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A simple model to predict river floods - a contribution to quantify the significance of soil infiltration rates

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Abstract

River floods associated to extreme rainfalls are a threat to mankind since ancient times. The isolated factors that contribute to river floods are not yet well understood and flood forecast is still not precise. The amount of rainfall that reaches the rivers by runoff is a major factor associated to floods. Agricultural production occupies the largest portions of land, thus, even small changes in soil water infiltration on agricultural soils may result in significant changes in flood frequencies and intensities. Agricultural activities like field traffic, tillage, crop rotation and fertilisation affect soil infiltration rates. Some trends, such as the increasing discharge of animal wastes and the decreasing lime balance of soils (bivalent cations on the account of monovalent ones), are expected to reduce soil aggregate stability which, consequently, may diminish soil water infiltration rates. A simple model was used to estimate the effect of single factor soil water infiltration rate on flood frequencies and intensities using climate data of 30 years from Braunschweig (Germany). Isolating the effect of soil water infiltration rate on river floods, its reduction will keep floods as frequent as usual, but the frequency of extreme flood is expected to increase significantly.

Soil water infiltration rates of less than ~15 mm h^{-1} were estimated to be associated with a rapid increase of extreme floods frequencies. In this context maintaining soil infiltration of agricultural land becomes a new aspect in terms of civil defence against river floods and farmers should be advised and encouraged to keep the infiltration capacity of their soils by all means of agricultural measures as high as possible.

Key words: flooding, infiltration rate, liming, modelling, soil physics, soil fertility

Zusammenfassung

Ein einfaches Modell zur Prognose von Überflutungen - ein Beitrag zur Bedeutung der Infiltration

Überflutungen durch Flüsse zählen zu den immer wiederkehrenden Katastrophen, die Besitz und Leben von Menschen bedrohen. Dennoch sind die einzelnen Faktoren, die am Zustandekommen von Überflutungen beteiligt sind und deren komplexes Zusammenwirken in vielen Bereichen auch heute noch unbekannt. Der wesentliche Faktor ist die Menge an Wasser, welches die Flüsse durch Oberflächenabfluss erreicht. Landwirtschaft ist der flächenmäßig größte Landnutzer, und es ist daher anzunehmen, dass schon geringfügige Veränderungen der Infiltrationsrate von Böden signifikante Auswirkungen auf Häufigkeit und Ausmaß von Überflutungen haben. Landwirtschaftliche Bodennutzung, wie die Befahrung von Böden mit schwerem Gerät, Bodenbearbeitung und Fruchtfolgegestaltung beeinflussen die Infiltration von Böden. In der Düngung führt steigender Einsatz von Gülle und eine tendenziell rückläufige Kalkzufuhr zu einer tendenziell stärkeren Beladung von Bodenaustauschern mit einwertigen- auf Kosten von zweiwertigen Kationen, was sich negativ auf die Stabilität des Bodengefüges und somit auf die Infiltration auswirkt.

In dieser Arbeit wird ein einfaches Modell vorgestellt, mit dem der Einzelfaktor "Infiltration" auf Häufigkeit und Intensität von Überflutungen simuliert werden kann. Erprobt wurde das Modell an Klimadaten aus Braunschweig und Abflussdaten der Schunter. Es zeigte sich, dass verringerte Infiltration zwar keinen Einfluss auf die Häufigkeit von Überflutungen, wohl aber auf deren Intensität hat. Unterhalb von Infiltrationsraten von ~15 mm h^{-1} nahm in diesem Modell die Häufigkeit extremer Überflutungen stark zu.

Die Ergebnisse dieser Arbeit unterstreichen sehr deutlich die Sensibilität von Böden hinsichtlich ihrer Schutzfunktion gegen Hochwässer. Landwirtschaftliche Politik ist daher gut beraten, Beratungs- und Förderungsmaßnahmen auch hinsichtlich ihrer Auswirkungen auf die Infiltrationskapazität von Böden zu überprüfen, denn die Erhaltung und Erhöhung der Infiltration von Böden ist ohne Frage ein wichtiger Beitrag zum Zivilschutz.

