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Modelling surface and subsurface flow of water and erosion at clayey, subsurface drained agricultural field

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Abstract: In Finland, the major part of diffuse phosphorus load to water ways is carried with soil material eroded from clayey and silt arable fields. According to several field studies, subsurface drain flow carries a large amount of sediment besides overland flow. Cesium 137 measurements indicated that most of the soil material transported through subsurface tile drains originates from the soil surface layer. The goal of the study was to create a process based model which could be used to simulate sediment transport via overland flow and subsurface drains at clayey, subsurface drained agricultural fields. The model was developed and tested with data from a clayey field in southern Finland.

The developed modeling system is distributed and dynamic in nature and it is divided into surface and subsurface parts. The former includes 2-D overland flow and coupled erosion, and the latter 3-D subsurface flow and coupled transport models. Overland flow is modelled with a kinematic wave approximation of the St. Venant equations. A standard mathematical approach to erosion modeling was adopted with a sediment continuity equation and hydraulic erosion based on shear stress of the flow. Preferential and soil matrix flow and transport in subsurface domain were implemented with a dual-permeability approach. Both pore domains in dual-permeability flow and transport models were implemented with Richards and advection-dispersion equations respectively. The partial differential equations were solved implicitly with a finite volume method.

The Sjökulla experimental field site in southern Finland comprises a field section of 3.3 ha within a larger area of arable land. The topography of the field is undulating with the maximum slope of almost 5%. The clay content of the soil varies from 38% to 90% increasing with depth. In the study years, small grain crops were grown in the field. The time series used in the modelling were from May-November 1996 and May-October 1998. They included hourly values of overland and subsurface drain runoff rates, groundwater level and meteorological data. The water quality data comprised total suspended solids (TSS) concentrations in subsurface and surface runoff samples. In addition extensive data on soil physical properties were available from a field section of about 1 ha within the experimental site.

A novel part of the study was to simulate both overland and subsurface drain sediment loads simultaneously with linked process models. The sediment was allowed to move freely between field surface and soil matrix and macropores in the tillage layer. Under the tillage layer, sediment was allowed to move only in macropores. The model was calibrated with data from 1998 and validated with data from 1996.

Runoff rates produced by the flow model where in good agreement with the measurement data for both calibration and validation years. Sediment loads during calibration year were quite similar to measured ones even though there were some differences in the dynamics. However the present model structure and/or parameterization cannot explain the very high sediment load from subsurface drains during the validation year. The effect of grid resolution was inspected with two relatively low resolution grids. Among other things the lowest resolution grid produced less drainage runoff and had a tendency to cut down drain runoff peaks.

Keywords: *Modelling, agricultural field, preferential flow and transport, erosion, clay soil*

1. INTRODUCTION

Abatement of nutrient losses induced by agriculture is one of the main tasks in water resources protection in Finland as in many other countries. Phosphorus load from agriculture accounts for 60% and nitrogen load for 50% of the total human induced load to water courses (Nyroos et al. 2006). About 90% of these losses are assumed to originate from field cultivation. The primary focus of water pollution control is reduction of phosphorus load which is regarded the main factor for eutrophication of the surface waters. In Finland, major part of diffuse phosphorus load is carried with soil material eroded from clayey and silt fields (Tattari & Rekolainen 2006).

In general, overland flow carries most of the eroded soil from arable fields to open channels and other water bodies. However, several studies in Finland (e.g. Turtola et al. 2007, Paasonen-Kivekäs et al. 2008) and in other Nordic countries (e.g. Øygarden et al. 1997, Laubel et al. 1999) on fine textured soils have shown that considerable amount of eroded soil can also be transported via tile drains. In low permeable soils, the soil particles are assumed to move with preferential flow via macropores and backfilled drain trenches to drain lines. Cesium 137 measurements on Finnish clayey fields (Uusitalo et al. 2001) have indicated that most of the soil material transported through subsurface tile drains originates from the soil surface layer.

The goal of the study was to create a process based model which could be used to simulate sediment leaching via overland flow and subsurface drains at clayey, subsurface drained agricultural fields. The new erosion model introduced in this paper is coupled to a flow model developed for clayey fields in a previous study (Warsta et al. 2008). The model was developed and tested with data from a clayey field in southern Finland.

