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Effect of soil shrinkage on runoff generation in micro and mesoscale catchments

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Abstract Catchments dominated by clay rich soils might show distinct seasonality over several spatial scales. We present a microscale catchment study in southern Germany which gives an understanding of the hydrological processes dominating clay soil catchments. Shrinkage and swelling of soils lead to a highly nonlinear threshold behaviour of individual events, strongly dependent on the respective soil moisture state. With understanding the microscale catchment processes, we are able to find links to the behaviour of larger clay soil catchments as well. Thus, mesoscale catchment studies in the Kostroma basin, Russia, show a very similar system response and seasonality due to dominant clay rich soils, though the climatic pattern varies with some respect. We think that the impact of clay soils in runoff generation is observable over several hydrological scales, indicating the importance of integration of specific soil properties in mesoscale runoff investigation.

Key words clay soil catchment; process identification; soil shrinkage; tile drains

INTRODUCTION

Modelling hydrological system response at different scales is hampered by the nonlinear nature of hydrological processes. A thorough understanding of how nonlinear hydrological processes are initiated in different states of a system, how they operate in different landscapes and their impact at different scales, is necessary to decide whether they dominate the system response at a certain scale or may be neglected. Threshold behaviour is often reported as a fundamental characteristic of hydrological dynamics where the system switches between different "dynamic regimes". An obvious example of two different regimes are rainy and dry seasons during a year. Similarly, evaporation may be subject to different regimes, either controlled by atmospheric demand or by soil hydraulic properties (Dooge, 1986). Another example is surface runoff generation which is often conceptualized as a threshold process. Grayson *et al.* (1997) observed two regimes of catchment behaviour associated with wet and dry states. Another important example of a threshold process is the switch between well mixed matrix flow and preferential flow paths in the subsurface (Flury *et al.*, 1994). Zehe & Blöschl (2004) showed recently that even in well observed research catchments, the interplay of typical uncertainty of initial conditions and the threshold nature of preferential flow causes a strongly state dependent uncertainty in predicted rainfall runoff response.

The present study addresses another important threshold phenomenon: shrinkage and swelling of clay soils lead to a strongly non stationary infiltration capacity and soil volume change due to varying water content. Here, we are more interested on the effect of shrinkage of soils on catchments in the micro- (2.3 km²) and the mesoscale (356–683 km^2) than on an exact description of processes on the plot or field scale. We think that local processes of shrinkage and swelling imprint towards the hydrological behaviour on larger scales, so that a discussion of shrinkage of clay soils is necessary to understand mesoscale catchment behaviour of catchments dominated by clay soils.

Internal shrinkage and swelling of clay minerals like smectites or vermiculites due to exchangeable interlayer cations may influence shrinkage characteristic of soils or clay pastes (Olsen & Haugen, 1998; Kariuki & van der Meer, 2004). But more likely, shrinkage behaviour of soils is not so much a function of the internal swelling capacity of specific clay minerals, but of the volume fraction of additional components in the soils and especially the size and structure of the clay minerals (Wilding & Tessier, 1988), which influence interparticle porosity (Chertkov, 2000a, 2003). The shrinkage characteristic curve describes the volume change of soils in relation to a specific water content (McGarry & Malafant, 1987; Braudeau *et al.* 1999). Four zones of volume change are usually distinguished: zero, residual, normal and structural shrinkage (Braudeau *et al.* 1999). The "normal" shrinkage zone is usually most important for the volume change in soils (Peng & Horn, 2005), volume loss is proportional to water loss. A deformation of pores occurs instead of a penetration or displacement of air in the pores (Bronswijk 1988; Chertkov 2000a). Thus the volume change of the pores also influences the hydraulic function of the matrix in non-rigid soils (Kim *et al*. 1999; Chertkov, 2004; Peng & Horn 2005) as well as leading to the development of cracks even in saturated soils, which then allows preferential infiltration into lower soil horizons (Bronswijk, 1988; Novák *et al.*, 2000; Šimůnek *et al.*, 2003; Wells *et al.*, 2003). If the soil wets up above a certain threshold, the cracks successively close and surface runoff generation will dominate, as for example found in vertisols of northern Mexico by Návar *et al.* (2002). For temperate climate zones the normal and structural shrinkage zone are most important, as volume changes in these shrinkage zones lie in the reach of typical soil moisture changes.

Field sites with clay soils are often tile drained for improving agricultural practice (Attenberger, 1989) in regions with temperate or humid climate. Though removing excess water from the fields, tile drains also tend to remove solutes such as herbicides quicker than wanted through macropores and shrinking cracks in wet and dry conditions (Kohler *et al.*, 2001; Honisch *et al.*, 2002; Stamm *et al.*, 2002), leading to an alteration of surface waters both in quality and quantity. Furthermore, as land consolidation is a common practice to enhance agricultural use, it is of major interest whether subsurface drainage of cracking clay soils does increase the risk of rapid solute transport and does alter runoff production or not (Reid & Parkinson, 1984).

