AGU FALL MEETING 2011
San Francisco, California, USA | 5-9 December

Universität der Bundeswehr München

# Process-oriented Simulation of Runoff Generation on Arable Fields Using a Physically Based Hydrological Model

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**H43B-1195**

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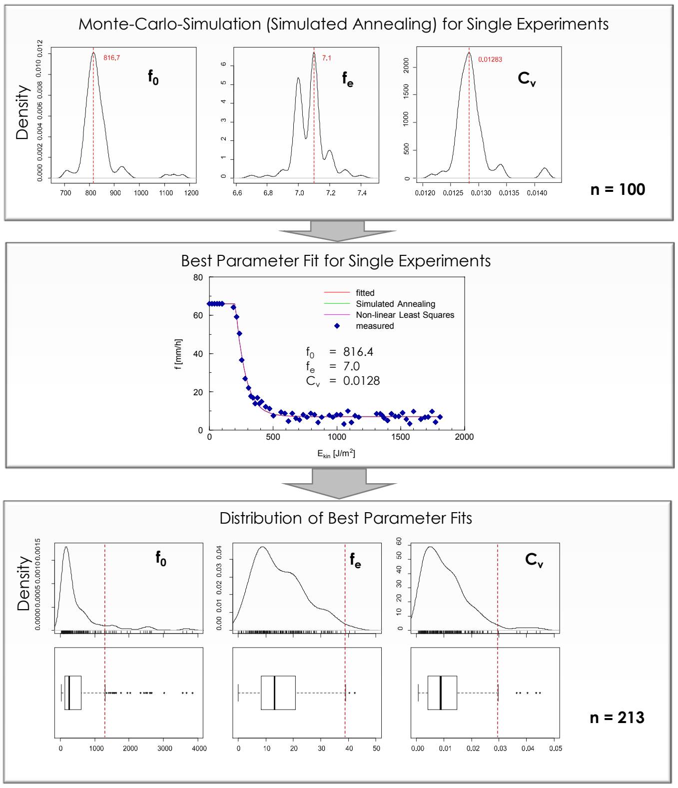
## Objectives/ Motivation

Runoff generation in agricultural catchments is highly variable in space and time. On arable fields the runoff generation process is governed by different boundary conditions that are either time-invariant (e.g. soil texture) or variable in seasonal (e.g. crop stage, soil cover, soil moisture) or in single event (e.g. rainfall intensity) terms. These boundary conditions are assumed to affect the processes connected to infiltration. The sealing of soils is known to be of significant importance for surface runoff and erosion on tilled fields.

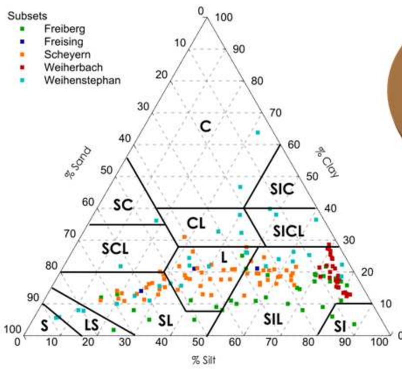
In Germany, modern flood protection strategies include distributed flood control measures. On arable fields these measures comprise of increasing infiltration ability and thus maintain the natural retention capacity of landscapes due to different tillage practices such as conservational tillage or no-tillage. In this research we analyze a database of infiltration measurements on arable soils to obtain a process-based approach to quantify the effects of different tillage practices on runoff generation.




## Experimental Data

Sprinkler experiments from different research groups in Germany have been collected and merged into a database of 726 single experiments with 24384 runoff measurements (SEIBERT ET AL. 2011).

Experiments have been carried out in sequences on partly the same plots, thus a total of 209 different soil textures to be found in Germany are included. The database respresents the typical Loessial soils that are abundant in Central European landscapes used for agriculture. Soils with a high fraction of fine material (fine to very fine silt) are predominantly affected by soil crusting and well respresented in the database by soil types SIL (silty loam), L (loam) and SL (sandy loam) (Figure 1).



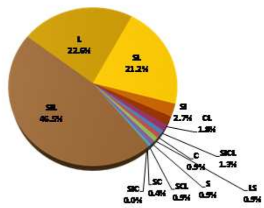




Figure 1: Distribution of soil types in the experimental data base (left: Texture Triangle according to USDA soil classification, right: pie chart of soil types)

## Infiltration into Crusting Soils

Tillage practices have a significant effect on the runoff generation process. Bare soils are prone to forming soil crusts during extreme rainfall events, and soil crusts promote surface runoff and erosion. Due to the impact of raindrops, the topsoil aggregates are broken and form a layer of a few millimeters to centimeters with very low hydraulic conductivity.

The infiltration process driven by sealing of the topsoil can be described by a modified Horton-Type Equation:

$$f_{pot}(E_{kin}(t)) = (f_0 - f_e) \cdot e^{-C_v \cdot E_{kin}(t)} + f_e$$

where the potential infiltration capacity $f_{pot}$ is a function of the effective cumulated kinetic energy of rainfall intensity.

