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Hillslope sediment transport across climates and vegetative influences

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Erosion occurs across the globe to varying extents according to the climatic, biological, and anthropological influences present. With the rise of modeling, computing power, and data sharing, research is beginning to develop in several distinct, challenging directions in terms of being able to represent the likely causes of soil erosion across different contexts. While geologists, geomorphologists, hydrologists, agronomists, and soil geochemists all take an interest in erosion estimates for the sake of varying landscape evolution and environmental quality inquiries, debate has carried on over the decades regarding parameter estimation, conceptualization, and scale.

Currently, the methods that dominate erosion prediction modeling rely on some form of the empirical relationship captured by the Universal Soil Loss Equation (USLE; or Revised/Modified Universal Soil Loss Equation), which estimates erosion using the experimental plot as the unit of analysis. By dividing erosion into six distinctive parameters based on precipitation, soil erodibility, slope length, slope gradient, landcover, and management practice, modeling efforts isolate the challenge as estimating these parameters through proxies given unavailable resources and time to replicate plot experiments that underpin the experimental relationship between the variables. Unfortunately, over 40 years of research has shown this endeavor to be problematic and likely functioning outside of the intended purpose (Boardman, 2006). Wischmeier and Smith (1978) attest to the localized nature of the 30,000 years worth of plot-based data (Stocking, 1995).

Rather than relying on these developed relationships between the factors studied in the USLE, other authors recommend revisiting the underlying influences that climate can have on the transport of sediment (Kinnell, 2004, 2005, 2010, 2014, 2015). Greater attention to the processes that help conceptualize erosive processes are needed. For instance, beyond the USLE, at the other ends of the empirical spectrum are efforts focusing on the hydrological process representation (larger) or texture-based infiltration processes (smaller), which would then permit inclusion of sediment transport through separation of the flow above the soil and below the soil. Above the soil, if trying to calculate the overland flow that will later be used to estimate erosion, Burt and McDonnell (2015) issue a wake-up call regarding further use of methods such as the Curve Number, which has 50 years of use and yet is known as something that has been shown to "not work." Below the soil, the use of pedotransfer functions to determine infiltration or other hydraulic properties that would allow for hydropedological processes to be simulated in hydrologic and erosion models also encounters challenges. Similar to the USLE, these smaller scale functions encounter issues in their expansion of use beyond the developed context in which they were first formulated, in some cases underestimating infiltration capabilities by a factor of 10, especially in more diverse climates (Ramírez et al., 2017).

McDonnell et al. (2007) recommend not being caught up in the heterogeneity and process complexity but rather moving forward toward classification, defining scaling behavior, and emergent properties. This sentiment can also be found in the works of Klemeš (1983) and Dooge (1986), who discuss searching for laws at the appropriate scale. Recently, this call for scaled process importance has been re-articulated as serving as the fourth paradigm (Peters-Lidard et al., 2017), needing rigorous hypothesis testing (Beven, 2018), and having the potential for integration with Earth System Models (Fan et al., 2019). Many who focus on physics-based approaches rather than empirical ones are realizing that the small-scale matrix-flow laws are continually disappointing efforts at larger basin scales (Beven, 2018). If erosion studies are to advance, especially from hydrological perspectives, a clearer approach will need to arise that considers other approaches to scaling beyond the to-date upscaling and downscaling. What is needed is more aggregation of context specific, climate-dependent patterns and behavior from which research questions can be refined and developed further.

Richardson et al. (2019) analyze a wide-ranging data set from across sites in different parts of North America, Europe, South America, and China to investigate how climate (specifically aridity), lithologies, and measurement methodology interact with soil movement estimates using a diffusivity-like parameter to describe hillslope sediment flux. Their analysis finds that large controls on the sediment transport parameter investigated by Culling (1963), D, can be represented through a measure of how wet the climate is below 250 mm and above 500 mm of annual precipitation. Within each of these ranges, however, the movement of soil has several potential influences, notably vegetation and lithology.

Richardson et al. (2019) compile a data set spanning middle latitudes in combination with their new estimates of the sediment transport coefficient (D) as calculated through the combination of high-resolution topographic data with published erosion rates (E), soil densities (ρ_s), and bedrock densities (ρ_r) to contextualize the following equation into varying climate classifications:

$$D = -\frac{\rho_r}{\rho_s} \cdot \frac{E}{\nabla^2 z}. \quad (1)$$

The climate classifications consist of mean annual precipitation (MAP) ranges to describe the wetness of the climate and an aridity index (MAP/PET) to describe the water available to vegetation, where PET is potential evapotranspiration.

As vegetation increases within dry climates (desert to light forest transition), soil creep increases; however, mitigating influences are also expected to occur. For ranges of mean annual precipitation between 50 and 250 mm, this increase of average D (cm^2/yr) occurs on

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a factor of 4 over the wetness scale. For wet ranges, 500 mm to 1500 mm, *D* increases at a lower rate for a given increment in mean annual precipitation or aridity. Here, tradeoffs may be occurring that counteract increased sediment transport efficiency. Furthermore, while forested, savannah, and grassland sites had decreasing mean values of *D*, these differences were not significant at the 95% level.

Starting with precipitation and aridity does help to distinguish between some major influences on hillslopes and the resulting expected erosion estimates. While seemingly intuitive, this fact is surprisingly underappreciated in some hydrological analyses of erosion on hillslopes and catchments using extrapolated relationships based on one or the other climate (Boardman, 2006; Stocking, 1995). Expanding beyond climate influences to demonstrate vegetation and lithology factors shows that clearer distinctions are available when MAP is between 50 and 250 mm.

Richardson et al. (2019) identify these distinguishable relationships but also suggest further work to help distinguish factors resulting in residual variance of *D* in compiled estimates. First is the impact of soil thickness, which could help explain underestimation by a factor of 2, 5, or 10 depending on the ratio of erosion rate to maximum soil production rate. This provides an entry point for hydrologists and other interested researchers to expand beyond these demonstrated relationships to include data from experimental catchments to more clearly define these transport parameter differences. Furthermore, the vegetative influence, while a proxy for life in general, can have both strong influences in soil creep efficiency but also bind soils in place and decrease rainsplash. These more nuanced vegetative impacts have been debated at the regional scale (De Vente et al., 2013) and provide further entry points for geographers and geomorphologists to tackle further development of this larger scale perspective on erosion process conceptualization.

Remaining questions by the interested researcher might relate to these relationships under more tropical climates or even changing climates. For example, it is increasingly suggested that trends in precipitation may demonstrate intensity increases as the climate shifts (Roderick et al., 2019), necessitating non-stationary modeling of hydrology and erosion patterns. Though the work from Richardson et al. (2019) presents 50-year averages of mean annual precipitation (from 1950 to 2000), the projected future mean annual precipitation for these regions may remain relatively stable but could increase in intensity or shift the seasonal timing of arrival, meaning potential increases in erosion (Nearing et al., 2004) and shifts in these relationships between climate, vegetation, and *D*, the sediment transport parameter. Nonetheless, this framework and common conservation equation approach could help advance further soil erosion studies and bring to fruition the integrated scaled laws for which many researchers have advocated, to deal with measurable data and the scientific and practical problems at hand (Brutsaert, 2005; Burt and McDonnell, 2015; McDonnell et al., 2007; Peters-Lidard et al., 2017).

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