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

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Introduction 1/2

- Sediment loss via subsurface drains can be a significant factor in the total annual sediment load at southern Finnish clayey fields
- The objective of the study was to simulate soil erosion and loss of sediment via overland flow and subsurface drains
- A novel simulation model was developed to tackle the problem
- Data from Sjökulla (AU, HY) and Hovi (SYKE, MTT) experimental fields was used to test the model
- Only a few earlier modelling studies (e.g. Larsson et al. 2007)

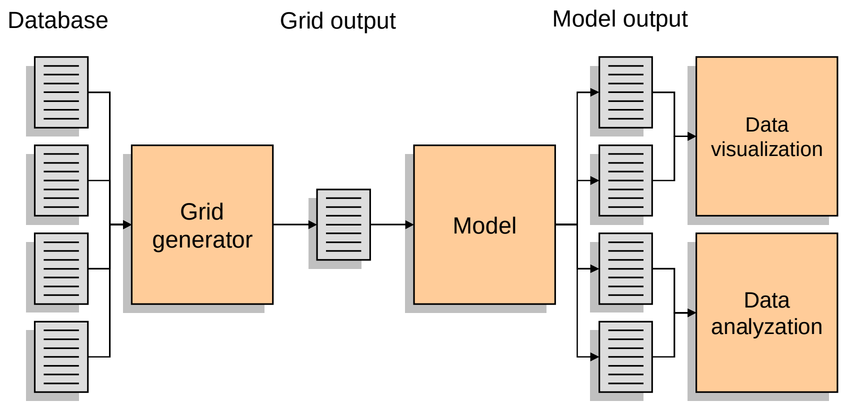
Erosion at Sjökulla field

Introduction 2/2

- According to ^{137}Ce measurements most of the sediment lost from the fields originates from the surface
- Sediment is transported into the tile drains with preferential flow
- Apparently most of the preferential flow takes place in dynamic shrinkage cracks
- The contribution of earth worm tunnels is evident in the autumn when shrinkage cracks are mostly closed
- The erosion processes of cohesive soils are somewhat obscure
- The erosion rate is less than evident from particle size due physical and chemical properties
- At certain moisture levels the soil loses it composition increasing erodivity significantly

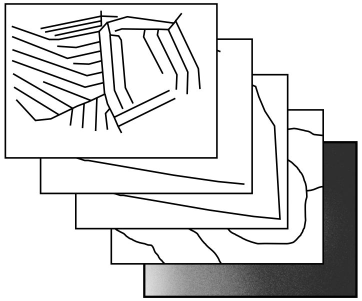
Sediment in the tile drain weir water

Modelling system pipeline



Grid generator 1/2

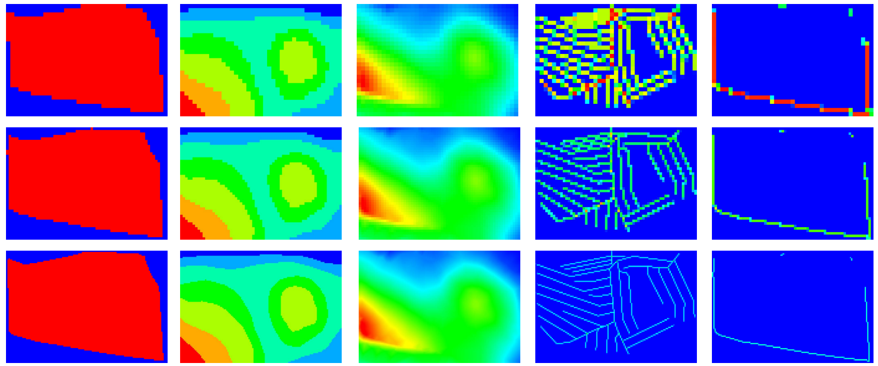
- A custom program was used to discretize input data into computational grids
- Input data is given in vector, tabular data and high res. raster formats
- Advantage is that initially simulations can be done with low resolution grids
- Resolution can be increased until simulation results do not change significantly anymore – grid resolution independent results
- Currently only rectangular grids are supported – cells outside the field area are marked as inactive and not modelled



Input data: drains, ditches, active field area, soil profiles, DEM etc.