The main objective of the present study is to shed light on how soil shrinkage and related threshold behaviour affects catchment scale rainfall–runoff response. Our special emphasis is on the role of antecedent soil moisture conditions as a controlling variable, though the lack of soil moisture measurements forces us to revert to alternative indices, as for example pre-precipitation depths. Understanding this control is a prime precondition for modelling runoff generation in catchments with clay soils. To our knowledge Harvey (1971) is the only author who specifically links the behaviour of a mesoscale catchment to the existence of clay rich soils. He describes a strong seasonality in runoff generation. Recent hydrological studies rather concentrate on the plot or field scale (Reid & Parkinson, 1984; Mohanty *et al.*, 1998; Heppel *et al.*, 2000; Needleman *et al.*, 2004) but neglect runoff behaviour on a catchment scale.

MATERIALS AND METHODS

Microscale catchment

Study area and land consolidation The Tannhausen catchment with the Sechta creek (Fig. 1a) is a headwater catchment of the Danube River located in northern Baden-Württemberg, Germany (49°00′E, 10°20′N). The 2.3 km² large catchment is dominantly covered with fields (62%) and meadows (30%). Forest (<5%) and settlements (1%) are less significant. The catchment is situated in an area with gentle hills, 500 to 550 m above sea level.

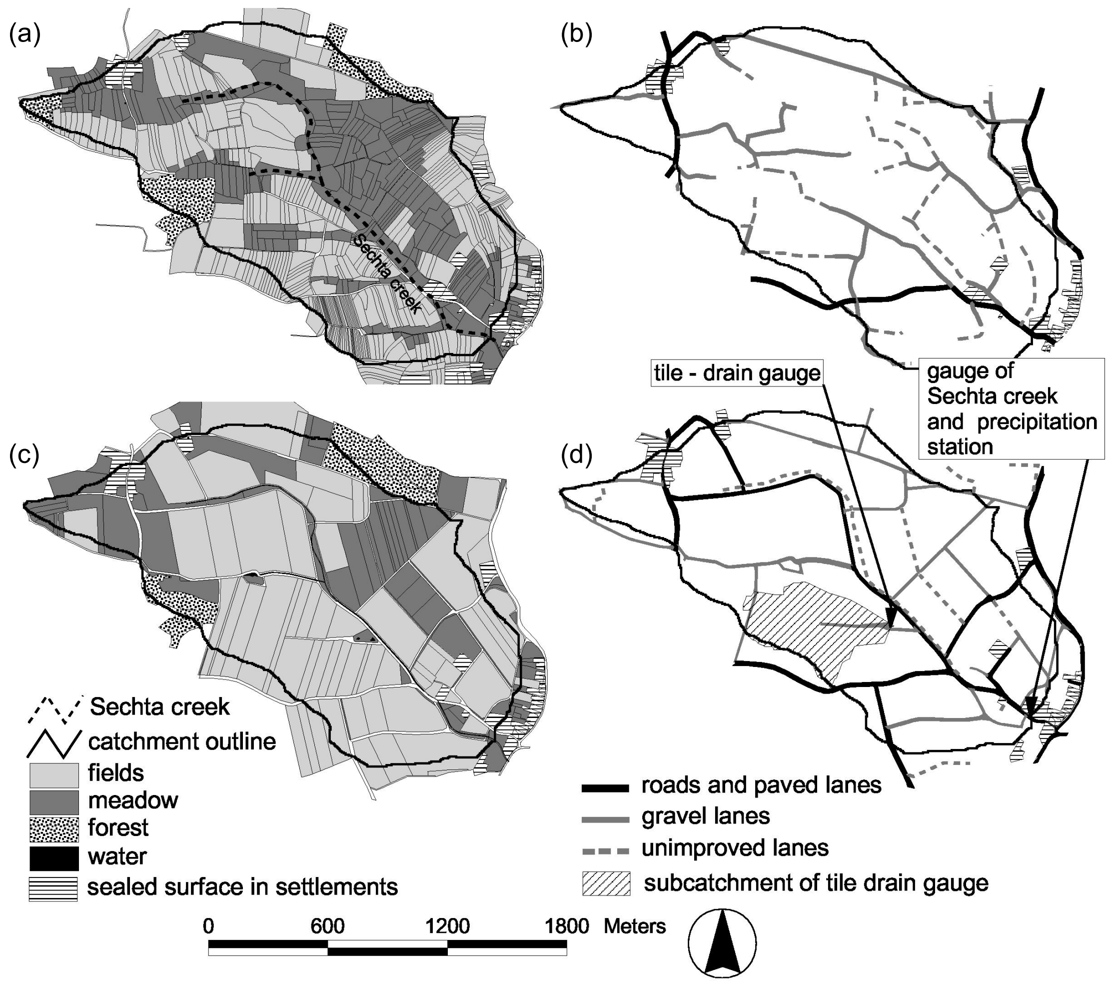

Fig. 1 Changes through land consolidation in the Tannhausen catchment: property boundaries in 1992 (a) and 2004 (c); status of road system in 1992 (b) and 2004 (d). Location of hydrological devices are added in map (d).

