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Dye tracer visualization of flow patterns and pathways in glacial sandy till at a boreal forest hillslope

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ABSTRACT

Dyes are valuable tracers in visualizing flow patterns and pathways in soil. We applied the dye *Acid Blue 9* to unsaturated and saturated soil profiles at a boreal forest hillslope consisting of glacial sandy till, and determined the soil physical properties from soil samples. The objective was to characterize preferential flowpaths, investigate their porosity, extent and connectivity, and complement earlier findings on subsurface flow formation at the site. According to the results, preferential flowpaths were formed by roots, erosion related to soil water flow, freezing–thawing cycles, and soil fauna. The role of roots and stones in the formation of preferential flowpaths was emphasized. Porosity of preferential flowpaths was 5.1 ± 1.8%, and they extended to a depth of about 55 cm from the soil surface; the deepest roots reached the same depth. When the soil saturated, individual preferential flowpaths self-organized into continuous and well-connected lateral flow systems along the slope. At the slope shoulder, preferential flow network covering the entire soil profile, as well as preferential flowpaths on the underlying bedrock surface, were considered crucial for runoff generation. In the midslope area, runoff generation was characterized by lateral preferential flow and the transmissivity feedback phenomenon. At the slope foot, preferential flowpaths in soil below the eluvial horizon were the major runoff contributors. A full saturation of the soil profile at the slope is unlikely under natural conditions. However, lateral flow was found to occur also in unsaturated soil.

1. Introduction

Preferential flowpaths characterize soils at forested hillslopes (e.g., Uchida et al., 2005). They are networks of large pores (i.e. macropores), soil pipes and other void spaces in soil that are typically formed in forest soils by soil fauna, roots, erosion caused by water flow, and freezing–thawing phenomena (Aubertin, 1971; Beven and Germann, 1982, 2013; Koch et al., 2013). Preferential flow refers to all fast flow phenomena that are associated with a fraction of the total soil pore space, either accelerating or delaying the transport of dissolved matter, depending upon the location of the matter compared to the locations of the preferential flowpaths (Allaire et al., 2009). Preferential flow networks can remain stable for decades in forest soils (Hagedorn and Bundt, 2002), and both the vertical infiltration of water and solutes into soil, as well as their lateral movement along hillslopes towards streams and catchment outlets are affected by preferential flowpaths (e.g., Klaus et al., 2013). In addition to the abovementioned factors, swelling and shrinking processes can form preferential flowpaths in clay or organic soils; in agricultural fields, the efficiency of field drainage relies on the existence of preferential flowpaths that can transport water and solutes rapidly from the soil surface to the subsurface drains (e.g., Alakukku et al., 2010).

Assessment of the type, extent and connectivity of preferential flowpaths, as well as the quantification of preferential discharge in forest hillslopes usually rely on tracer studies. While dye tracers have been used for visualizing the preferential infiltration into soil (e.g., Backnäs et al., 2012; Shougrakpam et al., 2010; Bogner et al., 2008) and the lateral preferential flow in hillslopes (e.g., Anderson et al., 2009; McGuire et al., 2007; Noguchi et al., 1999), ion and isotope tracers have been used for calculating the fraction of event vs. pre-event water, and the fraction of preferential vs. matrix flow in the total runoff from hillslopes (e.g., Laine-Kaulio et al., 2014a; McGuire et al., 2007; Lepistö et al., 1994). In agricultural sites, recent studies have included X-ray computed tomography to provide 3-D images of preferential flow networks in intact soil columns in laboratory conditions (e.g., Koestel and Larsbo, 2014; Luo et al., 2007; Mooney and Morris, 2004).

Studies on dye tracer visualization of preferential flow in forest soils have typically focused on fine-grained clay and loam soils (e.g., Wang and Zhang, 2011; Shougrakpam et al., 2010; Bogner et al., 2008), and characterization of preferential flowpaths in glacial tills with a coarser texture and high stone content has gained less attention. However, glacial tills are common in boreal forest environments in the Northern

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Hemisphere, and the main surface deposits in Fennoscandia (Beldring, 2002). Finnish soils, for instance, are dominated by Podzols with sandy till deposits (Yli-Halla and Mokma, 2002). 72% of forest land in southern Finland and 81% of forest land in northern Finland are on mineral soils of which 63% and 75%, respectively, are covered with medium to coarse textured glacial tills (Tomppo et al., 2011). Even though glacial till soils are generally considered to have a low hydraulic conductivity (e.g., Lind and Lundin, 1990), they may contain preferential flowpaths that significantly increase the subsurface water flow and solute transport velocities and amounts in forested hillslopes (e.g., Laine-Kaulio et al., 2014a).

According to Haldorsen and Krüger (1990), characteristics of tills that have the greatest influence on their hydrogeological properties are porosity, pore size distribution, macropore networks, heterogeneity and anisotropy; these properties are controlled by grain-size distribution, spatial distribution and orientation of soil particles, soil structural properties, and the degree of compaction of till. The soil structure of till has the strongest influence on the hydraulic conductivity, which decreases rapidly with depth, similarly to the volume of preferential flowpaths (e.g., Laine-Kaulio, 2011; Lind and Lundin, 1990). The higher volume of preferential flowpaths and the higher hydraulic conductivity of soil near the soil surface lead to a non-linear increase in lateral discharge when the soil saturates and water table rises to the highly conductive layers near the soil surface; this is called the transmissivity feedback phenomenon, and it characterizes runoff generation in many till hillslopes (e.g., Bishop, 1991). However, preferential flow in the soil material on the bedrock surface has been found the major source of runoff at hillslopes with very shallow (50–70 cm) till layers (e.g., Ilvesniemi et al., 2010).