2. MATERIAL AND METHODS

The spatial and temporal variation of erosion phenomenon dictated that a dynamic and distributed model solution would be best suited to our problem. In order to capture sediment leaching via overland flow and through subsurface drains a classical method of dividing the flow of water and transport of sediment into separate overland and subsurface components was adopted. Additional features needed were: simulation of vegetation (evapotranspiration), preferential flow and transport, clay soil shrinking and swelling and drainage.

The most important properties of the system are:

- Distributed, field-scale model (spatial variations)
- Dynamic, aimed for longer simulations, single events are also possible (temporal variations)
- 2-D overland flow and coupled erosion (sediment production, transport of sediment to open ditches)
- 3-D subsurface flow and transport including preferential flow (transport of sediment to the drains)

2.1. Description of the data

Data from an on-farm monitoring site (Kirkkonummi, Sjökulla, 60º15’ N, 24º27’) in southern Finland was used to develop and test the model. The experimental site for runoff and groundwater measurements used in the modelling, embodied a field section of 3.3 ha within a larger area of arable land (Figure 1). The topography of the field is undulating with the maximum slope of almost 5%. The field borders consist of roads, ditches, arable sub drained land and alluvial land. In the study years, small grain crops were grown in the field. Ploughing or stubble cultivation was used in autumn and seedbed preparation in spring. Soil within the field is classified (Soil Survey Staff 1998) as a very fine Aeric Cryaquept (Peltovuori et al. 2002). The clay content varies from 38% to 90% increasing with depth.

The yearly precipitation in southern Finland ranges between 600-700 mm and evapotranspiration 300-400 mm. Snow forms about 30-40% of the annual precipitation. The time series used in the modelling were from May-November 1996 and May-October 1998. They included hourly values of overland and subsurface drain runoff rates, groundwater level and meteorological data.

The water quality data comprised total suspended solids (TSS) concentrations in subsurface and surface runoff samples. Samples of tile drain outflow were collected manually at irregular intervals throughout May-November 1996. An autosampler with 4-hour sampling interval was used in May-October 1998. Samples of surface runoff during the study periods were always collected manually. When calculating the hourly estimates of TSS losses, the hourly runoff volumes were multiplied by the measured or estimated concentrations.

Extensive data on soil physical properties were available from a field section of about 1 ha within the experimental site (Alakukku et al. 2003, 2009). Van Genuchten water retention characteristics for three soil layers were also available from a previous study. A detailed presentation of the experimental field and measurements can be found from Paasonen-Kivekäs et al. (2008).

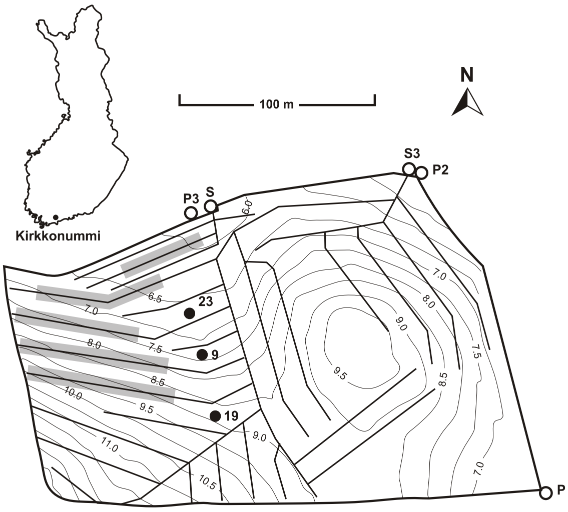

Figure 1. Location of Kirkkonummi in Finland and Sjökulla experimental field layout. Contour lines are marked with thin black lines (elevations are in [m]) and drainage network with thick black lines. P and S represent measurement weirs of surface and subsurface runoff rates. Points 9, 19 and 23 refer to groundwater observation tubes at Sjökulla field.

2.2. Description of the numerical model

The numerical model can be divided into four model parts: overland flow, overland erosion, subsurface flow and subsurface transport. The erosion model is coupled to the overland flow model and the subsurface transport model to subsurface flow model. Partial differential equations are solved with finite volume method. The basic control volume is hexahedric in shape i.e. deformed cube. A more thorough explanation of the flow model is available in Warsta et al. (2008).

