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# Spatially distributed simulation of water balance and sediment transport in an agricultural field

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ABSTRACT

Runoff and sediment transport are distinctively three-dimensional (3D) processes and occur through overland, tillage layer and subsurface pathways. The objective was to quantify water balance and sediment concentrations in runoff waters and to assess sediment loads via surface runoff and drainflow in a clayey, subsurface drained field section using the FLUSH model. The model can simulate field scale two-dimensional overland flow and 3D unsaturated and saturated subsurface flow, including preferential flow in macropores. The erosive processes, comprised of hydraulic and raindrop splash erosion, occur in the overland domain while suspended sediment is conveyed from the field surface to subsurface drains via preferential transport in macropores in the subsurface domain. The study site, located in southern Finland, is a clayey, subsurface drained field section with an area of 12 ha and an average slope of 2.8%. The growing seasons and the following autumns of two years with distinctly different rainstorm characteristics were modelled. The simulated sediment loads via tillage layer runoff and drainflow were 85 and 117 kg ha$^{-1}$, respectively in 1988, and 63 and 189 kg ha$^{-1}$ in 1984. Despite the high precipitation in October 1984 (143 mm), erosion in the field area was low due to minimal surface runoff and consequently minimal hydraulic erosion. The suspended sediment at the site was generated by raindrop impacts and the eroded material was transported to the open ditch through tillage layer flow and subsurface drainflow. The model was able to reproduce the measured sediment concentrations in the main open ditch into which both tillage layer runoff and drainflow are discharged from the field. Spatially distributed erosion simulations facilitate the detection of net erosion and deposition locations in the field and could be used to design intensive measurement campaigns and guide erosion control practices in the future.



## 1. Introduction

Water balance and sediment loads in agricultural fields are tightly coupled in the Nordic countries, where hydrometeorological conditions are characterized by a short growing season with wet soils, and high runoff and sediment load generation potential outside the growing season. Sediment export from cultivated fields into open waterways poses problems due to the environmental effects of sediment itself, such as siltation and increased turbidity, and due to the particle bound nutrients, pesticides and heavy metals that are potentially released into receiving rivers and lakes (e.g. Boardman and Poesen, 2006). Suspended sediment is mainly generated by erosive impacts caused by raindrops and by hydraulic erosion on the field surface of cultivated soils in high latitudes (e.g. Boardman and Poesen, 2006). Erosion remains an elusive, spatial and stochastic process, and the processes that lead to large sediment loads in one field might produce only a little erosion in another site (Bärlund et al., 2009). Erosion is affected by climate and weather, cultivation and drainage practices, the topography of the field and the surrounding areas, and the soil type and moisture conditions. The variety of these controlling factors makes it difficult to generalize sediment load estimates computed from

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measured concentrations and discharge volumes in individual experiments.

In empirical studies, sediment loads are estimated from field or small catchment-scale runoff and sediment concentration data using various schemes (e.g. Bechmann and Stålnacke, 2005; Puustinen et al., 2005; Paasonen-Kivekäs et al., 2008). The effects of tilling on erosion and nutrient loads in cultivated fields in high latitudes are recognized and investigated in several studies (e.g. Chapman et al., 2005; Puustinen et al., 2005; Turtola et al., 2007; Uusitalo et al., 2007; Muukkonen et al., 2009; Ulén et al., 2010; Skøien et al., 2012), while research on the effects of seasonal and annual hydrological variations on erosion are more scarce (e.g. Puustinen et al., 2007). In clayey, subsurface drained fields, preferential flow in soil macropores has a large impact on water balance, flow pathways and sediment transport because a notable part of the annual sediment load can be lost via drainflow (e.g. Øygarden et al., 1997; Turtola et al., 2007; Paasonen-Kivekäs et al., 2008). Different lines of research have produced evidence for the direct and short routes from the surface to the subsurface drains including Caesium-137 (Laubel et al., 1999; Uusitalo et al., 2001), colloid and particle tracer studies (McKay et al., 1993; Jacobsen et al., 1997; Joel et al., 2012) and matching sediment concentrations in surface runoff and drainflow (Turtola and Paajanen, 1995; Uusitalo et al., 2001; Paasonen-Kivekäs et al., 2008). In some cases the soil profile is found to filter suspended sediment from the water moving in the macropores (Turtola and Paajanen, 1995; Jacobsen et al., 1997; Turtola et al., 2007).

