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Effects of conservation tillage on storm flow: a model-based assessment for a mesoscale watershed in Germany

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Abstract The hydrological model LARSIM was used to assess the flood mitigating effect of conservation tillage within the 195-km^2 loess covered watershed of the River Glems, Germany. In order to adequately account for the effect of conservation tillage on the infiltration process and the formation of infiltration-excess overland flow, LARSIM was extended by an infiltration module. The new module was parameterized with the results of small-scale field studies, enabling one to upscale these results to the watershed scale. Modelling scenarios for River Glems show that only the peak discharges of floods caused by convective rain events of high intensity are mitigated by introducing conservation tillage. Since most floods in the mesoscale watershed are caused by advective precipitation events of moderate intensity, the overall effect of conservation tillage on peak discharges of given return periods is negligible.

Key words flood mitigation; hydrological model; infiltration-excess; land-use scenario; LARSIM; loess soil; River Glems; runoff generation; soil management practice

INTRODUCTION

One major goal of the "IAHS Decade on Predictions in Ungauged Basins" (PUB) is to advance our ability to predict the effects of land surface alterations on hydrology. One way to reach this target on the watershed scale is to implement process-based approaches into existing hydrological models (Bronstert, 2000). These process-based modules help to reduce prediction uncertainty, because they can be parameterized with physically meaningful values which can be derived from field experiments.

The question, whether changing agricultural practice from conventional to conservation tillage in loess areas may help to mitigate flood discharges at the watershed scale, is closely related to the above-mentioned target of PUB. Conventional tillage involves mouldboard ploughing and harrowing, while conservation tillage is characterized by less soil disturbance, reduced penetration depth without topsoil inversion and higher soil coverage with mulch residues and intercrops (Tebrügge & Düring, 1999). Most small-scale field experiments show that the infiltration capacity of loess soils is increased by conservation tillage, which is mainly attributed to an increased vertical connectivity of macropores (Gerlinger, 1997; Hangen *et al*., 2002). There is also some experimental evidence that the soil's total water storage capacity may be increased because of less compaction and the additional connection of deeper soil layers (Buczko *et al*., 2003). Moreover, mulch residues and intercrops increase interception losses and evapotranspiration on conservation tillage sites.

Based on these findings, it has often been concluded that conservation tillage leads to a reduction of infiltration-excess overland flow and consequently to reduced flood discharges in watersheds of variable size (for a discussion see: Niehoff, 2001). However, it is difficult to upscale field experiments and predict the effects of tillage conversion on the watershed scale, because the commonly used conceptual hydrological models cannot be directly parameterized with experimental results (e.g. Bronstert, 2000).

The hydrological model LARSIM allows the discrimination of different land-use classes (i.e. fields with conventional and conservation tillage) on a high spatial resolution (Bremicker, 2000). However, its soil module is based on a conceptual approach. Therefore, we enhanced LARSIM by implementing an infiltration module which allows one to explicitly account for the formation of infiltration-excess overland flow. The enhanced model was used to run tillage scenarios for the agricultural mesoscale watershed of the River Glems in southwest Germany. The model results help to elucidate the influence of tillage conversion on flood discharge at the watershed scale.

STUDY SITE

The River Glems drains a catchment area of 195 km^2 near the city of Stuttgart in southwest Germany (Fig. 1). The northern part of the densely populated watershed is under intensive agricultural use. The soils in this area are dominated by silty Luvisols above loess. At present, 37% of the catchment area (72 km^2) is under tillage. All fields are conventionally managed by mouldboard ploughing and harrowing. Average air temperatures range between –2°C in January and 16°C in July. The long-term average precipitation is about 750 mm per year. Precipitation is mostly due to large scale advective events. Consequently, most floods are caused by long lasting advective rain events (including rain on snow). However, thunderstorms with high rain intensities (>25 mm h^{-1}) may occasionally cause floods during summer (Haag *et al*., 2004).