Schlüsselworte: Basensättigung, Bodenphysik, Infiltration, Kalkung, Modell, Überflutung

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1 Introduction

River floods associated to extreme rainfalls are a threat to mankind since ancient times. Some European countries are frequently and seriously hit by river floods like most

Fig. 1
Eilenburg, Germany, flooded by the river Elbe in August 2002 (Die Welt, 2002

recently the catchments of the river Elbe in Germany (Fig. 1), the ones of Odra and Wistula in Poland (WDR, 2002) or the areas along the Dutch Rhine (IKSR, 2002).

River floods have increased in number and severity. Within the 20th century the water level of the river Rhine at Cologne exceeded 21 times the nine meter threshold (normal is 3.03 m). Three of these floods were called "century floods" (Fig. 2). In the last 20 years Cologne alone suffered seven floods with water levels above 9.35 m (WDR, 2002). Meanwhile flood disasters threaten repeatedly regions all over Europe causing severe losses in values and life quality (Drösser & Rauner, 2002) (Fig. 2).

There are many reasons for excess river floods. Certainly the expansion of urban areas on cost of areas to which floods can escape without causing damages has the largest share in the complex interaction of factors. Germany alone looses every day 129 ha of agricultural land to urbanisation (BMU, 2002). The factor addressed by this paper is the ability of soils in not "sealed" areas to contribute to the prevention of excess flooding by infiltration. River discharge peaks are a direct consequence of runoff, which accounts for not infiltrated or intercepted rain. The unpredictability of extreme rainfall events and the difficulty in treating them statistically or mathematically in models makes the prediction of floods a difficult task. Therefore, current understanding about factors that cause floods and flood forecast technology is far from being precise, comprehensive and available in most regions which experience hazards (Pielke, 1999).

In actions aiming to control floods, usually most attention is given to flood plain management to buffer peak flows (Strobl, 1997), instead of reducing runoff production. The role played by agricultural management may thus have been underestimated. Urbanization impacts soil infiltration rates dramatically, reducing the amount of infiltrated and intercepted rainfall and accelerating the runoff to the river and channel systems. The influence of soil water infiltration rates in rural areas is less studied and understood. Small variations in infiltration rates might have a more significant impact on floods than urbanization, because of the much larger areas involved (Fig. 3).

Soil water infiltration rates are hardly ever monitored on agricultural sites. In large catchments (e.g. the Rhine with 185.000 km^2) even small decreases in agricultural soils infiltration capacity may have disastrous effects on flooding in downstream regions (see also Schütze, 2002). A high spatial and temporal variability of this parameter

Fig. 2
Elbe floods near Bad Düben, Germany, August 14, 2002 (Die Welt, 2002).

Fig. 3
Agricultural land near Braunschweig flooded by the Oker river (BZ, 2002)

restricts any attempt of successful direct measurement of infiltration rates over large areas, compatible with the scale to be considered in river flood models (Vieira et al., 1981; Nielsen, et al. 1983).

Basic soil science knowledge indicates that soil structure, especially water stable aggregates, influence a wide range of physical, chemical and biological properties of soils (Rillig et al., 1999; Schachtschabel et al., 1998). Aggregate stability is affected by several factors including soil chemical management. Liming, due to the flocculating action of bivalent cations Ca^{2+} and Mg^{2+} in soil solution improving clay aggregation, is known as a soil structure stabilizing factor (Beese et al., 1979; Ceratzki, 1957, 1972; Ellies (1990); Gaheen & Njos, 1978; Schachtschabel & Hartge, 1958; Sommer, 1972; Sommer et al., 1972; Wolkewitz, 1960, 1963). The stabilization effect of the bivalent cations on secondary pores created by tillage increases soil infiltration capacity (Scheffer, 1972; Scheffer & Meyer, 1972; Wichtmann, 1972). In this context the effect of Ca^{2+} is much more pronounced as the one of Mg^{2+} (Dontsova & Norton, 2002; Keren, 1991). The same way as for acidification from atmospheric sources (Rogasik et al., 2002) the application of manures and slurry has an opposite effect on soil structure, because the high amounts of NH_4^+ and K^+, characteristic for animal excretions, exchange Ca^{2+} and Mg^{2+} from clay surfaces and increase bivalent cation leaching (Chizikova, 1995; SVV, 2002). Clay saturation with monovalent cations reduces soil structure stability and decreases soil infiltration rates (Aldrich & Martin; 1954; Amer, 1960; Auerswald, et al., 1996; Bloemen, 1980; Chen et al., 1983; Haynes & Naidu, 1998; Suarez et al., 1984).

