EGU23-10371, updated on 27 Apr 2024
https://doi.org/10.5194/egusphere-egu23-10371
EGU General Assembly 2023


# Coping with the complexity of landscape evolution and how high-resolution topography can help

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Since the end of the 19th century, geomorphologists have been on a relentless quest to unravel the mysteries of landscape evolution and explain the diversity of the resulting forms. However, a quantitative model of landscape morphodynamics that is relatively universal and applicable at various time scales still eludes us. This raises an important question: are we, geomorphologists, dumber than the average scientist, or is landscape evolution particularly complex to decipher? ChatGPT tells us that, indeed, landscape evolution is complex.

As for many natural phenomena, the complexity of landscape evolution results from 3 elementary components: processes, stochasticity, and heterogeneity. **Process geomorphology** tackles the complex morphodynamics emerging from the diversity and interactions of physical, chemical, and biological processes that shape the Earth. **Stochastic geomorphology** addresses the role of fluctuations in the drivers of landscape evolution, such as the frequency-magnitude distribution of precipitation events, landslides, earthquakes, or fires. **Heterogeneous geomorphology** embraces the variable nature of the properties of landscape elements on which geomorphic processes operate or that they create. This includes, for instance, the distribution of grain sizes, the diversity of rock type, the fractal nature of rock fractures, or the spatial variations in vegetation size and type.

Accounting for all these sources of complexity, inasmuch as they can be quantified, is an untractable problem resulting in models of little explainability. Therefore, hypotheses had been and must be formulated to simplify the problem of landscape evolution comprehension and modeling. There is, arguably, a long tradition of emphasizing process complexity to explain landscape dynamics, neglecting or simplifying both stochastic fluctuations and heterogeneity. In this lecture, I shall discuss this view, emphasizing the now well-established importance of stochastic fluctuations, and how little we know of the role of heterogeneity.

On this latter topic, I shall illustrate with a variety of examples how time series of high-resolution and high-precision topographic data (4D data) offers unprecedented insights into landscape morphodynamics. Beyond quantifying and detecting a variety of processes and their temporal fluctuations, 4D data allow a systematic quantification of the heterogeneity (e.g., vegetation, grain size, ...) of landscape elements, and spatial variability of geomorphic rates, thus bringing us closer to formulating the role of heterogeneity in landscape dynamics. Yet, this goal can only be achieved if tools to harness the complexity and richness of high-resolution topographic data are developed

and made available.

Keywords: fluvial incision, landslides, floods, salt marshes, topo-(bathymetric) LiDAR, numerical modeling, machine learning.