MODELLING APPROACH

The hydrological model LARSIM

The hydrological model LARSIM (Bremicker, 2000) was used for the analysis presented below. It is based on distributed data of a digital elevation model, digital maps of land-cover and soil classification, the river network and geometries along with additional information about retention ponds and reservoirs. In the present case, the model is run on a 1 × 1 km^2 grid. To account for sub-grid variability, interception, snow accumulation and melt, evapotranspiration and soil water movement (including runoff generation) are simulated separately for 16 distinct land-use classes within each grid cell. In the original version of LARSIM, the land-use specific soil column is simulated with the Xinanjiang approach (Zhao *et al*., 1980), applying its modified form as described by Todini (1996). Runoff concentration within each grid cell is

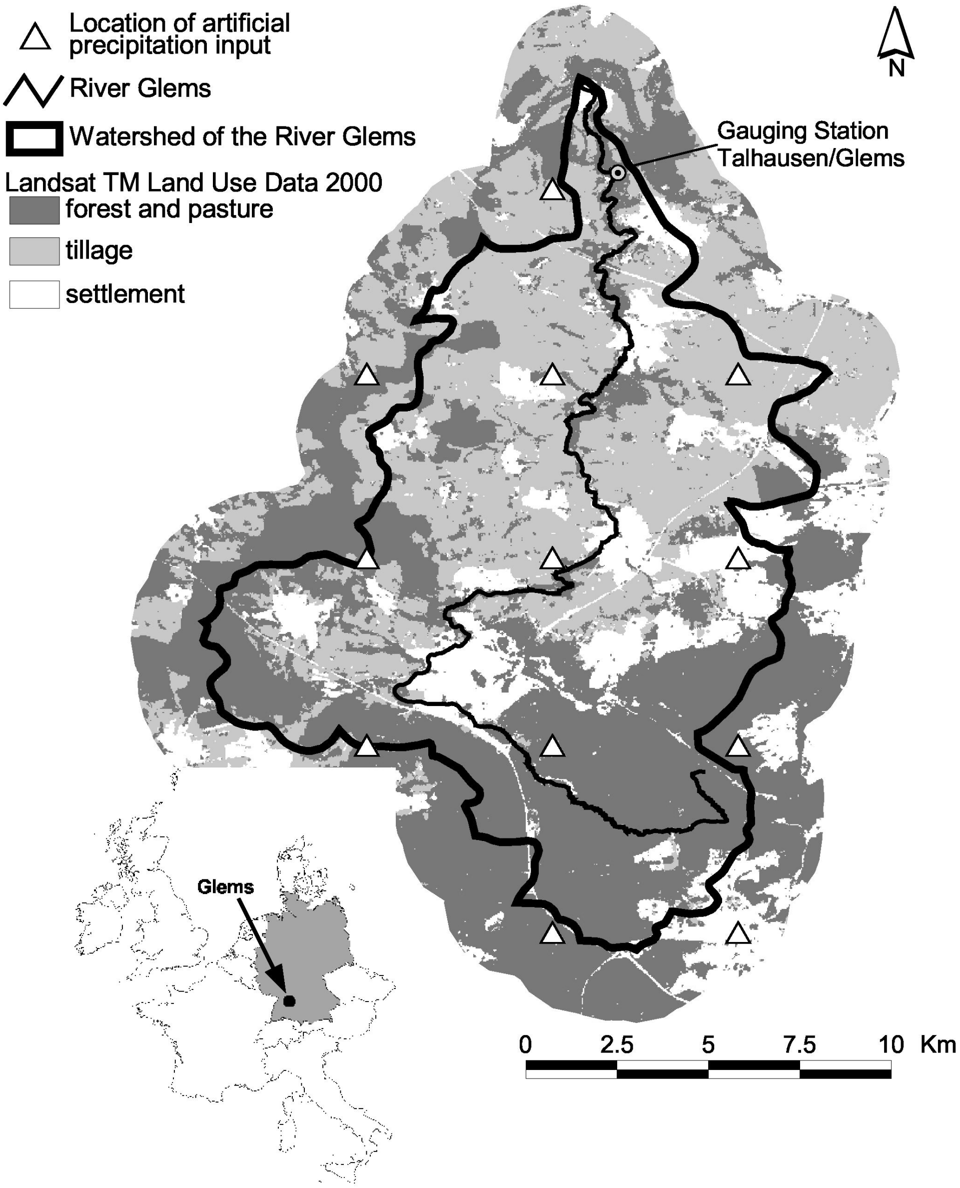

Fig. 1 The watershed of the River Glems; land-use, location of the streamgauge and locations of artificial precipitation input.

simulated with three parallel linear reservoirs: one for groundwater discharge, one for interflow, and one for direct runoff. Direct runoff comprises a mixture of fast subsurface runoff (e.g. lateral macropore flow) and overland flow. Flood routing within the river sections is performed with a kinematic wave approach.