The need for liming of soils in humid areas is primarily understood as the maintenance of soil structure (Finck, 1989; Schachtschabel, et. al., 1998). Under this perception, the soil chemical parameter for monitoring the lime status of a soil should be the composition of the cations present at the soil adsorbers, particularly the relation between mono- and bivalent ones. Considering that under "natural" conditions the most important monovalent ion competing with Ca^{2+} and Mg^{2+} at the soil adsorbers is H^+, the pH-value has become the most prominent parameter to determine the lime status and the lime requirements of soils (Kerschberger, 2000). The pH-value, however, is only sensitive to changes in the H^+ concentrations, not indicating any changes in the other monovalent cations. High amounts of NH_4^+ and K^+ discharged to soils in areas with intensive animal production (SSV, 2002) would leave the pH-values unchanged, but significantly shift the relation between mono- and bivalent cations away from optimum concentrations for clay flocculation and aggregate stabilization.

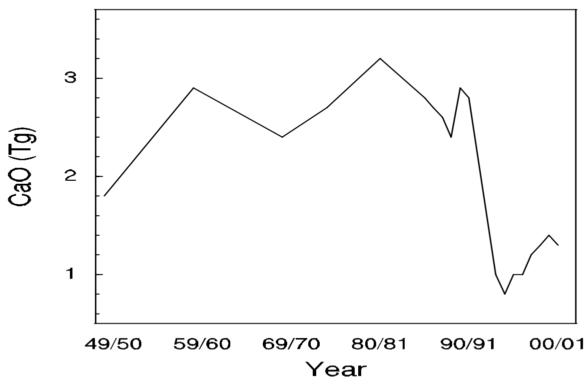

Fig. 4
Trends in the CaO balance of German agriculture – balance of basic and acidic substances derived from lime, N-, P-, and K-fertilisers (Pollehn, 2002)

Beside many other factors some trends in agriculture like a decrease in the lime balance of soils (Fig. 4), the increasing discharge of animal wastes (rich in NH_4^+ and K^+) but also the fact that professional agricultural advice recommends lime based only on pH threshold values (Kerschberger, 2000) instead of considering Ca^{2+} and Mg^{2+} soil saturation, may thus in the long run contribute to reducing soil infiltration rates.

This reduction is not traceable in large scale with common soil physical methods. Because of the difficulty to monitor, this reduction is and will not be observed experimentally. Any attempt for monitoring in large scales may fail because of methodological problems to deal with high spatial and temporal variability as well as the large hysteresis of treatments and effects (Mineev & Gomonova, 2001). With the impossibility of comprehensive monitoring a simple theoretical model, based on mathematical procedures and the basic physic of the involved phenomena can be useful to indicate the effect of soil water infiltration reduction on river floods.

The objective of this paper was to develop a simple model and to determine its sensibility to changes in soil infiltration capacity.