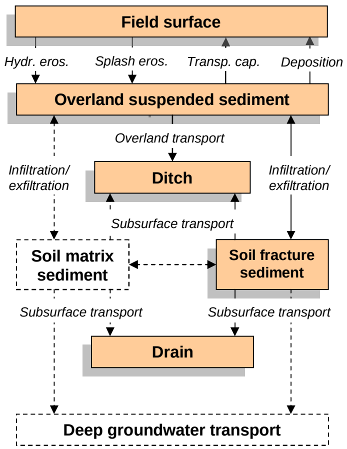
Grid generator 2/2

➢Discretized finite volume grids with different resolutions:

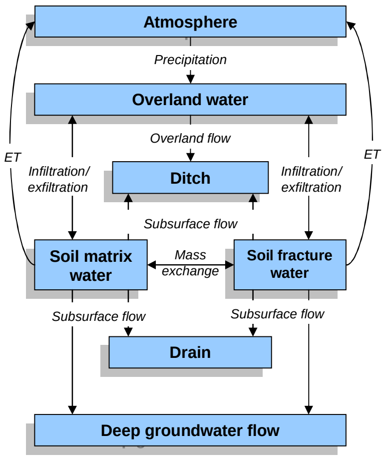


Active area Soil profiles Elevation Drains Ditches

Conceptual model



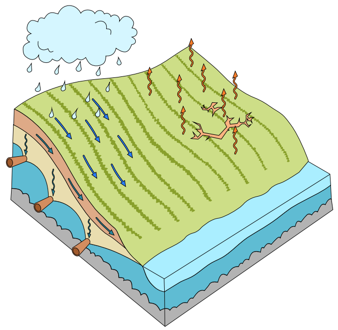
Sediment



Water

Basic model features

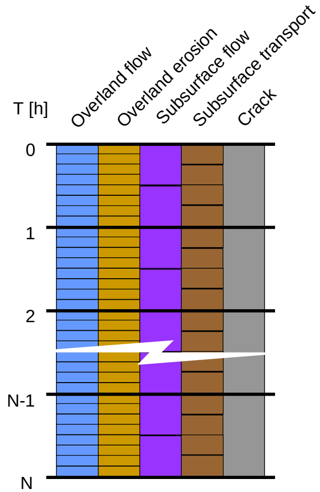
- Distributed, 2-D overland and 3-D subsurface models (unstructured grids, hexahedric control volumes)
- Dynamic simulations
- Implicit, iterative, finite volume schemes are used everywhere to solve the partial differential equations
- Submodels:
  1) Overland flow
  2) Overland erosion
  3) Subsurface flow
  4) Subsurface transport
  5) Soil shrinkage and swelling



Model features

Time stepping scheme

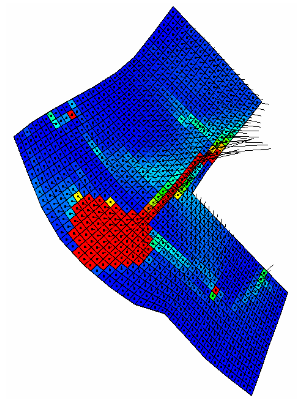
- The system contains several models operating in different time scales
- Overland flow < macropore flow < soil matrix flow
- The objective was to concentrate the temporal resolution of each model to optimal places to minimize the computational load
- Global time step is divided into sub time steps used by the models
- The amount of sub time steps are increased and decreased according to a predefined scheme
- The models are synchronized at the global time steps



Time stepping scheme

Overland flow model

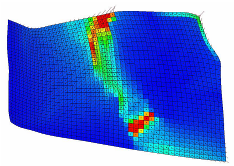
- A large depression in the Hovi DEM caused problems for the kinematic wave based overland flow model
- Diffuse wave based approach was implemented to fix the problem
- The water surface slope is calculated from elevation and pressure head differences
- Solved implicitly with bisection method and iteration



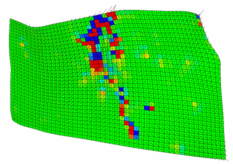
Water depths at the Hovi experimental field