Overland flow was modeled with a sheet flow analogy with kinematic wave approximation of St. Venant equations and Manning's friction equation. There are no definite physically based erosion models available for cohesive soils. Therefore a standard mathematical approach to erosion modelling was adopted. Sheet like hydraulic erosion, based on the shear stress of the flow, was used as a sediment producing mechanism (Taskinen & Bruen 2007). Infiltration of the sediment was taken care by the subsurface transport model. Currently only one sediment size category is supported.

Subsurface flow and sediment transport is based on a dual-permeability approach (Gerke and van Genuchten 1993). The total pore space of the soil is divided between soil matrix and fracture domains. Flow of water is modelled with Richards equation and transport of sediment with advection-dispersion equation in both pore domains. The capillary rise and unsaturated hydraulic conductivity were modelled with Mualem–van Genuchten style parametric water retention curves. Dual-permeability models use special mass transfer functions to move water and sediment between pore domains according to pressure/water content and concentration differences. In this study the transfer of water in the flow model was based on pressure.

In addition the subsurface model contained the following components: infiltration and exfiltration, evapotranspiration, flow to tile drains, deep groundwater flow and a simple model for soil shrinkage and swelling. Potential evapotranspiration (PET) was calculated with Penman-Monteith approach. The shrinkage and swelling of the clay soil was tied to the difference between cumulative precipitation and potential evapotranspiration. If the difference was positive the cracks got smaller and vice versa.

Currently the transfer of water and sediment between overland and subsurface domains is accomplished with explicit mass transfer functions residing in the subsurface flow and transport models. Infiltration will occur if there is water in the overland cell and the hydraulic head is higher than in the adjacent subsurface cell. Exfiltration will occur if the hydraulic head of the subsurface cell is higher than in the overland cell. The amount of infiltration is governed by the amount of water in the overland cell, conductivity of the soil, hydraulic gradient and the free pore space in the subsurface cell. Infiltration is first directed into the soil matrix and after the matrix is full to the fractures. Sediment is transported between domains with water (advection only) as a solute.

2.3. Model application

The model was calibrated with data from 1998 and validated with data from 1996. Calibration and validation were done manually by comparing model results to the runoff measurements visually. The following input data were needed for the model: hourly precipitation and calculated PET values, soil data for the subsurface models, surface characteristics for the overland models and the calculation grid including geometry of the field and initial and boundary conditions. The initial water level in the beginning of the simulation was set to the drainage level (0.8 m below soil surface). Subsurface drains were embedded into the grid according to the drain network plan (Figure 1).

Side boundary conditions were set to open ditches. A flux type boundary condition was set to the bottom of the grid to simulate the flow of water over the bedrock (deep groundwater flow). Soil shrinkage and swelling model was used to decrease hydraulic conductivity and macroporosity of the soil towards the end of the year. Two calculation grids (12x8x10 and 24x16x10 cells in x, y and z directions) were used to test the effect of grid resolution on results. Due to the relatively thick top subsurface layer (0.08 m) the layer was treated as saturated to increase conductivity and infiltration. The sediment was allowed to move freely between field surface and soil matrix and macropores in the tillage layer. Under the tillage layer sediment was allowed to move only in macropores.

Parameters of the soils used in the subsurface flow and transport models are presented in the Table 1. θ_S is saturated water content [-], α [m^{-1}] and β [-] are van Genuchten water retention curve parameters, K_{SH} and K_{SV} [m/h] are horizontal and vertical saturated hydraulic conductivities and PoreFr. is the fraction of the total porosity of the soil pore domain. Letters M and F in the soil type column refer to soil matrix and fracture domains. Mannings coefficient n [-] in the overland flow model was set to 0.5. A ponding threshold of 4.0 mm was used on the surface to delay overland flow initialization. Soil erodibility k_f [kg/m^2/s] and critical shear stress τ_c [N/m^2] in the erosion model were set to 2.0E-07 and 0.1 respectively.

Table 1. Soil parameters used in the subsurface models.