Mathematical models can be used to explain different factors affecting erosion because models facilitate separation of the water balance and sediment transport into individual components – such as surface and tillage layer runoff, drainflow and groundwater outflow – and thus disclose the underlying governing processes. Sediment loads from cultivated fields have been quantified by applying simple models (e.g. Lundekvam, 2007; Bechmann, 2012) and field scale process-based models (Knisel and Turtola, 2000; Tattari et al., 2001; Taskinen and Bruen, 2007a,b; Bärlund et al., 2009), as well as large-scale distributed models (e.g. Bärlund et al., 2007; Puustinen et al., 2010). Only a few previously published modelling applications quantify sediment load estimates via both surface runoff and drainflow (Knisel and Turtola, 2000; Larsson et al., 2007; Lundekvam, 2007; Warsta et al., 2013b).

When the models are calibrated and validated directly against empirically estimated sediment load accumulations, the assessment of the model performance may be biased by the method of comparison between model results and measurements. Firstly, the model can underestimate runoff but overestimate concentrations, which results in a load that is comparable to the load estimated from data for the wrong reasons. Secondly, the number of sediment concentration measurements is usually much lower than the number of runoff measurements, which leads to uncertainty in the derivation of the empirically estimated loads (e.g. Bechmann and Stålnacke, 2005; Puustinen et al., 2005; Paasonen-Kivekäs et al., 2008). Thirdly, the comparison between measured and simulated long-term load accumulations may hide periods of load under- and overestimation, which can compensate for each other over longer periods. Finally, erosion and sediment transport are spatially variable processes and both model applications and measurement campaigns should strive for simulating and detecting three-dimensional (3D) variables instead of only aggregated measures.

Water pollution control measures are implemented within agriculture fields, where the sediment source areas are located. The assessment of efficiency of these measures has been proven to be very difficult (e.g. Granlund et al., 2005). We propose that model simulations based on detailed 3D description of the field are a way forward in the estimation of management impacts on water balance, sediment loads and nutrient export.

Ulén and Bechmann (2012) identified several gaps in soil erosion knowledge in the Nordic countries including (1) the quantification of sediment transport in macropores to subsurface drains and (2) the utilization of spatially distributed models for assessing erosion. In this study we aim to demonstrate through a case study how the newly introduced FLUSH model (Warsta, 2011; Warsta et al., 2013a,b) can be applied to fill in these gaps. The leading objective is to assess the water balance and the sediment loads via different pathways during the growing seasons and following autumns in a subsurface drained field section in southern Finland. While suspended sediment concentrations are routinely measured in empirical measurement campaigns, modelling studies usually present only cumulative sediment loads or total loads during the investigated period (e.g. Knisel and Turtola, 2000; Tattari et al., 2001; Larsson et al., 2007; Lundekvam, 2007). We provide a more detailed picture of water and sediment processes by presenting both hourly simulated suspended sediment concentrations and measured concentrations not included in these earlier studies. Taskinen and Bruen (2007a,b) previously compared simulated sediment concentrations against measurements in surface runoff with an event based model. We will produce an hourly simulation of soil erosion during the growing seasons and the following autumns, and account for sediment discharge via both surface runoff and subsurface drains, focusing on the autumn periods with their high erosion risk after tilling. We also present 3D field scale, spatial distribution of the erosion affected by the topography of the site. Exploring the spatial distribution of field scale erosion processes is an extension of the commonly produced aggregated loads of one-dimensional (1D) or conceptual models lumped into the field scale (e.g. Knisel and Turtola, 2000; Tattari et al., 2001; Larsson et al., 2007; Lundekvam, 2007; Bärlund et al., 2009).

## 2. Materials and methods

The water balance, sediment concentrations in runoff waters and sediment loads of 1984 and 1988 of the Hovi monitoring field, located in southern Finland, are investigated with the FLUSH modelling system (Warsta, 2011; Warsta et al., 2013a,b). These years were chosen because they included recorded rainfall–runoff events with erosive potential in autumns. Temporal data including precipitation, runoff and sediment concentration measurements from the field site are shown in Section 3 in conjunction with the simulation results.

### 2.1. Site description

The Hovi field site is one of the small catchments where water flow and quality, including erosion, are monitored in Finland by the Finnish Environment Institute. The gathered data has been used to estimate sediment and nutrient loads for different land-use types in the whole of Finland (Vuorenmaa et al., 2002). The Hovi field represents clayey, subsurface drained fields, which are abundant in the southern and western parts of Finland. The detailed simulations will produce further evidence of the reliability of the monitoring system and the data. Runoff and water quality data from the Hovi field have been used in the estimation of the water balance, the environmental impacts of drainage, and erosion and nutrient loads in several previous studies (e.g. Seuna and Kauppi, 1981; Bengtsson et al., 1992; Puustinen et al., 2007, 2010). Moreover, Seuna and Kauppi (1981) studied the effects of subsurface drainage installation on the quantity and quality of runoff and Bengtsson et al. (1992) investigated the pathways of melt water movement using oxygen-18 as a tracer concluding that water reached subsurface drains via cracks and vertical sand–gravel drains.