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Towards a Unified Framework for Environmental Modelling: The Interplay Between Geometry, Geostatistics, and Biogeomorphology

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Abstract

Modelling natural systems increasingly requires quantitative approaches capable of capturing spatial heterogeneity, multi-process interactions, and the uncertainty inherent in environmental observations. This need emerges across a wide range of Earth - system applications, ranging from the characterization of geological structures to the assessment of hydro-geomorphological processes, where sparse data, complex geometries, and evolving ecological conditions limit the reliability of analyses. Developing modelling frameworks that explicitly account for spatial variability, uncertainty, and the interplay between physical and biological components is therefore essential for improving environmental assessments and supporting sustainable decision-making. In this perspective, two research contributions are discussed. First, we advance uncertainty-aware geological modelling through a stochastic-based tool that combines geostatistics, unstructured meshes, and reproducible workflow tracking by metadata. It quantifies spatial uncertainty for continuous and categorical regionalized variables, offering a flexible, self-contained framework for representing complex geologies and environmental datasets in 2D and 3D domains. Second, we focus on modelling rainfall-induced phenomena by jointly simulating hydrology and erosion processes. We explore how biodiversity-related information, such as vegetation cover and associated indicators, can be embedded into this framework. A real case study illustrates how variations in biodiversity, land cover dynamics, and meteorological conditions influence slope processes and model outcomes, focusing on analysis of pre- and post- fire event. As a future development, we propose unifying these directions through the integration of stochastic spatialization strategies for key environmental variables, particularly soil and eco-geomorphological attributes, coupled with explicit uncertainty quantification. This effort aligns with emerging national regulatory requirements and moves toward a comprehensive, uncertainty-aware modelling paradigm supporting more informed, transparent, and sustainable management of natural systems.

Keywords

Geostatistics, Stochastic Simulations, Geometry Processing, Biogeomorphology