Overland erosion model

- Currently the model uses a sheet like approach meant for non-cohesive soils
- Solution of the flow model is used to drive the erosion model
- Model consists of sediment continuation equation (e.g. Taskinen 2002) coupled with:
  1) Hydraulic erosion (Taskinen 2002)
  2) Raindrop splash erosion (Wicks and Bathurst 1996)
  3) Deposition (Stokes law)
  4) Transport capacity (Yalin 1967)
- Sediment infiltration is taken care by the subsurface transport model (advective only)
- Rill erosion approaches are being considered



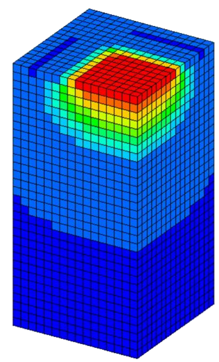
Water depths at Sjökulla experimental field



Soil erosion (kg) at Sjökulla experimental field

Subsurface flow model

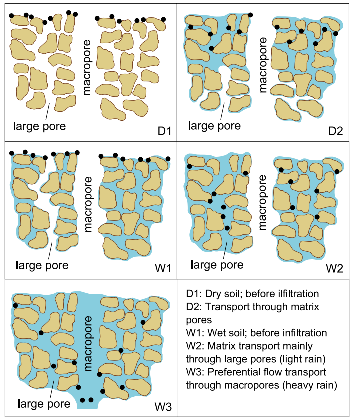
- 3-D unsaturated/saturated flow in soil matrix and macropores
- Dual-permeability flow model (Gerke and van Genuchten 1993a)
- Richards equation (Richards 1931) is used to model both pore systems
- Mualem-van Genuchten (van Genuchten 1980) water retention curves and unsaturated hydraulic conductivity
- Both pore systems have unique hydraulic parameters
- Implicit iteration is accelerated with either tridiagonal or pentadiagonal solution algorithms



3-D flow simulation test with the model

Subsurface transport model

- 3-D unsaturated/saturated solute transport in soil matrix and macropores
- Solution of the flow model is used to drive the transport model
- Dual-permeability transport model (Gerke and van Genuchten 1993a)
- Advection-dispersion equation is used to model both pore systems
- Implicit iteration is accelerated with either tridiagonal or pentadiagonal solution algorithms
- Suspended sediment is only allowed to move in the macropores



Transport via macropores

Exchange of water and solutes between poresystems

- Soil matrix and macropore flow and transport equations are connected with mass transfer functions
- The rate of water exchange is directly proportional to pressure head or water content difference between the pore systems
- Solute transfer function consists of advective and dispersive components
- Advective solute transport uses water mass transfer function
- Continuum model – individual macropores are not simulated but the geometry is taken into account in the mass transfer functions

Water exchange between pore systems:

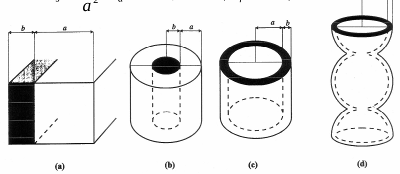
$$\Gamma_w = \alpha_w (h_f - h_m) \qquad \alpha_w = \frac{\beta}{a^2} K_a \gamma_w$$

$$K_a = 0.5 (K_f(h) + K_m(h))$$

Solute exchange between pore systems:

$$\Gamma_s = \alpha_s (1 - w_m)(c_f - c_m) + \Gamma_w c^*$$

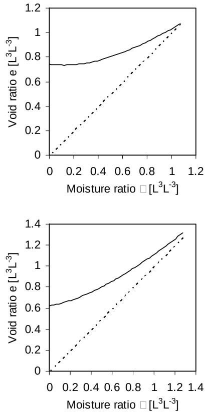
$$\alpha_s = \frac{\beta}{a^2} D_a \qquad D_a = 0.5 (D_f + D_m)$$