Within the last 12 years, land consolidation has been undertaken in the catchment. Most of the landscape reconstruction was conducted between 1995 and 2000. Besides a reorganization of property values (Fig. 1(a),(c)), the landscape was remodelled for more effective land use. The position and make of the main road remained, but the country lane system was totally remodelled (Fig. 1(b),(d)). The total length of roads and country lanes, also referred together as "roads", before and after land consolidation stayed equal at about 14 km. Build up and sealing changed substantially, grass lanes dominated the catchment until 1998. Since 2001, most lanes are either paved or gravelled. The paved and gravel lanes are accompanied by ditches adding to a surface drainage system. Around the 1930s subsurface drainage implementation started, gradually covering up to two thirds of the agricultural area with tile drains. During the course of land consolidation the amount of tile drains increased by 14%. Since 2001 almost all fields are tile drained with a spacing of about 8 m and an approximate depth of 0.8 m; only a few meadows are drained as well (Fig. 2(a)). The diameter of the tile drains is around 60 mm, the collector drains are usually 200 mm; the material and conditions of drains vary by virtue of different implementation ages. Four small flood reservoirs of up to 2000 m^3 of volume were constructed in the late 1990s. An examination of runoff-changes due to land consolidation is not finished yet and is the subject for further publications.

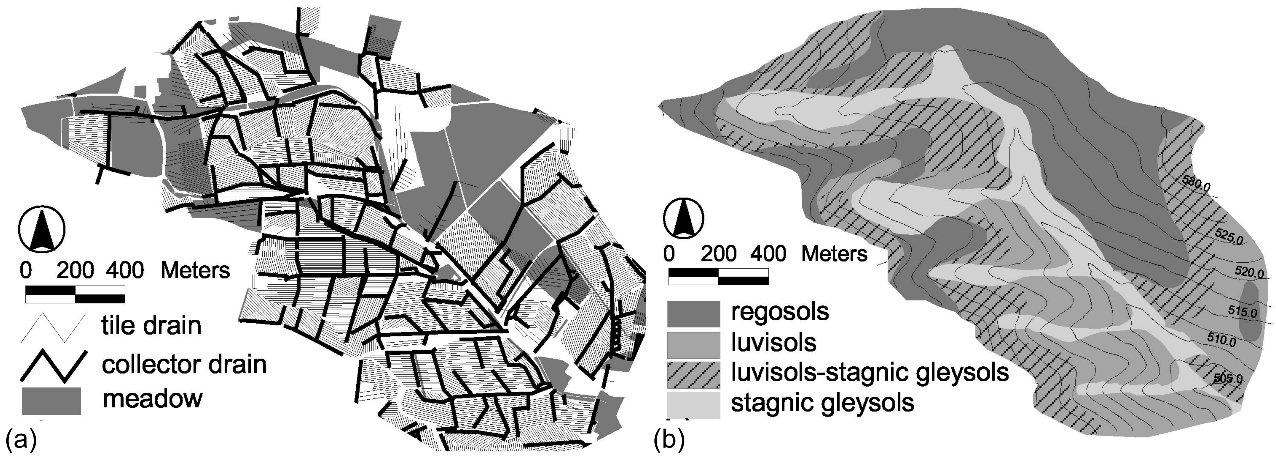

Fig. 2 (a) Soil type distribution in the Tannhausen catchment and location of Sechta creek. The western side consists of five small subcatchments, the eastern side of a rather plane hillslope; (b) tile drain system, meadows are shaded to show their drainage status.

Geology and soil types Basic geological formations consist of lower Jurassic sediments, dominated by clayey and marly rocks. At the rim of the catchment clayey sandstones are found. During the last ice age, up to 1 m of loess accumulated on the eastern hillslope. Cryoturbation and solifluctuation occurred as well, mixing the loess with lower sediments, leaving rather clayey material with low carbonate content for soil development. Dominating soils are luvisols, regosols and stagnic gleysols as well as mixed variants of these types (Fig. 2(b)). The luvisols dominate the southern part of the catchment. Regosols dominate the rather plane eastern slope and the upper parts of the northwestern subcatchments. The stagnic gleysols are found in the depression lines and besides the creeks. The saturated hydraulic conductivity range from 10^{-6} to 10^{-8} m s^{-1} for the soil matrix, though the shrinking capability of the soils alters the soil water movement substantially. Grain size distribution of 34 samples in the Tannhausen catchment are available (Puskas-Schulérus, 1992). More recently, soil samples were taken and analysed for major shrinkage-swelling properties: shrinkage and liquid limits after the DIN 18122 (1997) and the soil solid phase by DIN 18124 (1997). Mineral composition was determined with X-ray diffraction, a standard method in clay mineralogy.