Experimental evidence from field studies, especially in the context of lateral preferential flow, suggests that preferential flow processes vary considerably from site to site (Weiler and McDonnell, 2007). Characteristics of preferential flow networks, together with other soil properties, characteristics of the underlying bedrock, and climatic conditions, can be considered the key factors controlling the runoff generation at different sites but also at different locations of a same site. At the MaiMai experimental hillslope in New Zealand, preferential flowpaths have been identified to consist of soil pipes in the soil material on the bedrock surface at a depth of about 60 cm (e.g., McDonnell, 1990). At a forest site in South-East Germany, preferential flowpaths have been linked to rooting activity within a depth of about 1 m from the soil surface (e.g., Bogner et al., 2010). A variable stone content characterizes our site, the forested hillslope in Kangaslampi, Finland, and is expected to affect the subsurface water flowpaths and patterns. The Kangaslampi slope has a glacial till soil cover above a low-permeable bedrock, and according to earlier studies including ion tracer experiments and solute transport modeling, runoff generation in the midslope area of the Kangaslampi site is characterized by preferential by-pass flow and the transmissivity feedback phenomenon (Laine-Kaulio et al., 2014a; Laine-Kaulio, 2011). The model results have clearly indicated that water flow and solute transport should be considered in two separate, but connected pore domains with strongly differing hydraulic properties at least in the uppermost 50 cm of the soil profile (Laine-Kaulio et al., 2014a).

In this study, we present a visualization of flow patterns and pathways in the midslope area of the Kangaslampi hillslope. We use the dye tracer *Acid Blue 9* to expose the preferential infiltration into unsaturated soil, as well as the lateral subsurface flow downslope near the water table under steady state conditions. In addition, we determine the porosity of preferential flowpaths at three elevation levels of the slope. The objective is to characterize preferential flowpaths in soil, investigate their porosity, extent and connectivity, and complement earlier findings on subsurface flow formation at the site. We utilize findings available from dye tracer studies at the slope shoulder and slope foot (Backnäs et al., 2015) and from ion tracer simulations in the midslope area (Laine-Kaulio et al., 2014a). The main hypothesis is that the dominant flow mechanisms behind the runoff generation in different parts of the hillslope are not the same because the soil profile thickness and the detailed characteristics of the preferential flow networks are different. Stones are expected to play a bigger role in the formation of preferential flowpaths than reported from other sites.

2. Material and methods

2.1. Study site

The Kangaslampi area in Eastern Finland (Fig. 1a) has been subject to long-term monitoring and a series of studies in forestry and hydrology (e.g., Finér et al., 1997; Laurén et al., 2005; Laine-Kaulio et al., 2014a, 2014b). The area belongs to the middle boreal forest zone. The long-term (1971–2000) mean annual air temperature is +1.9 °C, the mean annual maximum of soil frost depth is 22 cm, and the mean annual

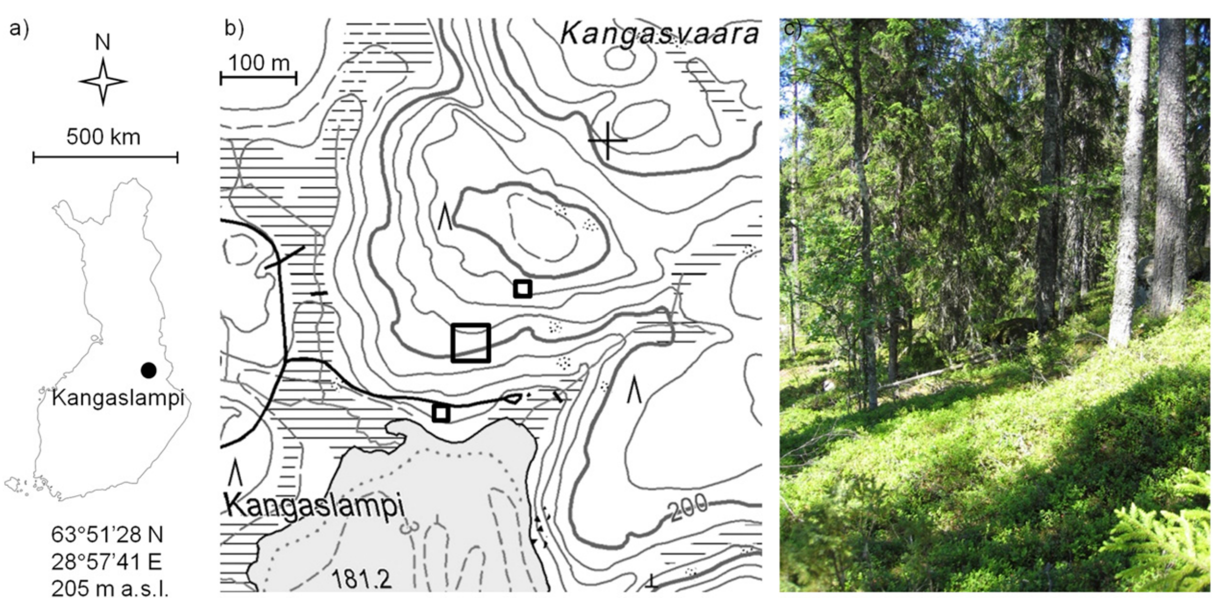

Fig. 1. Location of the Kangaslampi study area in Finland (a), locations of the slope foot, midslope and slope shoulder study plots in the experimental hillslope (for the slope portion terms see, e.g., Miyazaki, 2006) (b), and view on the midslope area (c).