2 Model description

The model converts rainfall data, recorded in intervals of one hour in discharge of a simplified river system. It assumes a rectangular watershed of length L (m) and width W (m), draining to a river flowing lengthwise in its middle (Fig. 5) and having, at the end of the watershed, a discharge rate Q (m^3 h^{-1}). For every time step (dt, 1 hour in the present study) rainfall (P, m) is read from a data file and weighed against soil infiltration capacity (I, m h^{-1}), surface storage at the end of the previous time step (S_{t-1}, m) and surface storage capacity (S_{max}, m), calculating the volume of infiltrated water (F, m^3), the volume of runoff

$$T_F = \frac{D}{v_F} \text{ and } T_R = \frac{D}{v_R}$$

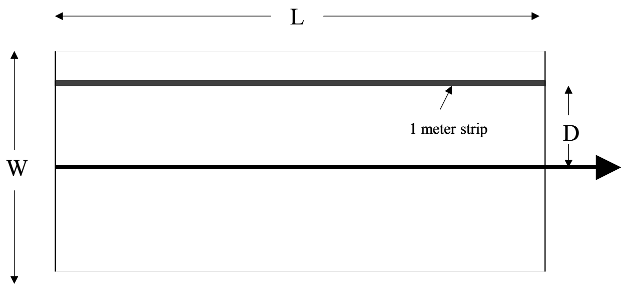

Fig. 5
Schematic representation of the watershed used for simulations

water (R, m^3) and the new surface storage (S_t, m). Infiltrated water and runoff water are then moved towards the river at different velocities: v_F (m h^{-1}) for infiltrated water, v_R (m h^{-1}) for runoff water. Because the water from areas at a greater distance from the river will take a longer time to reach the river, the watershed was divided in strips with a width of dd (1 meter in the present study), at a distance D (m) from the river and parallel to it. The travel time for infiltrated water (T_F, h) and for runoff water (T_R, h) can be calculated for each strip knowing velocities v_F and v_R, as shown in Fig. 5.

If rainfall occurs (i.e., $P > 0$), four scenarios are possible

1. Rainfall exceeds infiltration capacity plus surface storage reserve: $P > I.\mathrm{d}t + (S_{max} - S_{t-1})$.

In these cases the infiltration rate will equal infiltration capacity, surface storage will reach its maximum and exceeding water will be converted in runoff:

$$F = I.\mathrm{d}t.L.\mathrm{d}d$$
$$R = [P - I.\mathrm{d}t - (S_{max} - S_{t-1})].L.\mathrm{d}d$$
$$S_t = S_{max}$$

2. Rainfall exceeds infiltration capacity, but surface storage reserve is sufficient to absorb excess: $I.\mathrm{d}t < P \leq I.\mathrm{d}t + (S_{max} - S_{t-1})$.

In these cases, no runoff will occur, infiltration rate will equal infiltration capacity and surface storage will increase:

$$F = I.\mathrm{d}t.L.\mathrm{d}d$$
$$R = 0$$
$$S_t = S_{t-1} + P - I.\mathrm{d}t$$

3. Infiltration capacity exceeds rainfall plus surface storage: $I.\mathrm{d}t > P + S_{t-1}$

In these cases, all rainfall and surface storage water will infiltrate. No runoff will occur and final surface storage will be zero:

$$F = (P + S_{t-1}).L.\mathrm{d}d$$
$$R = 0$$
$$S_t = 0$$

4. Infiltration capacity exceeds rainfall but is smaller than rainfall plus surface storage: $P < I.\mathrm{d}t \leq P + S_{t-1}$

In these cases, no runoff will occur, infiltration rate will equal infiltration capacity and surface storage will decrease:

$$F = I.\mathrm{d}t.L.\mathrm{d}d$$
$$R = 0$$
$$S_t = S_{t-1} + P - I.\mathrm{d}t$$

If no rainfall occurs (i.e., $P = 0$) while surface storage exists ($S_{t-1} > 0$), stored water will infiltrate. Therefore:

1. If surface storage exceeds infiltration capacity ($S_{t-1} > I.\mathrm{d}t$), infiltration rate will equal infiltration capacity and surface storage will decrease:

$$F = I.\mathrm{d}t.L.\mathrm{d}d$$
$$S_t = S_{t-1} - I.\mathrm{d}t$$

2. If surface storage is smaller than or equal to infiltration capacity ($S_{t-1} \leq I.\mathrm{d}t$), infiltration will equal surface storage:

$$F = S_{t-1}.L.\mathrm{d}d$$
$$S_t = 0$$

After computation of runoff and infiltrated volumes in each strip, it is supposed that only a fraction of these volumes (f_F for infiltrated water, f_R for runoff water) will reach the river after T_F or T_R hours. Summing of water volumes originating from all strips along time results in discharge rates Q at the end of the watershed as a function of time.