Hydrological equipment and data Since November 1991, discharge was measured by means of a V-notch weir and precipitation was observed by a rainfall tipping bucket, both with 6 min temporal resolution. Time series were checked continuously over the years and weekly inspections of the devices guarantees a high data quality. A temperature device was added in 1999 to the weir. Since 2001, drainage discharge from a completely tile drained subcatchment of approximately 0.2 km² size was collected by means of a V-notch weir box (Fig. 1(d)). In addition, temperature and climatic data from a weather station were available from Aalen city at a distance of 20 km.

We use several thresholds of precipitation depths, runoff peaks or precipitation sums to compare runoff events and to estimate dominating processes or areas which might be active in runoff generation. We applied the unit hydrograph approach to about 263 events, clear snowmelt events which showed runoff coefficients larger than 1 were excluded. We also compared the tile drain discharge of the summers 2002–2004 with runoff at the catchment outlet. For all years we used a minimum of 70 L s^{-1} of runoff peaks for selecting 149 maximum runoff events, which is twice the monthly average runoff. Additionally we examined 114 summer events for the years 1992–1994 and 2001–2004 to determine changes through landscape remodelling and to better understand the impact of shrinkage and cracks. We omitted the hydrological years of 1995–2000 because major changes in land consolidation was conducted then and so runoff might not present a static landscape condition.

Mesoscale catchment

For the comparison of runoff patterns in small and mesoscale catchments dominated by clay soils, we use hydrological investigations in parts of the Volga River basin in Russia. We chose three mesoscale catchments in the Kostroma basin which are dominated by clay-rich soils which evolved from glacial debris loam and clay.

The study is based on analysis of precipitation-runoff events, based on time series of precipitation depth, runoff and temperature. The analysis of runoff generation was based on a concept of time variant runoff coefficients (constant percentage approach with variable initial losses) and a regionalized unit hydrograph approach for the simulation of runoff concentration. Observations of snow-cover depth were used to calibrate a snow-compaction model which we advanced from a model of Bertle (1966, Helms, personal communication).

RESULTS FOR MICROSCALE CATCHMENT

The climate conditions of the Tannhausen catchment are humid temperate. Average annual rainfall was 651 mm during the observation period from 1992 to 2004. The standard hydrological year in Germany runs from November to October as October is usually dry and has lowest water levels in rivers.

Concerning the precipitation regime of the Tannhausen catchment, November to April have a precipitation depth of 262 mm which is lower than for the months May to October with 389 mm. Snowfall events occur but are usually not too extensive due to a generally warm observation period. A look at Fig. 3(a) gives an idea of the average yearly precipitation–runoff regime; the hydrological year 2004 presents this with an adversative seasonal behaviour. Figure 3(b) plots rainfall duration, depth and intensity for the investigated events, two time spans are significant: we define the months November to March as “winter” and the months June to September as “summer” as they show similar variability in precipitation length and intensity. The precipitation depth features an even distribution over all months. The months April, May and October show a behaviour which is transient to this winter and summer behaviour, according to the precipitation, but also the runoff regime.

Concerning the runoff regime of the Tannhausen catchments, summer events, though with higher precipitation depths and higher rainfall intensities (Fig. 3(b)), usually produce significant smaller runoff peaks than winter events (Fig 3(a)), a substantial initial loss can be observed at all times for individual events. Also, runoff coefficients show a distinct seasonality in between winter and summer periods. Runoff coefficients in winter are high, reflecting high soil moisture conditions. Frozen soils or snowmelt events are not so dominant in winter as the temperature curve reflects in Fig. 3(a). Interestingly, runoff coefficients do not fall below a certain value (0.2) which is not a matter of the preselection we conducted for these events (Fig. 4(a),(b)). In