The major hydrological effect of altering the tillage system is a change of the infiltration capacity, and the resulting change of infiltration-excess overland flow. Since the Xinanjiang approach implemented in the original LARSIM model lumps fast subsurface runoff and overland flow to direct runoff, it cannot be used to investigate the effects of conservation tillage on flood discharge. Therefore, the Xinanjiang soil model was extended by an infiltration module, allowing the discrimination of fast subsurface runoff and infiltration-excess overland flow.

This enhanced soil model is depicted schematically in Fig. 2. The actual infiltration capacity (I) is expressed analogously to Horton's exponential infiltration model (Horton, 1939), based on a minimal and a maximal infiltration capacity ($I_{\min}$, $I_{\max}$) and a decay factor (b):

$$I = I_{\min} + \left(I_{\max} - I_{\min}\right) \cdot \exp\left(-b \cdot \frac{W - W_{per}}{W_{\max} - W_{per}}\right) \tag{1}$$

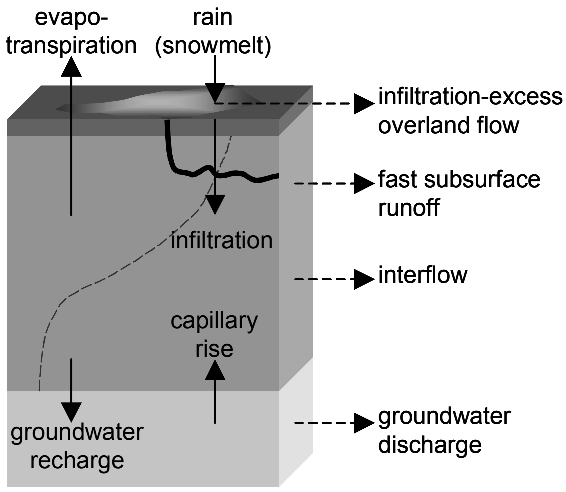

Fig. 2 Schematic sketch of the enhanced soil module of LARSIM.

The relation between the model's actual soil water content (W), its maximum water storage capacity ($W_{\max}$) and the water content at the wilting point (W_{per}) is used as a surrogate for the time after the onset of rainfall. Note that after a long dry spell, when W approaches its minimum of W_{per}, I approaches $I_{\max}$. On the other hand, with rainwater infiltrating into the soil column and W approaching $W_{\max}$, I asymptotically approaches $I_{\min}$. The decay factor b determines how fast I approaches $I_{\min}$. Its value can be derived from infiltration experiments, just as in Horton's original approach. The parameters $W_{\max}$ and W_{per} are derived from soil classification maps, whereas $I_{\max}$ and $I_{\min}$ are calibration factors which can be derived from small-scale infiltration experiments. It is important to note that the infiltration process is modelled separately for each land-use class within a grid cell. It is thus possible to discriminate the land-use classes conventional tillage and conservation tillage by choosing different values for $I_{\max}$ and $I_{\min}$.

Note that whenever rainfall intensity exceeds the actual infiltration capacity of the model soil, infiltration-excess overland flow is generated. The other three runoff components depicted in Fig. 2 are generated according to the Xinanjiang approach. Thus, when applying the extended soil model, runoff concentration is simulated with four (instead of three) parallel linear reservoirs, because direct runoff is divided into fast subsurface runoff and overland flow. Saturation overland flow can also be included in the extended soil model. However, it was neglected in the present study because it is of minor importance within the watershed of River Glems (Haag *et al.*, 2004).

Model calibration and validation

Utilizing measured hydro-meteorological data as forcing variables, the above described model was calibrated using measured discharge at the streamgauge of Talhausen for the years 1997–2000. The model was validated for 2001–2003. For any single year of the calibration and validation period, correlation coefficients of 0.85 to 0.92 and Nash-Sutcliffe coefficients of 0.70 to 0.85 were obtained.

Measured rain data with a high temporal resolution were only available for seven years (1997–2003). Since the present study focuses on major floods, it was necessary to simulate a longer time span. Therefore, in addition to measured data, we also ran the model using a 30-year record of artificial precipitation with a high temporal and spatial resolution (Fig. 1), which was provided by the LfU. The artificial rain data set had been generated by Bárdossy *et al.* (2001), applying external-drift-kriging and a simulated-annealing algorithm (Bárdossy, 1998). The artificial data have proven to represent measured precipitation appropriately with respect to intensity and overall amount as well as temporal and spatial distribution and correlation (Bárdossy *et al.*, 2001).

