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Changes in streambank erodibility and critical shear stress due to subaerial processes along a headwater stream, southwestern Virginia, USA

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Abstract

Despite more than 40 yr of research attributing temporal changes in streambank erosion rates to subaerial processes, little quantitative information is available on the relationships between streambank erodibility (k_d) and critical shear stress (τ_c) and the environmental conditions and processes that enhance streambank erosion potential. The study goal was to evaluate temporal changes in k_d and τ_c from soil desiccation and freeze–thaw cycling. Soil erodibility and τ_c were measured monthly *in situ* using a multiangle, submerged jet test device. Soil moisture, temperature, and bulk density as well as precipitation, air temperature, and stream stage were measured continuously to determine changes in soil moisture content and state. Pairwise Mann–Whitney tests indicted k_d was 2.9 and 2.1 times higher ($p<0.0065$) during the winter (December–March) than in the spring/fall (April–May, October–November) and the summer (June–September), respectively. Regression analysis showed 80% of the variability in k_d was explained by freeze–thaw cycling alone. Study results also indicated soil bulk density was highly influenced by winter weather conditions ($r^2=0.86$): bulk density was inversely related to both soil water content and freeze–thaw cycling. Results showed that significant changes in the resistance of streambank soils to fluvial erosion can be attributed to subaerial processes. Water resource professionals should consider the implications of increased soil erodibility during the winter in the development of channel erosion models and stream restoration designs.

Keywords: Subaerial processes; Freeze–thaw cycling; Streambank erosion; Soil erodibility; Critical shear stress

1. Introduction

Streambank retreat is a function of multiple processes working in concert to cause what is casually referred to as "streambank erosion" (Lawler et al., 1997). In reality, research has identified three main processes by which most "erosion" occurs: subaerial processes, fluvial entrainment, and mass wasting (Hooke, 1979; Lawler, 1992, 1995; Lawler et al., 1997; Couper and Maddock, 2001; Wynn and Mostaghimi, 2006b). Specific definitions of

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these processes used from this point forward were adapted from those proposed by Lawler et al. (1997). Erosion is defined as the detachment and removal of particles or aggregates from the streambank surface. Fluvial and subaerial processes are typically recognized as the main contributors to streambank erosion as defined in this study. Subaerial processes are the result of local climate, including the wetting and drying or freezing and thawing of the surface soil, which leads to an overall weakening of the soil surface, as well as direct erosion (Couper and Maddock, 2001). Fluvial erosion is the detachment and entrainment of soil particles or aggregates as a result of hydraulic forces applied directly to the streambank by flowing water. Mass failure of a streambank occurs when geotechnical instability causes streambank collapse. Streambank retreat is the collective loss of bank material from subaerial processes, fluvial entrainment, and mass failure (Lawler et al., 1997). This study focuses on the tendency for subaerial processes to weaken the surface soil, and the resulting implications to soil erodibility, rather than quantifying the physical amounts of erosion caused by these processes.

Subaerial processes dominate streambank retreat in the upper reaches of river systems, delivering soil directly to the stream channel and making the banks more vulnerable to flow erosion by reducing the packing density of soils and destroying imbrication (Thorne and Tovey, 1981; Abernethy and Rutherfurd, 1998). Measured average erosion rates exclusively from subaerial processes range from 13 mm/yr (Prosser et al., 2000) to as high as 390 mm/yr (Yumoto et al., 2006). Lawler (1993) estimated bank retreat from needle-ice formation accounted for 32–43% of the total bank retreat measured along the River Ilston, West Glamorgan, UK; Yumoto et al. (2006) attributed 20–60% of the annual bank retreat measured along a small mountain stream in central Japan to subaerial erosion. Subaerial processes as a whole have been characterized as “preparatory processes” as they increase soil erodibility (Wolman, 1959; Lawler, 1993; Couper and Maddock, 2001).

Subaerial processes are the result of changing weather conditions that affect soil moisture quantity, state, or movement within streambank soils (Thorne, 1982). Subaerial processes have been subdivided into three main categories based on soil moisture conditions; Lawler et al. (1997) classified these categories as pre-wetting, desiccation, and freeze–thaw. Pre-wetting incorporates mechanisms that increase the streambank soil moisture content. These mechanisms can include prolonged high flows, groundwater rise, and infiltration of precipitation (Lawler et al., 1997). Desiccation of the bank surface leads to soil cracking and exfoliation (Lawler et al., 1997). Freeze–thaw processes occur in streambank soils from the freezing of soil moisture during cold nights and subsequent thawing from warmer daytime temperatures and/or solar heating of the streambank soil. For cohesive bank material, Lawler et al. (1997) suggested subaerial processes had the greatest influence on streambank erodibility. Research has shown significant increases in erosion following subaerial processes (Lawler, 1993; Prosser et al., 2000; Couper and Maddock, 2001; Yumoto et al., 2006).

Hanson and Cook (2004) utilized the following form of the excess shear stress equation to estimate erosion rates, E_r:

$$E_r = k_d(\tau_e - \tau_c) \quad (1)$$

where E_r = erosion rate (m/s), k_d = soil erodibility (m^3/N-s), τ_e = effective stress (Pa), and τ_c = critical shear stress (Pa).

Soil erodibility reflects the rate at which erosion occurs while the critical shear stress is the stress at which erosion starts. Both k_d and τ_c are considered properties inherent to a given soil. The effective stress is the hydraulic force applied to the streambank soil, per unit area; the effective stress is also referred to as the particle or grain shear stress. Often, when the values of soil erodibility and critical shear stress are specified for a watershed model, average values of k_d and τ_c are chosen or calibrated to represent the soil characteristics of large stream reaches (Allen et al., 1999). In contrast to this standard practice, a study by Wynn and Mostaghimi (2006b) on the relative impacts of soil properties, root density, and subaerial processes on streambank erosion indicated both k_d and τ_c were influenced by freeze–thaw cycling, suggesting these parameters may vary seasonally. Studies have also shown that k_d and τ_c can vary by up to four and six orders of magnitude, respectively, along the same river reach (Hanson and Simon, 2001).

Models such as SHE, SWAT, WEPP, and CONCEPTS use forms of the excess shear stress equation for determining rates for overland and channel erosion (Byne, 1999). The Système Hydrologique Européen (SHE; Abbott et al., 1986a,b) is a distributed, mechanistic, watershed-scale model that incorporates both surface and subsurface hydrologic processes. The Soil and Water Assessment Tool (SWAT, Neitsch et al., 2002) is a physically based watershed model designed to predict the impacts of management practices on water quantity and quality in large complex watersheds over long time periods. Designed to evaluate the movement of water and sediment on hillslopes and within small watersheds, the Watershed Erosion Prediction Project (WEPP; Flanagan