3 The case study

A practical example, using 30 years of climate data from Braunschweig (Germany, 52°17,62´N; 10°26,79´E) was used to estimate the increase of flooding events by changing soil infiltration rates (NLWK, 2001).

Digital data recording precipitation continuously in intervals of one hour from January 1, 1966 to December 31, 1999 were used to estimate discharge. The theoretical channel system was an area of 1,000 m long and 200 m wide, with the channel located in the center of the area, as shown in Fig. 5. The variable selection for calculating the simulation was based on criteria described in Table 1.

Data from the Süpplingen river discharge measurement station, located at the higher part of the river Schunter

Table 1
Variables description, values and units used in the case study

Variable	Meaning (unit)	Definition criteria	Value
L	Watershed length (m)	Representative for a first order drainage channel	1,000
W	Watershed width (m)	Representative for a first order drainage channel	200
S_{max}	Surface storage (mm)	Mean value for conventional tillage according to Onstad (1984)	3
v_F	Velocity of infiltrated water (m d^{-1})	Mean value used for modeling (Lile et al. 1997; Selroos et al. 2002)	0.7
v_R	Velocity of runoff water (m s^{-1})	Mean value for gently sloped areas according to Stone et al. (1995)	0.2
f_R	Fraction of runoff water reaching the river	Discount a minor part of runoff that may be intercepted before reaching the channel system.	0.9
f_F	Fraction of infiltrated water reaching the river	Based on the measured relation of rainfall amount and river discharge in the Süpplingen watershed.	0.3

watershed (52°13.67′ N; 10°54.16′ E), comprising 4700 ha land in East/North-East of Braunschweig, were used to estimate f_F, which is the main variable that defines the amount of rain that will reach the river system. To do so, the total amount of water flowing through the river in the period between January 1, 1966 and December 31, 1999 was divided by the total amount of rain from the same period. The result of this calculation was that 30 % of the rain reaches the rivers, or $f_F = 0.3$.

Different flood intensities were chosen according to the positive deviation of single day discharge values in relation to the mean discharge of the seven previous days. Negative deviations (decreasing discharge) or less than two times the mean values of the seven proceeding days were not considered as flood. All single day discharges greater than an established number of times the mean seven days preceding discharges were considered flood events. These were estimated separately for discharges > 2 and < 3 times the previous mean seven days (indicated as $\mathbf{D_{2-3}}$); > 3 and < 4 times ($\mathbf{D_{3-4}}$); > 4 and < 5 times ($\mathbf{D_{4-5}}$) and > 5 times ($\mathbf{D_{>5}}$). Thus, $\mathbf{D_{2-3}}$ represents only slight elevations of the river discharge level and $\mathbf{D_{>5}}$ will account only for the extreme floods.

The same mathematical procedure was applied to the river discharge data recorded in Süpplingen, resulting in measured floods based on the same criteria as applied for the estimated discharge values. The estimated intervals for flood intensities $\mathbf{D_{2-3}}$ <....< $\mathbf{D_{>5}}$ calculated by averaging the flood intervals of soil water infiltration rates ranging from 1 mm h^{-1} to 32 mm h^{-1} and the calculated flood intervals for Süpplingen are shown in Table 2.

The estimated and calculated (real) intervals were different in magnitude because the area representing them are not comparable (20 ha in the case study and 4700 ha in Süpplingen). A small area was chosen for the case study to reduce the amount of variables to be considered for discharge calculations. A larger area would, for example, require information about branching of waterways and the infiltration of runoff water. By using a smaller area the inclusion of this kind of variable was avoided resulting in a simple model that allows evaluating the effect of one single parameter. Nevertheless, the rate between calculated and estimated values was relatively constant (~ 4). Greater intervals of flood events by increasing the size of the watershed area may be expected. To allow a comparison of the model estimated and calculated data this “area effect” was compensated by lowering the flood intensity criteria for Süpplingen, applying a constant to all discharge deviations of 1.5. In this manner, the $\mathbf{D_{2-3}}$ deviation was calculated based on a positive deviation of 2 ÷ 1.5 = 1.3, the $\mathbf{D_{3-4}}$ by 3 ÷ 1.5 = 2.0, etc. The discharge intervals from these weighed calculations are presented