The flood frequency analysis of the simulated 30-year hydrograph matches well with the frequency analysis of the measured long-term discharge record (data not shown). This finding shows that the calibrated model is also valid for extreme floods with return periods beyond 10 years.

Specification of the land-use scenarios

To analyse the effect of tillage conversion, we introduced an additional land-use class for conservation tillage, and ascribed 10, 20 and 50% of the area originally classified as conventionally tilled arable fields to this new class. Since there was no further information about the likely location of the conservation tillage sites, we assumed a conversion rate of 10, 20 and 50% within each 1×1 km^2 grid cell. As discussed above, the major hydrological effects of converting tillage practice from conventional to conservation are changes of the infiltration capacity, the soil water storage capacity, the interception and the evapotranspiration. Based on the results of a literature review (see Gerlinger, 1997; Haag *et al.*, 2004), these effects were taken into account by changing the land-use specific parameters of the new land-use class as follows: I_{min} and I_{max} were increased by a factor of 1.33 and W_{max} was increased by a factor of 1.05. Figure 3 demonstrates that the effect of these changes on the modelled infiltration process are very similar to those observed in field experiments. The effects of inter-crops and mulching were taken into account by adjusting the leaf area index and the albedo during the winter months, which causes increased interception capacities and evapotranspiration for the newly introduced land-use class of conservation tillage.

According to the local agricultural authorities, about 10 to 20% of the farmers would be willing to change their soil management to conservation tillage. Thus, the 50% scenario is primarily used to give hints to what would be theoretically possible. The three scenarios were driven by the artificial rainfall data described above. They can thus be evaluated by comparison with the above mentioned long-term validation run, which assumes 0% conservation tillage.

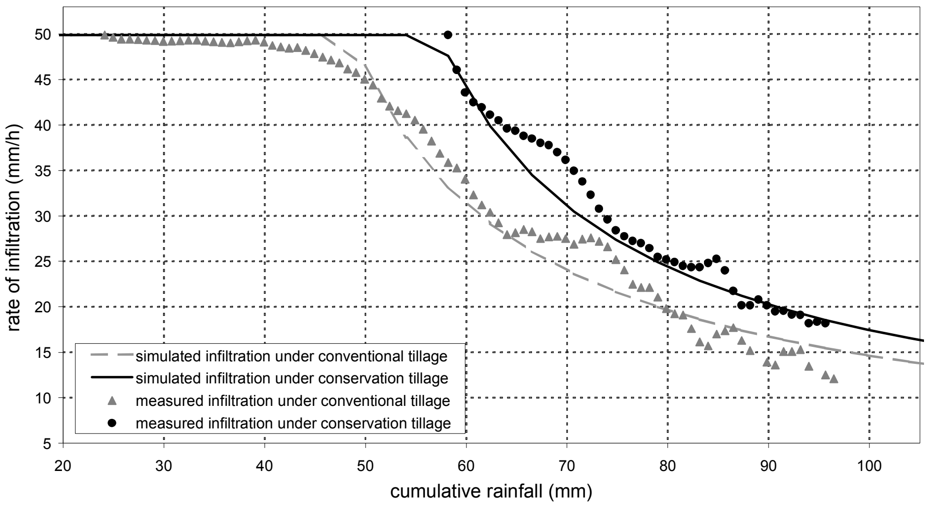

Fig. 3 Numerical infiltration experiments with the infiltration module for a model soil under conventional and conservation tillage, along with experimental results from Gerlinger (1997).