Macropore geometry Gerke and van Genuchten 1996

Soil swelling and shrinking model

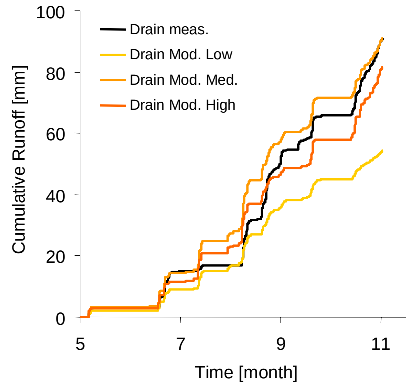
- Drying of the soil creates crack networks that can reach into considerable depths
- Wetting of the soil causes the matrix to swell closing the shrinkage cracks
- A physically sound approach based on the moisture state of the soil was adopted
- Shrinkage curves were measured by Kankaanranta (1996), parametric shrinkage curves by Kim(1992) were fitted to measurement data
- The fraction of macropores is changed according to the moisture state of the soil
- The hydraulic conductivity is linearly related to the size of the cracks



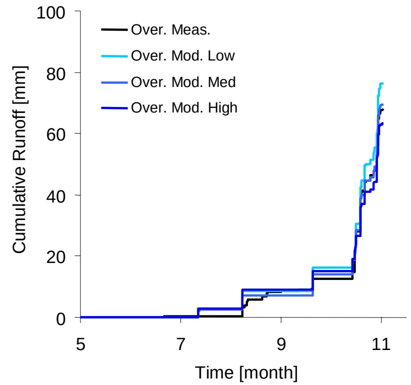
Shrinkage curves from Sjökulla (Kankaanranta 1996)