Table 2
Mean estimated and calculated flood intervals for Süpplingen

	Flood Intensity			
	D_{2-3}	D_{3-4}	D_{4-5}	$D_{>5}$
	Interval (d)			
Model estimate	16	282	776	955
Calculated data	72	86	231	235
Model/ Calculated ratio	4.5	3.3	3.4	4.1

graphically in Fig. 6 (large dots) for a water infiltration rate of 14.5 mm h^{-1}, the mean value for this parameter in agricultural soil (Warrick & Nielsen, 1980). This infiltration rate also resulted in the best coincidence of measured and estimated discharge data, except for the $\mathbf{D_{4\text{-}5}}$ flood intensity. Also, in Fig. 6 the estimated mean flood intervals were represented in relation to soil water infiltration rates ranging from 1 mm h^{-1} to 32 mm h^{-1}. Surface water infiltration rates are considered as a soil parameter with high variation in space and time (Warrick & Nielsen, 1980) but an infiltration rate of 1 mm h^{-1} is considered very low for agricultural soils while 32 mm h^{-1} is very high, and these extremes will usually not occur in tilled soils. The mean infiltration rate of the study area is very likely to be somewhere between these values.

The good coincidence of the estimated and observed flood intervals can not be considered as a model validation. The weighting factor that was applied to the calculated data to compensate the different scales of the case study and the measured values areas, and the lack of monitoring or measuring of soil water infiltration rates in the Süpplingen watershed do not allow a direct comparison. Although, the good coincidence may indicate that the basic physical processes of floods were correctly considered in the simple model and that the estimated data are thus useful to describe with relatively good accuracy the more complex real flood processes.

The $\mathbf{D_{2\text{-}3}}$ flood intensity accounts only for slight elevations of the river discharge level and is little affected by changes in soil water infiltration rates. The mean interval was calculated in 15 days for $\mathbf{D_{2\text{-}3}}$. By shifting from condition $\mathbf{D_{2\text{-}3}}$ to $\mathbf{D_{>5}}$ it is expected that the influence of soil infiltration rates becomes more significant. For infiltration rates less than ~ 20 mm h^{-1}, the interval between extreme floods is reduced very rapidly. Very low infiltration rates (not expected to occur in agricultural soils) showed a small difference for $\mathbf{D_{3\text{-}4}}$, $\mathbf{D_{4\text{-}5}}$ and $\mathbf{D_{>5}}$. For high soil infiltration rates the interval for extreme floods ($\mathbf{D_{4\text{-}5}}$ and $\mathbf{D_{>5}}$) was approximately one year and was reduced to ¼ of that (~ 90 days) by extremely low infiltration rates. According to this simple model, by reducing soil water infiltration rates the river is expected to change its discharge level within the same frequency as usual, but the extreme floods intervals are expected to decrease rapidly, i.e. only the intensity of the events is changed.

This also becomes evident when observing the calculated river discharge levels from two years (1-1-1998 to 31-12-1999), shown in Fig. 7 for water infiltration rates of 2, 4, 8 and 16 mm h^{-1}.

The number of flood events is not affected when the soil infiltration velocity was increased from 2 mm h^{-1} to 8 mm h^{-1}, but the maximum discharge decreased rapidly within the same flood event. The increase of infiltration velocity to 16 mm h^{-1} was enough to keep the discharge level almost invariable, slightly fluctuating around the mean in the considered period.

The estimated effect of the reduction of the single factor soil water infiltration rate on river floods was expected not to influence the intervals of small variations of river discharge. The extreme floods were most significantly affected by soil water infiltration rates of less than ~ 15 mm h^{-1}, which is considered as a mean value for agricultural sites. In this case, the interval between events was drastically reduced. Isolating the effect of soil water infiltration rate on river floods, its reduction will keep floods as frequent as usual, but the frequency of extreme flood is expected to increase significantly.