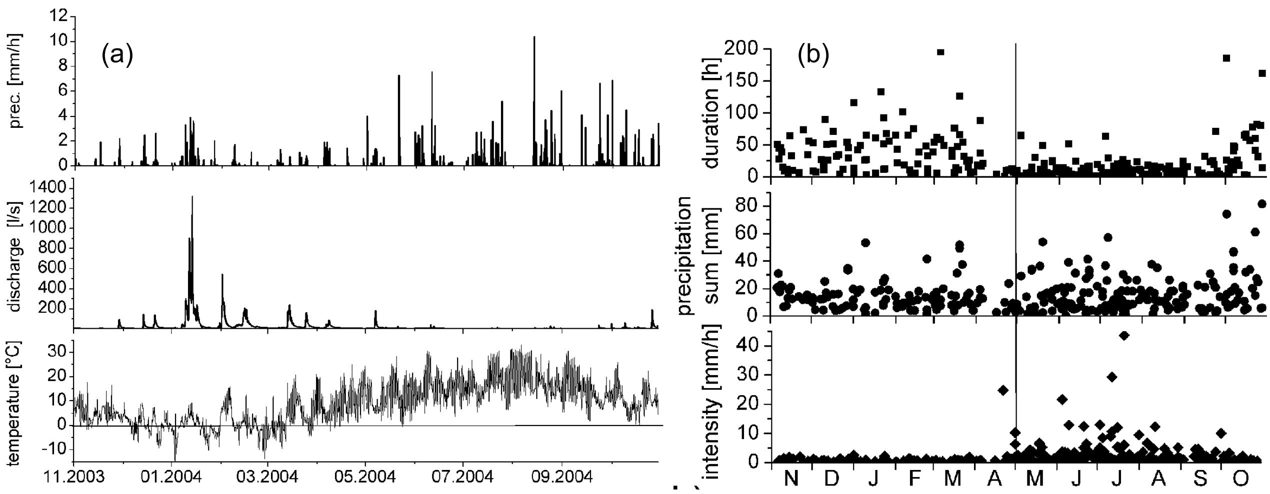

Fig. 3 (a) Hydrological year 2004, seasonality of both precipitation intensity and runoff is distinct (aggregated to 1 hour time steps), temperature shows that runoff in winter is not necessarily due to snow or frozen soil. (b) Distribution of precipitation duration, sum and intensity of 263 investigated events. Whereas precipitation events with similar sums are distributed evenly over the year, intensity is two-fold in summer and winter. Exemptions are April and October, showing a transitional character.

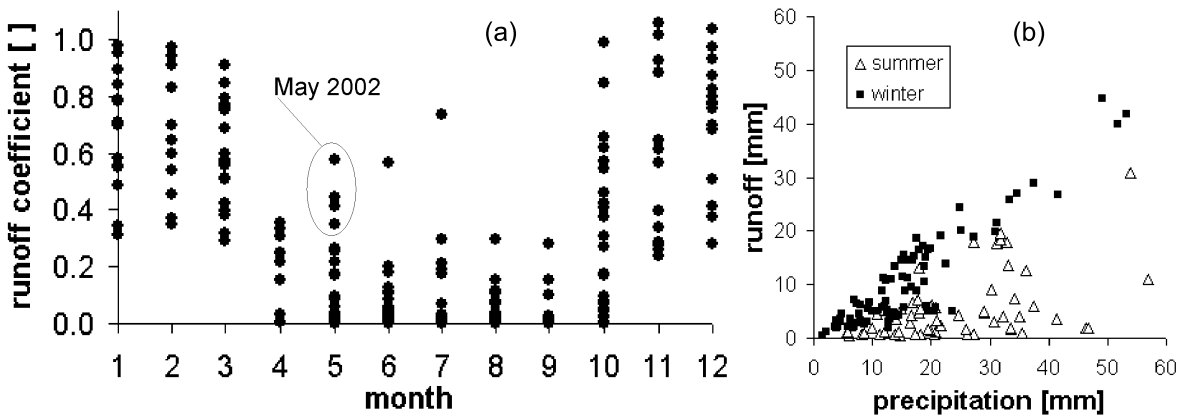

Fig. 4 Runoff coefficients from 149 events with peaks higher 70 L s^{-1} from Tannhausen catchment (1992–2004); (a) month wise plot of runoff coefficients, high coefficients in May are from 2002; (b) scatter plot for runoff and precipitation, summer includes October. Despite similar precipitation sums, summer runoff is distinctly lower.

summer, only seldom occurring long lasting cyclonal events can produce higher runoff coefficients as Fig. 4(a) shows for two events in June and July. October is transient as runoff coefficients are distributed over the whole range whereas other months group more evenly.

Almost all maximum discharge events occur in winter time. From 15 maximum events with peaks larger than 1000 L s^{-1}, only one event occurred in summer. Five events originate from the combination of snowmelt and rain, the other 10, including the largest events, originate from long lasting cyclonal rainfall. These types of events often show maximum discharge shortly after times with highest rainfall intensity. To express this in other words, with a high initial moisture content of the soils in winter, rainfall is almost completely transformed to runoff and so rainfall intensity is imprinted on discharge peaks. In summer, cyclonal events are more rare and seldom additionally lead to high runoff peaks, only one exemption in July 1996 led to a maximum runoff peak of more than 1000 L s^{-1}.

To show the typical summer and winter behaviour of the catchment of the complete observation period, we picked out two events from 2002 in November and July (Fig. 5), which show similar precipitation progress and antecedent precipitation sums. The runoff pattern is also similar but experiences very different peak heights, in summer rising to only 32 L s^{-1}, in winter rising up to 785 L s^{-1}. This high initial loss in summer and very low initial loss in winter with high maximum discharge is observed with almost all investigated events.

Tile drain discharge was observed in the summers of 2002–2004. The dry summers of 2003 and 2004 only yielded few events which showed reactions at the tile drain outlet and the catchment gauge. In 2002, a relatively wet summer with a precipitation depth of 483 mm, multiple tile drain discharge events could be examined. From May to October 2002, 13 precipitation events showed a reaction only at the catchment gauge, another 13 events both at the drainage and the catchment gauge, another 10 events did not show any reaction. Events which showed reactions at the drainage gauge needed at least a precipitation sum of 12 mm. Two types of events can be distinguished: events which we presume to have higher antecedent soil moisture

