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Geomorphometry.jl: Analyzing and visualizing the shape of the Earth in Julia.

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Summary

Digital elevation models (DEMs) are fundamental datasets in the earth sciences, used in applications from flood risk assessment to habitat mapping and climate modelling. Analysing the shape of the Earth's surface—the domain of geomorphometry—requires algorithms for deriving terrain attributes (slope, aspect, curvature), classifying landforms, routing water flows, and visualising terrain. `Geomorphometry.jl` is a Julia (Bezanson et al., 2017) package that provides efficient, composable, and extendable implementations of these algorithms, designed to work with plain matrices as well as geospatial data types from the Julia ecosystem.

Statement of need

Of the three widely used dynamic languages—Julia, Python, and R—Julia was the only one lacking a dedicated package for geomorphometric analysis. `Geomorphometry.jl` fills this gap, enabling users to combine terrain analysis with Julia's broader scientific computing stack—differential equations, optimisation, GPU computing, and machine learning—without leaving the language.

The package implements over 30 functions spanning several domains (non-exhaustive):

- **Terrain derivatives**: slope, aspect, and curvatures via Horn (1981), Zevenbergen & Thorne (1987), and Minár et al. (2020).
- **Relative terrain indices**: roughness, Topographic Position Index (Wilson et al., 2007), Bathymetric Position Index (Lundblad et al., 2006), rugosity, entropy, percentile elevation (Lundquist et al., 2008), horizon angles, and Sky View Factor; at multiple scales.
- **Terrain classification**: Several Morphological Filters (Keqi Zhang et al., 2003; T. J. Pingel et al., 2013), and skewness balancing (M. Bartels et al., 2006; Marc Bartels & Wei, 2010).
- **Hydrological analysis**: depression filling (Barnes et al., 2014), flow accumulation (using D8 (Jenson & Domingue, 1988), D-infinity (Tarboton, 1997) or FD8 (Quinn et al., 1991) methods), and relative height models (Nobre et al., 2011).
- **Visualisation**: hillshading (Burrough et al., 2015), multi-directional hillshading (Mark, 1992), and Perceptually Shaded Slope Maps (T. Pingel & Clarke, 2014).
- **Cost-distance analysis**: friction-based spreading via Tomlin (Tomlin, 1983), Eastman (Eastman, 1989), and fast sweeping (Zhao, 2005).

`Geomorphometry.jl` was designed to be used (and extended) by researchers studying geomorphometry on global scales. Furthermore, it was designed to also teach geomorphometry, by providing several algorithms for a task and an exhaustive, visual documentation.

State of the field

Several mature tools exist for terrain analysis, but each involves trade-offs between performance and extensibility. In Python, `xDEM` provides DEM analysis with a focus on elevation change detection and uncertainty, while `RichDEM` offers optimised hydrological algorithms. In R, `MultiscaleDTM` (Ilich et al., 2023) focuses on multiscale terrain metrics. These Python and R packages are convenient but, being interpreted, can be slow on large datasets. At the other end of the spectrum, PCRaster offers a comprehensive modelling language with hydrological functions in C++, while `WhiteboxTools` (Lindsay, 2016) provides a wide range of geospatial algorithms in Rust. Both are fast, but the languages make them difficult to extend or modify for novel research by practitioners. Indeed, this was the original trigger for the creation of this package. Julia's design—expressive like Python, yet compiled to efficient native code—offers both qualities simultaneously, echoing the goals of the Julia manifesto (Bezanson et al., 2017).

Software design

`Geomorphometry.jl` operates on standard Julia `AbstractMatrix` types, making it compatible with any array-like data structure in the ecosystem. Geospatial awareness is added through package extensions for `GeoArrays.jl` and `Rasters.jl` rather than hard dependencies, keeping the core lightweight. The package is designed to be customizable and extendable, as shown in its core concepts:

- **Multiple algorithms:** Where several methods exist for the same task (e.g., slope, flow direction, cost-distance), users can select the most appropriate one. Algorithm selection uses Julia's multiple dispatch, making it straightforward to add new methods without modifying existing code—useful for both research and teaching.
- **Geospatially aware:** Package extensions automatically extract cell sizes and handle coordinate reference systems—including geographic (lat/lon) DEMs—preventing common user errors.
- **Multiscale analysis:** Relative terrain indices accept configurable stencil windows from `Stencils.jl`, enabling analysis at multiple spatial scales, on both CPU and GPU, extending the approach of Ilich et al. (2023).

Terrain derivative implementations are validated against GDAL's `gdaldem`, and flow direction against `pyflwdir`, ensuring consistency with established tools.

Research impact statement

The package was essential for analysis of DEMs on a global scale, and even creating new ones (Pronk et al., 2024). The hydrologic analysis methods were used to automatically detect levees in DEMs (Pronk et al., 2026). Furthermore, the package was used to demonstrate geomorphometry in the Python, R and Julia languages in the software chapter in the upcoming second edition of the Geomorphometry book (Hengl et al., 2009).

AI usage disclosure

AI tools are used in the creation of the software and documentation. Specifically, they are used to review implementations, find bugs or other inconsistencies. The same holds for documentation, where they are used for autocompletion, review and to fix grammar and spelling mistakes. No AI tools were used for critical components, such as the overall design, architecture, or validation of the package.

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