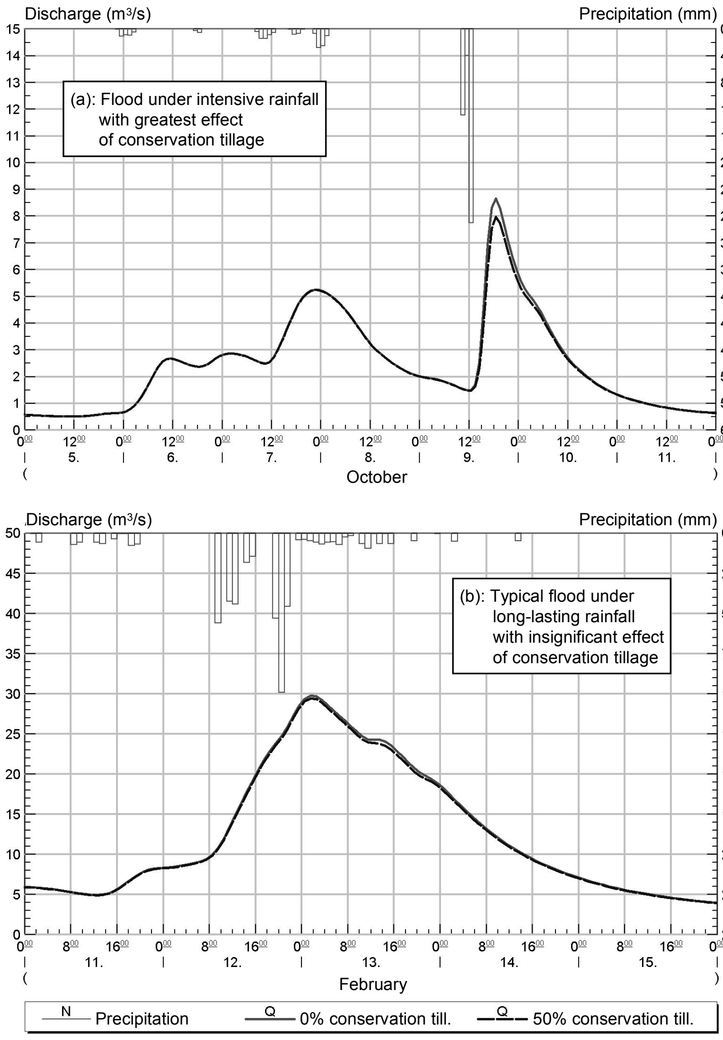

Fig. 4 Results of scenarios for the present tillage practice (0% conservation tillage) and assuming conservation tillage on 50% of all arable land.

RESULTS

Analysing the simulated effects of conservation tillage showed that generally only those events triggered by intensive rainfall (of at least ~ 25 mm h^{-1}) exhibit a visible reduction of peak discharge. Such an event is exemplified in Fig. 4(a) for the 0% and the 50% scenario. On the other hand, floods caused by long-lasting advective precipitation, are barely influenced by tillage practice, as exemplified in Fig. 4(b).

To further assess these qualitative findings, we analysed the simulated reduction of peak discharges of the largest yearly floods of the 30-year period, which result from changing the soil management from conventional to conservation tillage on 50% of all arable land. The frequency distribution of the resulting relative changes is shown in Fig. 5. For 21 out of 30 events, discharge peaks are reduced by <1.5%. For the flood exemplified in Fig. 4(a), the discharge peak is reduced by 7.9%. The remaining eight events show peak discharge reductions between 2.0 and 6.5% (Fig. 5). As could be expected, the 10 and 20% scenarios show the same pattern with a generally smaller reduction of peak discharges (data not shown).

Finally, we conducted a flood frequency analysis, using the largest flood peaks simulated for each year. For this analysis the Log-Gumble distribution was chosen out of 14 statistical distributions, because it fitted the data best. The results of the frequency analysis are summarized in Table 1. In general, there is a slight reduction for peak discharges of all return periods, when changing agricultural practice to conservation tillage. However, the resulting reduction is <1%, when assuming that 10 or 20% of all fields are under conservation tillage. Even with an unrealistically high proportion of 50% of conservation tillage, the resulting reduction of flood discharges with return periods between 2 and 100 years would be <2%.