Soil type	θ_S	α	β	K_{SH}	K_{SV}	Pore Fr.
TillageM	0.52	9.5	1.11	1.0E-2	1.0E-2	0.965
TillageF	0.52	7.0	2.0	0.25	0.5	0.035
SubSurfM	0.56	3.4	1.08	5.0E-4	5.0E-4	0.995
SubSurfF	0.56	7.0	2.0	0.0	0.5	0.005
MidSoilM	0.56	3.4	1.08	1.0E-5	1.0E-5	0.995
MidSoilF	0.56	7.0	2.0	0.0	0.5	0.005
BotSoilM	0.56	3.4	1.08	1.0E-6	1.0E-6	0.9999
BotSoilF	0.56	7.0	2.0	0.0	0.0001	0.0001

3. RESULTS AND DISCUSSION

Results from the calibration and validation runs are presented in Table 2 and Figures 2-5. All water and sediment balance components in Table 2 were converted to [mm] and [kg/ha] respectively by dividing them with the area of the field. Cumulative precipitation, PET and modelled evapotranspiration are presented in Figure 2. Measured and modelled cumulative overland and drain runoff rates and sediment loads are presented in Figures 3 and 4. Due to limited space only one hourly runoff figure is included (Figure 5).

Table 2. Modelled / measured mass balances for years 1998 and 1996.

Year	1998	1998	1996	1996
Storage/Runoff	Water [mm]	Sed. [kg/ha]	Water [mm]	Sed. [kg/ha]
Field surface (init.)	0 / n.d.	0 / n.d.	0 / n.d.	0 / n.d.
Soil matrix (init.)	1397 / n.d.	0 / n.d.	1397 / n.d.	0 / n.d.
Soil fractures (init.)	3 / n.d.	0 / n.d.	3 / n.d.	0 / n.d.
Field surface (end)	2 / n.d.	30 / n.d.	2 / n.d.	41 / n.d.
Soil matrix (end)	1401 / n.d.	216 / n.d.	1414 / n.d.	130 / n.d.
Soil fractures (end)	2 / n.d.	454 / n.d.	2 / n.d.	265 / n.d.
Precipitation	598	-	580	-
ET/PET	257 / 277	- / -	278 / 335	- / -
Surf. flow to ditches	78 / 68	2275 / 2367	61 / 58	1684 / 2669
Hydraulic erosion	- / -	4266 / n.d.	- / -	3284 / n.d.
Infiltration	520 / n.d.	1962 / n.d.	518 / n.d.	1559 / n.d.
Subsurface drains	104 / 91	1292 / 1282	110 / 104	1164 / 2937
Deep g.w. flow	153 / n.d.	0 / n.d.	109 / n.d.	0 / n.d.
Error	-1 / n.d.	0 / n.d.	-3 / n.d.	0 / n.d.

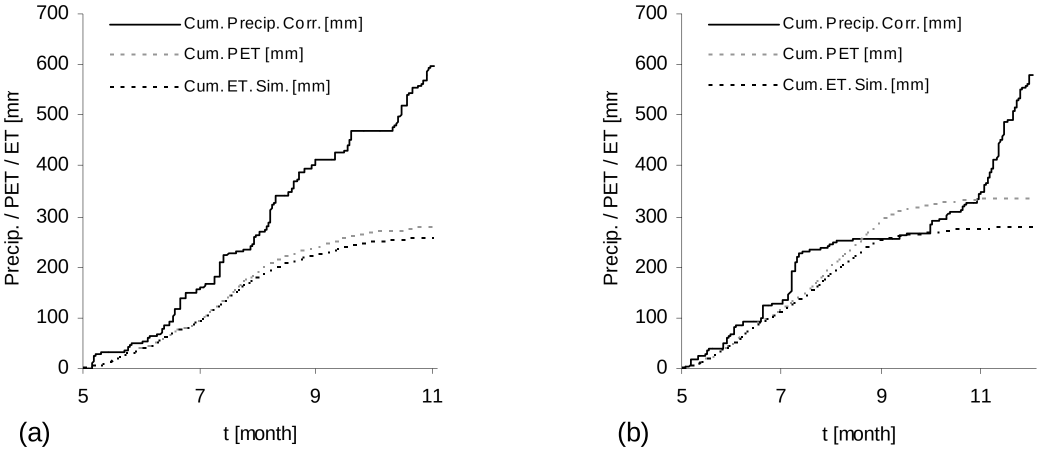

Figure 2. Cumulative precipitation and evapotranspiration for years 1998 (a) and 1996 (b).