This function has been fitted to single sequences of the experimental database, estimating the three parameters $f_0$, $f_e$ and $C_v$ using a combination of optimization algorithms Simulated Annealing and Non-linear Gauß-Newton.

From these fitted experiments two new sub-datasets have been derived for calibration (n=213) and validation (n=39). The highest fraction of outliers ($> 1.5 \cdot IQR + Q3$, red line in boxplots) are found in the determination of $f_0$ (10.3%). This parameter is physically very difficult to determine, and therefore a mere supporting point for the mathematical expression.

$f_e$ (0.9%) and $C_v$ (2.3%) hardly show any outliers after the optimization process. The heterogeneous database can thus be described with homogeneous parameters.

## Parameter Estimation

For the estimation of the parameters in the modified Horton equation techniques of linearised regression models and parameters describing soil and tillage boundary conditions are used. Parameters in the regression equations contribute significantly to the prediction of $f_e$ and $C_v$ (see p-values in Table 1). $f_0$ is estimated from the curvature of the Horton equation $C_v$.

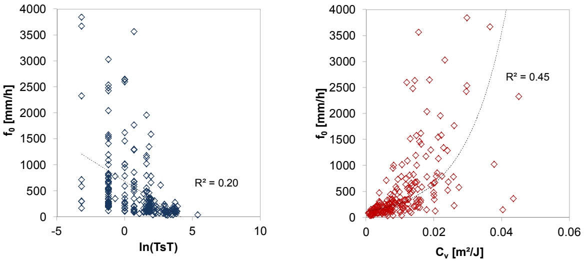



Figure 2: Correlation between parameters from the extended database

| p-value | $C_v$ | $f_e$ | $f_0$ |
|---|---|---|---|
| Intercept | 0.05 | 0.24 | ≤0.05 |
| Clay | 0.05 | ≤0.05 | |
| Silt | 0.05 | | |
| Sand | 0.05 | ≤0.05 | |
| $\sigma(d_g)$ 1) | ≤0.05 | ≤0.05 | |
| Skeleton | 0.06 | ≤0.05 | |
| $C_{org}$ 2) | ≤0.05 | ≤0.05 | |
| ln(TsT) 3) | ≤0.05 | ≤0.05 | ≤0.05 |
| $C_v$ 4) | | | ≤0.05 |

Table 1: p-values of the regression variables for the respective parameters of the Horton equation
1) standard deviation of the geometric mean particle diameter [µm]
2) Organic Carbon [%]
3) Time since tillage [in days]
4) previously estimated

$$C_v = 1.735 - 0.0002 \cdot \sigma(\mathrm{dg}) - 0.0169 \cdot Skeleton - 0.0037 \cdot C_{org} - 1.7120 \cdot Sand - 1.722 \cdot Clay - 1.717 \cdot Silt - 0.0022 \cdot \ln(TsT)$$

$$f_e = 3.3 - 0.4 \cdot \sigma(\mathrm{dg}) + 0.5 \cdot Skeleton + 4.6 \cdot C_{org} + 9.1 \cdot Sand + 21.5 \cdot Clay + 1.8 \cdot \ln(TsT)$$

$$\log(\mathrm{f}_0) = 2.253 + 28.556 \cdot C_v - 0.0946 \cdot \ln(TsT)$$

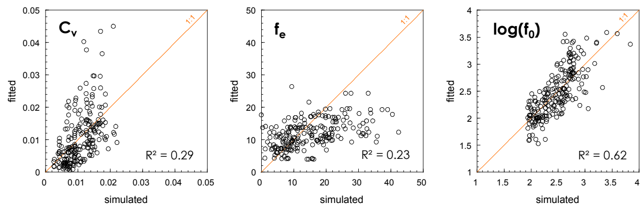



Figure 3: Simulated and fitted parameters using multiple regression

## Model Extension and Validation

The distributed hydrological modelling system WaSiM-ETH (Schulla & Jasper 2007) is a highly flexible tool in hydrological problems and has been used in numerous projects worldwide. In Version 8.10.04, WaSiM-ETH has been extended to implement the process-based runoff generation on arable soils. Surface runoff driven by a crusting top soil is simulated by an overlaying layer above the soil model of the unsaturated zone (movement is described by Richard's equation), and surface runoff is routed seperately from grid cell to grid cell by a kintematic wave approach until the runoff is discharged into the river system.

| Component | in WaSiM-ETH |
|---|---|
| Evapotranspiration | Penman-Monteith |
| Unsaturated Zone | Richards (van Genuchten) |
| Saturated Zone | Darcy |
| Macropores | Bypass-Flow |
| Runoff concentration (Interflow) | Single Linear Reservoir Cascade |
| Runoff concentration (Surface Runoff) | Kinematic Wave |
| Flood Routing | Kinematic Wave |