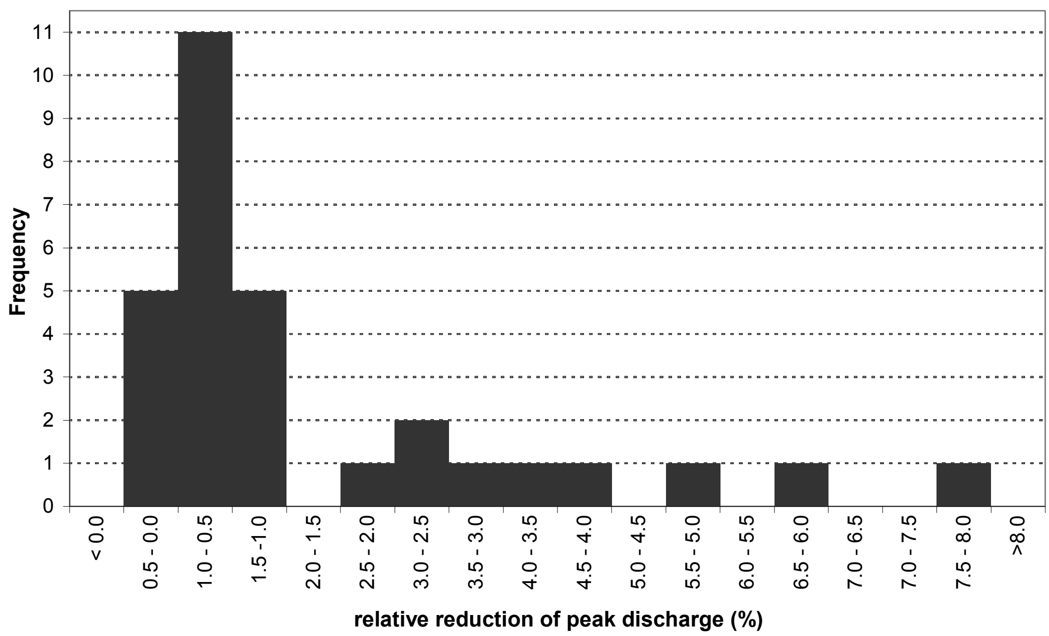

Fig. 5 Frequency distribution of the relative reductions of peak discharges of yearly floods, as caused by changing soil management from 0% to 50% conservation tillage within the watershed of River Glems.

Table 1 Calculated peak discharges of various return periods assuming 0, 10, 20 and 50% conservation tillage on all arable land, along with relative changes as compared to the 0% scenario.

Return period (years)	Peak discharge 0%–scenario ($m^3 s^{-1}$)	10%–scenario ($m^3 s^{-1}$)	10%–scenario (Δ %)	20%–scenario ($m^3 s^{-1}$)	20%–scenario (Δ %)	50%–scenario ($m^3 s^{-1}$)	50%–scenario (Δ %)
2	10.12	10.09	–0.3	10.06	–0.6	9.98	–1.4
5	14.89	14.84	–0.3	14.80	–0.6	14.66	–1.5
10	19.23	19.16	–0.4	19.10	–0.7	18.92	–1.6
20	24.58	24.48	–0.4	24.39	–0.8	24.16	–1.7
50	33.76	33.61	–0.4	33.49	–0.8	33.16	–1.8
100	42.82	42.62	–0.5	42.46	–0.8	42.03	–1.8

DISCUSSION AND CONCLUSIONS

The characteristics of the precipitation event triggering a particular flood are of outstanding importance for the flood mitigating effect of conservation tillage within the 195 km^2 watershed of the River Glems. For floods caused by long lasting (advective) rain events with moderate intensities (less than ~25 mm h^{-1}) fast subsurface runoff processes are the main cause of flood formation, whereas infiltration-excess overland flow on tilled sites is of little importance. Consequently, for this majority of flood events, increasing infiltration capacity by conservation tillage has very little effect on peak discharge. On the other hand, for a minority of floods which are caused by very intensive rain events (i.e. thunderstorms), infiltration-excess overland flow on tilled sites plays an appreciable role in flood formation. In these cases, the effect of increasing infiltration capacity by tillage conversion decreases infiltration-excess overland flow and consequently leads to a visible reduction of peak discharge. Using a different model and measured precipitation data, Niehoff *et al.* (2002) obtained similar results for another mesoscale watershed in Germany.

Since the clear majority of major floods at the River Glems streamgauge are caused by advective rain events, the resulting flood frequency distribution is barely affected by tillage practice. Even under the extremely optimistic assumption that soil management on 50% of the arable land (i.e. 19% of the watershed area) is changed to conservation tillage, peak discharges with return periods between 2 and 100 years, would only be reduced by <2%.

For similar climatological conditions, convective rain events and infiltration-excess tend to be more important for flood formation within very small watersheds (Bronstert, 2000). Hence, tillage conversion is likely to have an overall appreciable flood mitigating effect in such small (~10 km^2), loess covered, agricultural watersheds. However, as demonstrated in the present study and in that of Niehoff *et al.* (2002), the flood mitigating effect of tillage conversion diminishes at the mesoscale (~100 km^2). For large river systems (~10 000 km^2 and more) very intensive, convective rain events and infiltration-excess are usually of very little importance for flood formation (Bronstert, 2000). Consequently, there is most probably no appreciable flood mitigating effect of conservation tillage at the macro-scale.

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