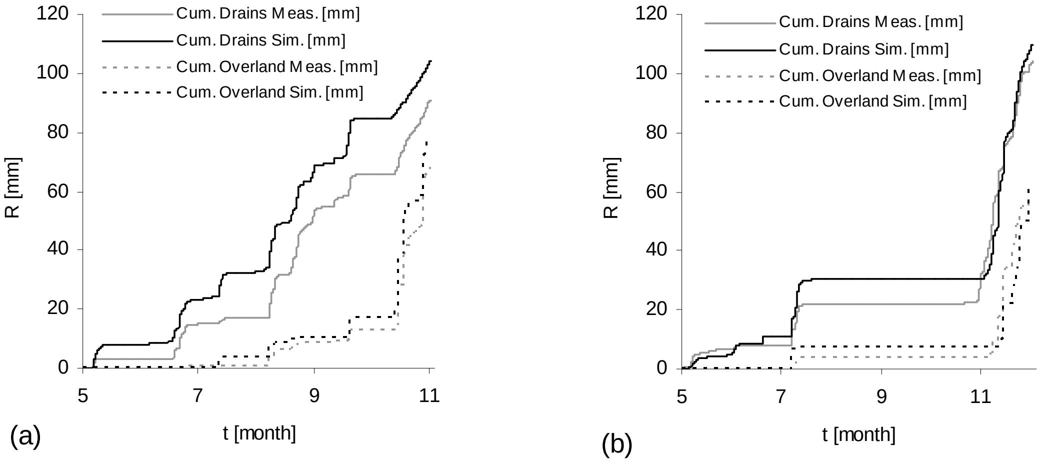

Figure 3. Cumulative overland and subsurface drain runoff rates for years 1998 (a) and 1996 (b).

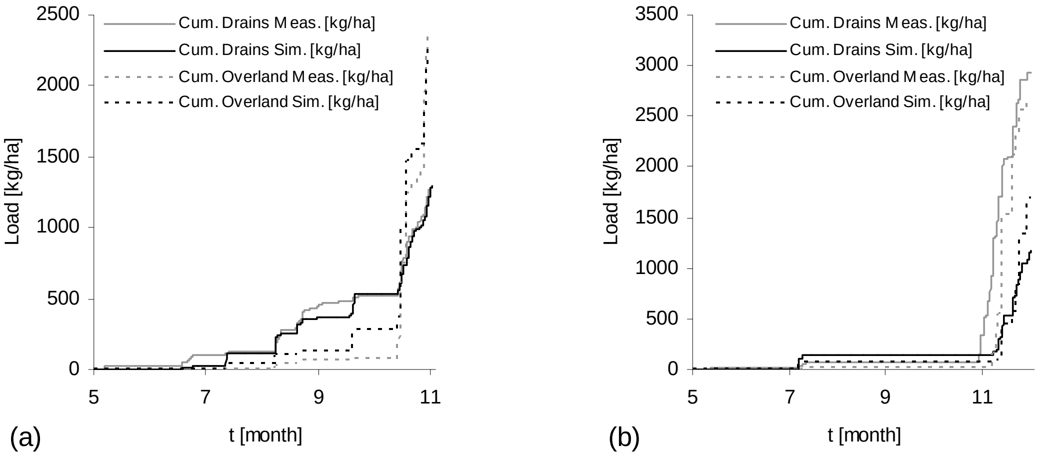

Figure 4. Cumulative overland and subsurface drain sediment loads for years 1998 (a) and 1996 (b).

