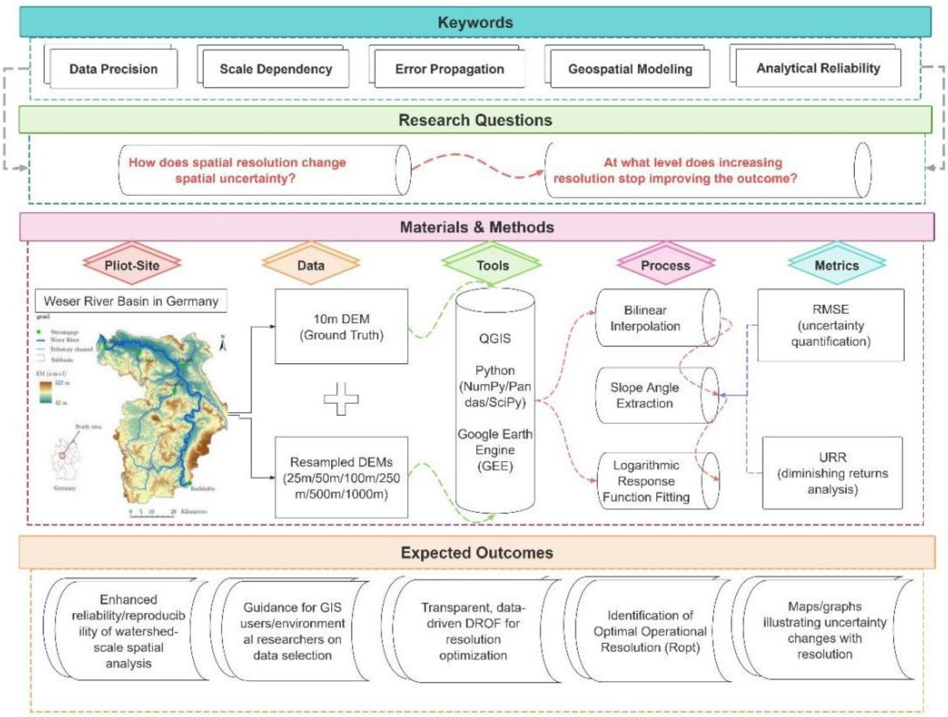

Figure 3:workflow

3 Results

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4 Discussion

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5 Conclusion & Outlook

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Special appreciation goes to the GIS Lab at [your institution] for technical assistance with QGIS and Google Earth Engine workflows. We also acknowledge [colleague names] for their insightful discussions on slope modeling and error propagation, and [name] for proofreading the manuscript and improving its clarity.

This study benefited from open-source software communities, particularly contributors to Python libraries (NumPy, Pandas, SciPy), whose tools enabled reproducible and scalable analysis. Their work embodies the collaborative spirit of modern geospatial science.

Data availability

We selected this journal based on several strategic and scientific considerations:

- Topical Alignment: The journal's scope includes geospatial modeling, environmental informatics, and uncertainty quantification—core themes of our study.
- Audience Relevance: Its readership comprises GIS analysts, hydrologists, and environmental scientists who directly benefit from resolution optimization frameworks and reproducibility in spatial analysis.
- Methodological Rigor: The journal emphasizes transparent, data-driven methodologies, which aligns with our use of RMSE, URR, and DROF metrics to quantify and interpret spatial uncertainty.
- Open Science & Reproducibility: Our workflow leverages open-source tools and public datasets, making it ideal for a journal that promotes reproducible research and open data practices.
- Impact & Visibility: The journal's indexing in major databases (e.g., Scopus, Web of Science) and its citation metrics ensure that our findings will reach a broad and engaged scientific community.

By publishing here, we aim to contribute to ongoing conversations around scale dependency, data precision, and operational resolution in environmental modeling.

Author Contributions

Dr. A. Müller

Conceptualization, Methodology Design, Supervision, Funding Acquisition

B. Schmidt, M.Sc.

GIS Data Processing, DEM Resampling, Visualization, Map Production

C. Nguyen, Ph.D.

Python Scripting, Statistical Modeling, RMSE & URR Computation, DROF Analysis

D. Patel, M.A

Literature Review, Writing – Original Draft, Reference Management

Declaration of Academic Integrity

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