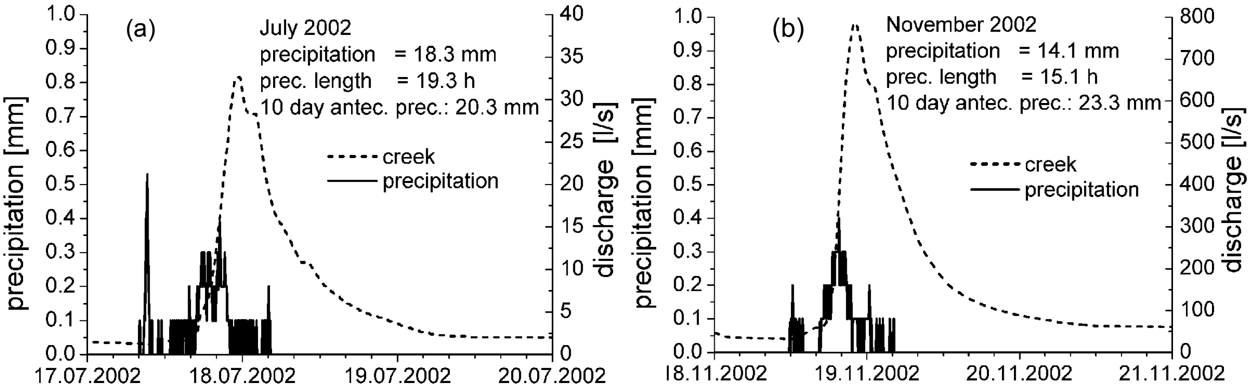

Fig. 5 Two rainstorms with similar antecedent rainfall sums and progress, the summer storm with 18.3 mm of precipitation gives a peak discharge of 32 L s^{-1} (a). The autumn event with 14.1 mm of precipitation has a peak discharge of 785 L s^{-1} (b). Note the similar runoff pattern which is often observed with precipitation events in similar heights and lengths in the Tannhausen catchment.

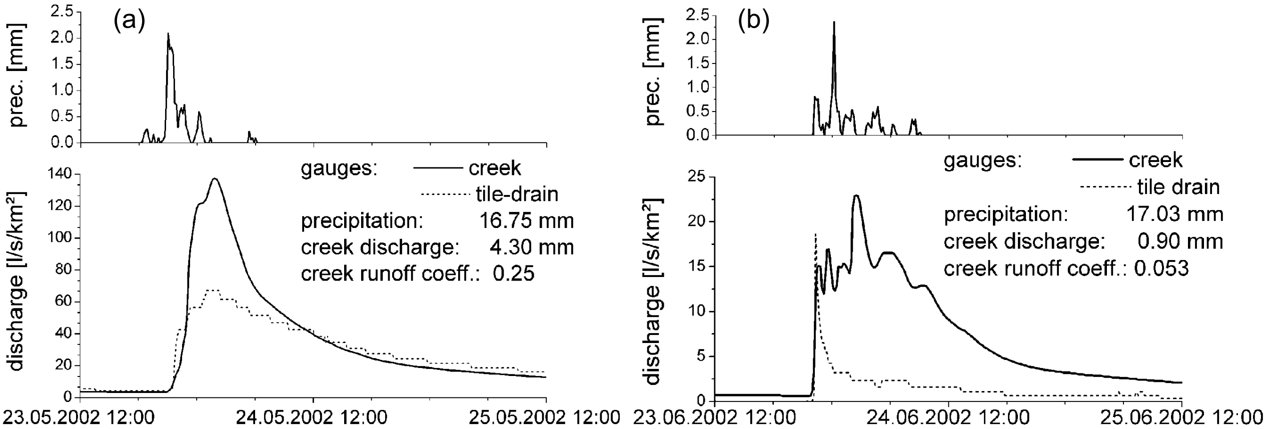

Fig. 6 Comparison of runoff at gauge and tile drain discharge in subcatchment for an event with high antecedent soil moisture (a), and low antecedent soil moisture (b).

conditions show that a high percentage of the total runoff at the catchment outlet is derived by the tile drains (Fig. 6(a)). Due to general high soil moisture states this type of tile drain contribution is typical for winters as well. For the plotted event (Fig. 6(a)) 87% of the normalized discharge volume at the catchment outlet is contributed by the tile drains. The values of tile drain contribution of events in a similar soil moisture state are equally high, though it has to be stated that the high values are based on a comparison of the totally drained subcatchment with the total catchment and that in reality these values might be overestimated by some extent. The second type are events with very low antecedent soil moisture conditions (Fig. 6(b)), often a quick response of the drainage is seen, but without contributing significantly to the total runoff volume. The tile drains have a distinct impact on the total discharge in the Tannhausen catchment, the processes leading to tile drain discharge are yet governed by the soil moisture state and are linked to cracks, especially in dry states of the soil (Fig. 6(b)).