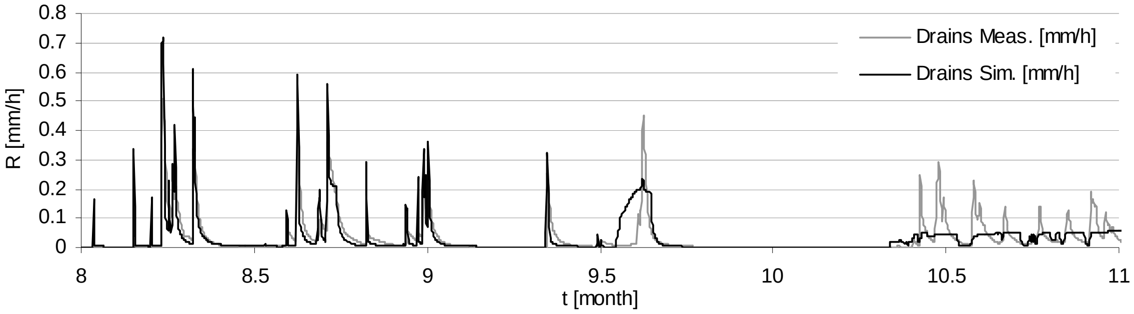

Figure 5. Detail of subsurface drain runoff in 1998 and the problematic phase in October.

Runoff rates produced by the flow model were in good agreement with the measurement data for both calibration and validation years (Figure 3) even though the drain runoff was pronounced. The flattening of drainage runoff peaks in the end of the year 1998 (Figure 5, October) was caused by the soil shrinkage and swelling model. The model decreases both the soil saturated conductivity and the volume of fractures with the same rate causing the flow to slow down to a constant slow seepage. The measurements show that the actual runoff peaks are only scaled down and retain their shape as if only some of the fractures close down and others remain as active preferential flow pathways. The calculated level of the groundwater table followed the dynamics of the measured level relatively well.

Sediment loads during calibration year were quite similar to measured ones even though there were some differences in the dynamics. The staircase effect of the modelled cumulative drain sediment load in 1998 (Figure 4a) is probably caused by the direct infiltration of the sediment into the macropores. The biggest problems in the study were experienced with the erosion model during the validation phase when the erosion model simply did not produce enough sediment (Figure 4b). The present model structure and/or parameterization cannot explain the very high measured sediment load from subsurface drains. One possible explanation is that in wet conditions permanent macropores can convey large amounts of very small clay particles from soil surface layers to tile drains even though the large fractures are closed during autumn rains.

The effect of grid resolution was inspected with two relatively low resolution grids. The results in the paper were calculated with the 24x16x10 cell grid. Lowest resolution version of the grid (12x8x10 cells) exhibited a tendency of breaking up the drain runoff peaks before they reached their maximum value according to the measurements. The change in grid resolution also changed the runoff distributions increasing drain runoff as the drainage network got more intricate and decreasing overland runoff and erosion. Separate dynamic time steps were calculated for overland and subsurface domains from Courant number using cell dimensions and flow velocities as constraints.

4. CONCLUSIONS

In the study an initial version of a process based erosion model was developed and tested on a clayey, subsurface drained agricultural field in southern Finland. A novel part of the study was to simulate both overland and subsurface drain sediment loads simultaneously with linked process models. This proved to be a challenging task for a number of reasons. Due to the lack of physically justified erosion models for cohesive soils, a very simple erosion model was used as a starting point. In addition a dual-permeability subsurface flow model was needed to simulate the moisture state and infiltration capacity of the soil which has a great impact on overland flow.

Results from the model were encouraging even though the validation results from the erosion model underestimated the sediment transport measured at the field severely. The most intriguing problem was definitely the measured high sediment output from the subsurface drains during the validation year which even exceeded overland sediment load. Spatial resolution of the calculation grids played a crucial part in the study causing uncertainty to the simulation results. The model was tested only with low resolution grids. Among other things the lowest resolution grid produced less drainage runoff and had a tendency to cut down runoff peaks. Still higher resolution grids are needed to asses if the runoff rates start to converge. Preliminary results indicated that this would happen.

Vast differences in time scales between overland, soil fracture and soil matrix flow events caused technical problems. Flow events especially in macropores were sudden and fast and it was difficult to anticipate them and adjust time steps accordingly. Large time steps during intensive flow events can cause serious sediment mass balance errors due to the advective components in the overland and subsurface transport models. An adaptive time stepping scheme was used to choose the most suitable time steps for the simulation. Due to problems with the scheme relatively small values were used for minimum and maximum time steps.

Future plans include further development of the erosion model and time stepping mechanism, tests with higher resolution grids and applications to nutrient transport problems. It is already possible to solve rough estimates of the total phosphorus loss with regression from the modelled sediment loads. Later on a submodel for nitrogen cycle will also be incorporated to the system.

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