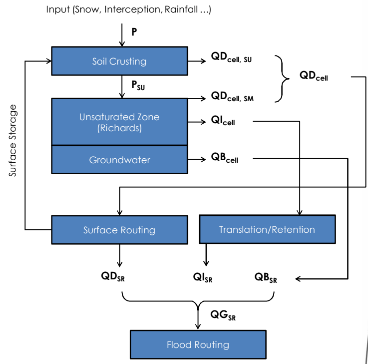



Figure 4: Components of the hydrological cycle and their mathematical approach in WaSiM-ETH (Version 8.10.04); flow diagram of model extension regarding runoff components

The extended model has been valuated on a subset of 24 experiments of the data base where climatic boundary conditions of the period prior to the experiment were available.

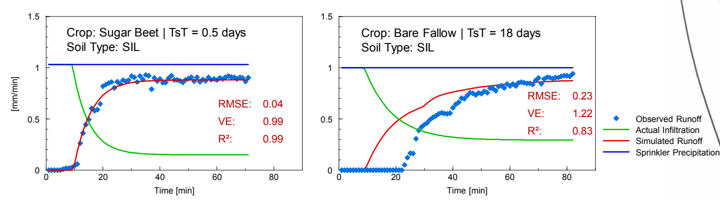



Figure 5: Uncalibrated model output of the extended WaSiM-ETH Model for the simulation of single sprinkler experiments. The difference in performance mainly depends on the correct estimation of time to runoff and the end infiltration rate $f_e$.

## Single Rainfall Event in *Scheyern*

The research farm *Scheyern* is located about 40 km north of Munich, Germany, in the Tertiary hills north of the Alps. In 14 small catchments (0.8 – 16.8 ha) runoff volume of single surface runoff events has been recorded. Catchments E01 – E06 have been managed by a soil conserving tillage (mulch, ploughless tillage, combination of work sequences).

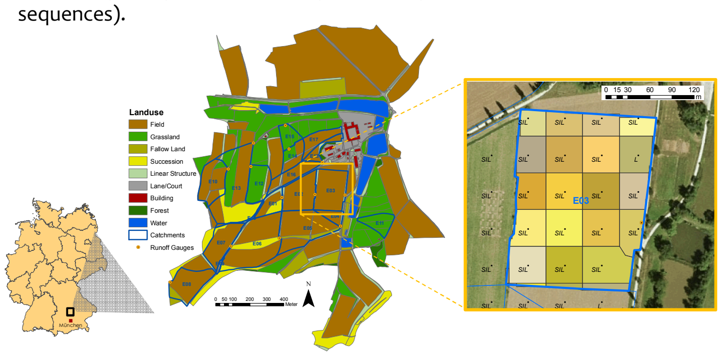
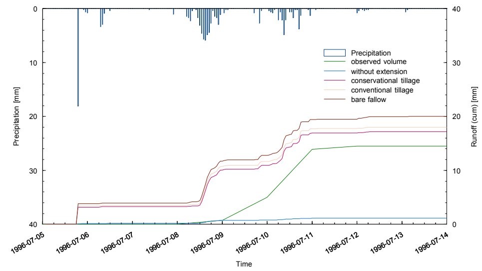



Figure 6: Location and landuse of the research farm *Scheyern*, delineation of catchments and regionalisation of soil parameterisation on catchment E03

A heavy rainstorm in July 1996 (107mm) has been modelled on catchment E03. Maize was seeded 74 day prior to the event (=TsT). Without the model extension runoff volume is highly underrated. The additional modules can describe the different tillage systems, but overestimate the observed runoff volume.




| *July 1996 on E03* | observed | without extension | conservational tillage | conventional tillage | fallow |
|---|---|---|---|---|---|
| Runoff volume [m³] | 613 | 49 | 724 | 760 | 845 |
| VE [-] | - | 0.08 | 1.181 | 1.24 | 1.378 |

Figure 7: Rainfall/Runoff Event from 07/05 – 07/14 and results of the model extension and different tillage praactices

## Summary and Outlook

The change in tillage practice towards a conservational tillage has been shown to protect the soil from forming a sealing crust and thus reducing runoff under the condition of heavy precipitation events. With the approach developed in this study this can be shown for single events on a process-based approach and on a very detailed spatial and time scale. The modules for soil crusting induced infiltration and surface routing are able to bring a higher precision to small scale applications.

In a next step the model is upscaled to the lower mesoscale to quantify the reduction of surface runoff due to adjusted tillage practices.

## References


Seibert, S.; Auerswald, K.; Fiener, P.; Disse, M.; Martin, W.; Haider, J.; Michael, A. and Gerlinger, K. (2011): Surface runoff from arable land - a homogenized data base of 726 rainfall simulation experiments. DOI: 10.1594/GFZ.TR32.2.

Schulla, J. & Jasper, C. (2007): WaSiM-ETH Model Description (available at http://www.wasim.ch).



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