In Fig. 7 the grain size distribution for 34 soil samples of the uppermost soil horizon are plotted, showing dominant silt and clay fractions and representing three different end members of soil types. The clay mineral fraction consists mainly of vermiculites; additionally there are small fractions of kaolinites and smectites. Other components are quartz and in small concentrations also feldspar; carbonates are missing almost completely. Swelling capacity of clay pastes of the Tannhausen soils range between 20–40 % of volume change according to values of a relative water content of 0.4–1.0 (Fig. 7(b)). A water content of 1.0 is related to the maximum possible water content at the liquid limit. We calculated the soil shrinkage curve after a model of Chertkov (2000a). We expect the bulk soils to have a similar shrinkage behaviour.

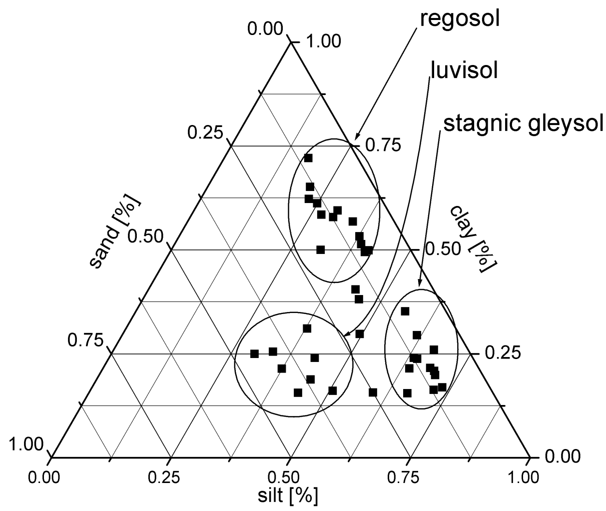

Fig. 7 Grain size fraction of 34 soil samples (samples are grouped to soil types by matter of sample location).

RESULTS FOR MESOSCALE CATCHMENT

Figure 8(a) gives an overview of the investigated mesoscale catchments of the Kostroma basin in northern Russia. Information about the state of these catchments is less profound as it is sparsely populated and not well observed. In the Verchnij Djar (683 km^2) and Rilovo (356 km^2) catchments, old subglacial till soils with a high clay content are found. The Emeljanovo catchment (597 km^2) has young subglacial till soils, also with a high clay content. Dominant soil type is a podzoluvisol in all catchments. The catchments are mostly forested as Landsat TM scene investigation revealed; the settled area is minor. The precipitation regime in northern Russia is characterized by snow accumulation in winter with low precipitation sums, and high precipitation sums from convective and cyclonal events in summer. In winter, snow accumulates and melts off again in March to April. Small runoff is observed in the winter months until these snowmelt events in spring. There are indications that runoff might be correlated to previous seasons but proof is needed yet. The yearly pattern of runoff coefficients in Fig. 8(b) displays lower coefficients in summer and higher

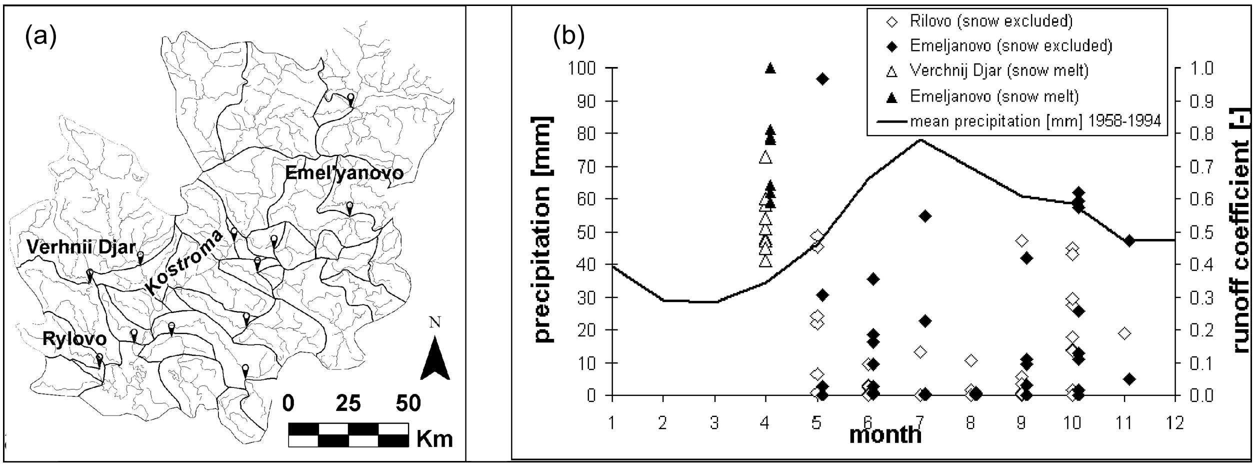

Fig. 8 (a) Overview of Kostroma basin and subcatchments. (b) Runoff coefficients of Rilovo, Emeljanovo and Verchnij Djar basins in northern Russia. Snowmelt in spring brings high runoff coefficients (events from different dates are combined in April, though occurring over a wider time span). Between June and September, a decrease of runoff coefficients can be observed, though precipitation intensity increases.

coefficients for the spring melt and also the transitions months May, October and November, in a very similar manner to our observations in the Tannhausen catchment or the results of Harvey (1971) and generally in an anticyclal pattern to precipitation sums and intensities. Seasonality is less pronounced though.