Calibration year 1998

Sjökulla cumulative runoff values



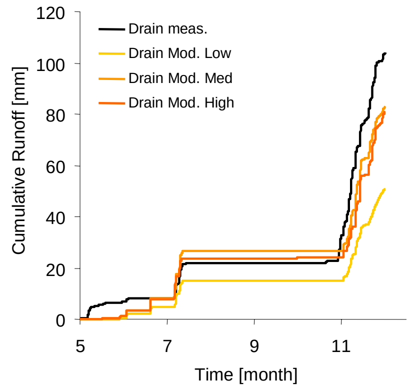
Cumulative drain runoff



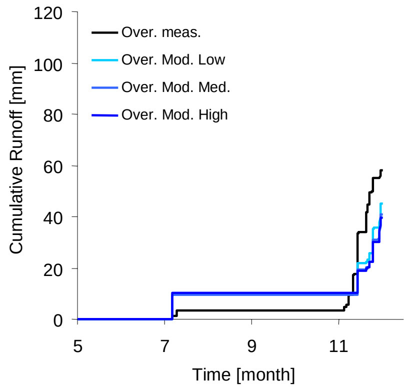
Cumulative overland runoff

Validation year 1996

Sjökulla cumulative runoff values



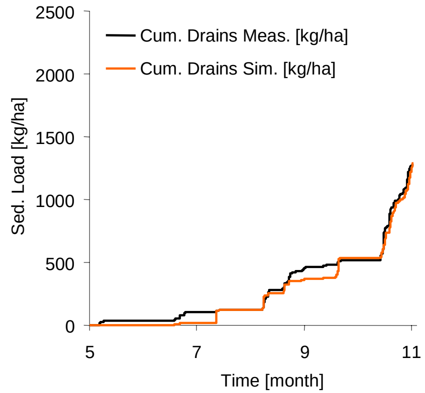
Cumulative drain runoff



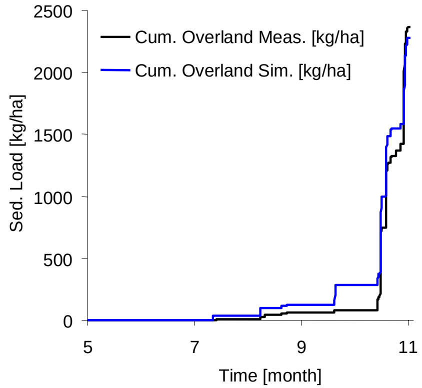
Cumulative overland runoff

Calibration year 1998

Sjökulla cumulative sediment loads



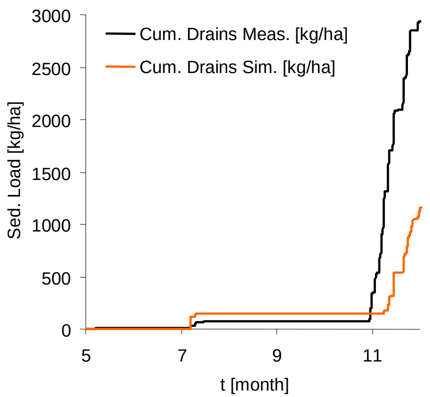
Cumulative sediment load via drains



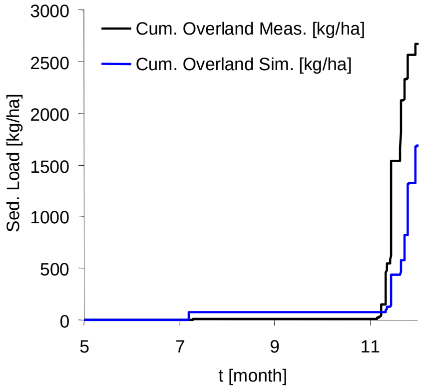
Cumulative overland sediment load

Validation year 1996

Sjökulla cumulative sediment loads

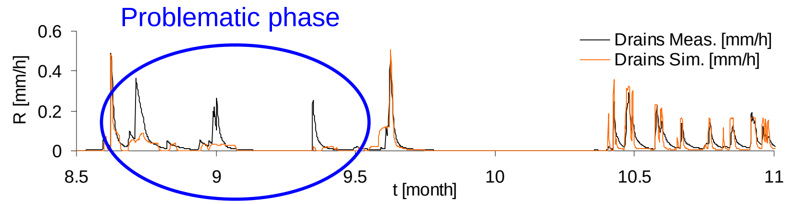


Cumulative sediment load via drains

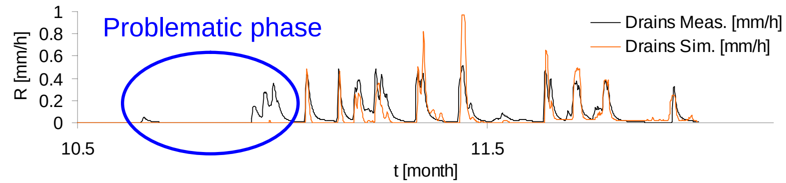


Cumulative *overland sediment load*

Problems with drain runoff results



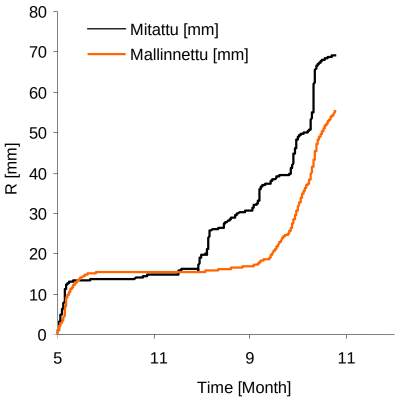
Drain runoff in calibration year 1998



Drain runoff in validation year 1996

Calibration year 1988

Hovi cumulative runoff values



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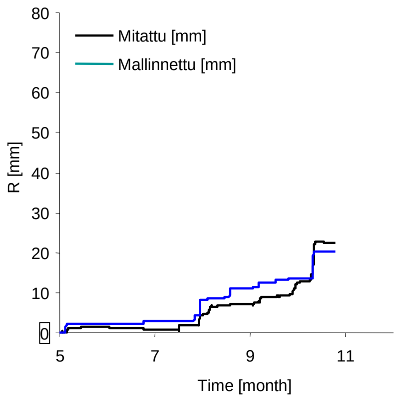

Pintavalunta

Some conclusions

- Soil shrinkage and swelling has a profound effect on the runoff distribution between overland and subsurface drains
- Some of the preferential flow paths stay open also in the fall
- The erosion of cohesive soils have properties not simulated well by the model (sjökulla 1998 vs 1996 results)

➢ Additional work still needed

Thanks for the audience

- Questions?