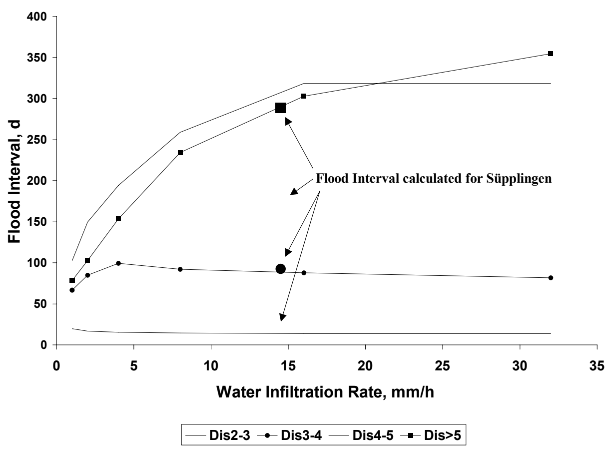

Fig. 6
Estimated intervals for flood intensities $\mathbf{D_{2\text{-}3}}$ <....< $\mathbf{D_{>5}}$ related to soil surface water infiltration rates (small dots and lines) and calculated flood intervals (large dots) for Süpplingen river discharge measurement station (Braunschweig)

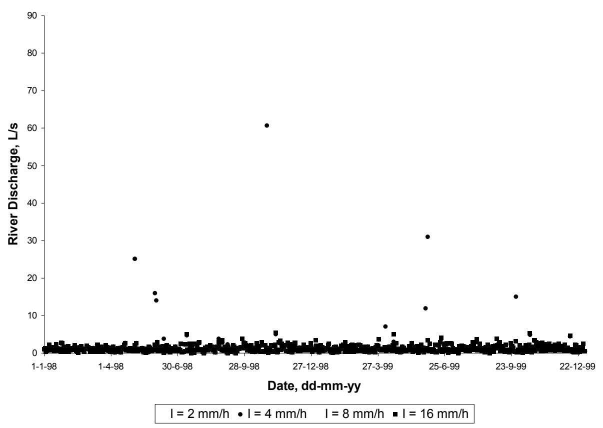

Fig. 7
Model estimated river discharge related to soil infiltration velocities of 2, 4, 8 and 16 mm h^{-1} for the period of 1-1-1998 to 31-12-1999

4 Conclusions

Water infiltration is one of the protective functions of soils (BMU, 2002; Schachtschabel et al., 1998) and can produce a high impact on the daily life of mankind. The model calculations presented in this paper reveal that even small losses in the infiltration capacity of agricultural soils can have an enormous effect on river floods. The isolated effect of reducing soil water infiltration rates on river floods is expected to be an increase of frequency of extreme flood events. Thus the increased number of severe floods in the last years (IKSR, 2002; WDR, 2002) might be to some extend due to losses in the infiltration capacity of agricultural soils. Among many other factors such as field traffic, crop rotation and tillage operations (Gaheen & Njos, 1978; Neufeldt et al., 1999) also fertiliser management affects soil infiltration.

From the viewpoint of soil chemistry research a possible mode of action could be a shift in the relation between mono- and bivalent cations by an intensified use of animal wastes on soils which diminish the lime status of soils leading to lower infiltration capacity. This would be widely undetected by the common monitoring practices of soil pH-values.

Under practical circumstances it is impossible to monitor soil water infiltration rates. In this case rules for soil application of manure and a recommendation protocol for liming that includes its effects on soil structural stability should be considered as a principle for policy definitions.

In this context maintaining soil infiltration of agricultural land becomes a new aspect in terms of civil defence against river floods and farmers should be advised and encouraged to keep the infiltration capacity of their soils by all means of agricultural measures (last but not least also by keeping a sufficient base saturation of soil adsorbers by liming) as high as possible.

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