SUMMARY AND DISCUSSION

In specific climatic conditions and especially soil moisture states, different processes or reactive surfaces contribute dominantly to runoff generation in the Tannhausen catchment; a short summary of these processes is given here. We focus on summer events because soil moisture changes give a stronger impact on runoff generation then. In winter a generally high soil moisture leads to a more uniform runoff generation behaviour. The process identification is derived from comparison of the investigated events of the whole observation period. It reflects a perceptual model for the Tannhausen catchment and of course cannot be seen as definite as hydrological processes tend to be of nonlinear character.

With dry soil moisture states and with medium sized rainfall events, in sum up to 20 mm, most surface runoff is generated from sealed surfaces around the settlements. Tile drains either do not react or bring a fast peak with a small discharge volume to total runoff due to shortcuts induced by shrinkage cracks.

Rainfall events in summer with sums of more than 20 mm and dry soil moisture states can experience up to 20 mm of initial loss or more before runoff is generated (Figs 5(a), 6(b)), even high intensity rainstorms are dominated only by runoff from sealed surfaces, including roads and lanes and pasture patches near the creek. The tile drains do not necessarily contribute in such summer events, but this is highly dependent on the antecedent soil moisture conditions and crack development.

The "transition" months April and May are still influenced by winter soil moisture conditions. In October runoff generation is dependent on the gradual soil moisture rise through declining evapotranspiration rates and so features the highest variability in runoff coefficients (Fig. 4(a)). The winter months are characterized through constantly high soil moisture states, continuous tile drain discharge and a quick response of the saturated fields to surface runoff.

Concluding the behaviour of the Tannhausen catchment, individual events show a classifiable behaviour but they are strongly dependent on soil moisture and antecedent climatic conditions so that predictions seem to be difficult without knowledge about actual soil moisture conditions. A spatial observation of soil moisture could be helpful for prediction of antecedent conditions (Zehe *et al*., 2005). On the other hand, seasonal prediction seems to be rather easy in clay soil catchments. The process study in the Tannhausen microscale catchment shows the strong domination of soil moisture for runoff generation. In winter the soil reacts like a sealed surface, contributing to most of the runoff volume. The precipitation pattern of an event dominates runoff generation. In summer the soil with its cracks reacts like a sponge, reducing surface runoff generation to sealed surfaces. This gives us an idea of how clay catchments react in general and across several spatial scales. We think that the patterns we can describe in the microscale catchment are helpful in understanding mesoscale catchments as well.

The observation made in the Tannhausen catchment, that rainfall conversion in summer is dominated by high initial loss, can be ascribed to crack infiltration and soil volume changes. Of course, higher water demand of crops and higher evaporation rates also govern the summer behaviour. But it is not possible to solely explain runoff behaviour with higher evapotranspiration rates as low matrix infiltration rates would lead to higher runoff peaks in summer and not to the observed low peaks anyway. With fluctuating soil moisture content, the swelling capacity leads to different volumes of the soil. This influences two phenomena in clay soils: (1) The development or decline of shrinkage cracks, dependent on the actual soil moisture conditions, leads to a change of dominating infiltration pathways (Chertkov *et al*., 2000b). In clay soils, a low infiltration capacity of the soil matrix of a clay soil might lead in fact to the quick development of infiltration excess runoff, but this runoff flows into the cracks and then moistens up the soil from the bottom and the planes of the cracks upwards (Bronswijk, 1988; Novák *et al*., 2000). (2) During the course of normal and structural swelling, the pores between the clay minerals expand and change their structure, leading to an increase of pore volume and so to a change of the soil hydraulic conductivity.

Crack development and soil shrinkage is especially a problem concerning irrigation on fields as high amounts of water is lost to the underground and necessary solutes are quickly removed from the root zone (Bethune & Kirby, 2001). But also in temperate regions, clay soils influence agriculture and the runoff generation processes which are essential for the prediction of flood generation in small and mesoscale catchments. The impact of local shrinkage processes cannot only be observed on the plot scale but also on the micro- and mesoscale catchments as shown for the Tannhausen and Kostroma catchments. Both scales have a similar seasonal pattern despite climatic differences and both can be attributed to clay rich soils. Harvey (1971) also describes a seasonal runoff behaviour in the River Ter catchment. He found specific unit hydrographs for events with dry and wet conditions, seasonally bound in summer and winter events and also unit hydrographs which are a combination of both, suggesting that these are derived in intermediate soil moisture conditions during transitional months.

This study gives an overall view of the specific processes dominating runoff generation in clay soil catchments, which seem to lead to similar seasonal patterns on different scales. Though this presentation is rather qualitative and still lacks some essential links between the different scales, we think that clay catchments are worth a special look, especially if seen in a frame for catchment classification like McDonnell & Woods (2004) suggest, as well as concerning the prediction of runoff generation in ungauged basins (PUB initiative).

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