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Use of terraces to mitigate the impacts of overland flow and erosion on a catchment

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ABSTRACT

The paper presents the impact of a historical system of terraces constructed centuries ago to mitigate the effect of a steep slope on overland flow. Systems of this type were constructed in past centuries by land owners, who then ploughed the land and grew crops on it. They used stones collected from the local agricultural fields as their terracing material. The influence of terraces on overland flow was simulated using the KINFIL. The overland flow is therefore reduced by greater infiltration of extreme rainfall excess flows on the terraces, and the KINFIL model shows to what extent the system of terraces can mitigate the resultant flood and soil erosion. The Knínice locality in North-Western Bohemia, with seven terraces and six field belts between them, was selected as the experimental catchment area. The results compare hydrographs with N-year recurrence of rainfall-runoff time, where N = 10, 20, 50, and 100 years, and the hydraulic variables, e.g. overland flow discharges of a design rainfall, hydraulic depths, flowing water velocity, and shear stress. The comparison provides hydraulic results with terraces and without terraces. The contrast between the results with and without terraces shows the positive role of the system of terraces in protecting the field belts.

Keywords: extreme precipitation; infiltration intensity; soil protection

In many mountainous parts of the landscape in the Czech Republic, there are localities with a dominant slope length parameter that can be interrupted by steps, by terraces, or by hedgerows. These technical and biotechnical measures were made by landowners since the late Middle Ages, when these highland areas were first colonized (Lőw and Míchal 2003).

Extensive agriculture has had a long tradition in North-Western parts of Bohemia. Steep slopes were protected by terraces made from stones collected from neighbouring fields. This practice kept many people alive, from the beginning of colonization up to the middle of the 20th century. The dimensions of the terraces vary according to the geographical diversity of the landscape, according to the height, width and length values in relation to the slope angles and slope lengths. All historical remnants of mediaeval landscape have important landscape formation and landscape stabilization attributes (Mérot 1999, Marshall and Moonen 2002).

The best positioning of the prevailing axis of the terraces corresponds with the direction of the contour lines when the direction of the water flow is perpendicular to them. This can mitigate overland flow and protects the effective field belt. These belts transform part of the flow, reduce its velocity, and enable it to infiltrate due to greater hydraulic conductivity.

MATERIAL AND METHODS

Description of the simulation is provided in Figure 1 and Figure 2. Figure 1 shows a map of a standard geographical situation with marginal

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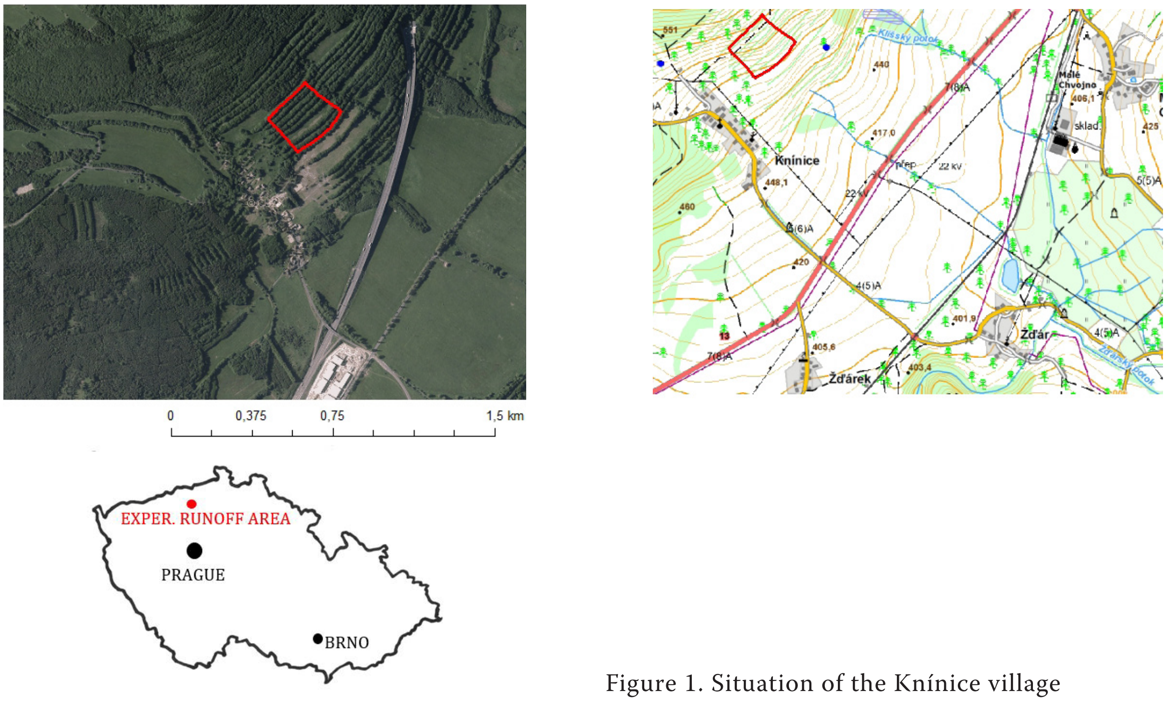

Figure 1. Situation of the Knínice village

views (on the left), where the terraces are covered by trees and shrubs which, from above, look like hedgerows. Figure 2 provides the scheme of the placement of typical stone terraces that serve as measures in support of infiltration and for mitigating overland flow discharges. A detailed view of two neighbouring terraces is provided in Figure 3. Their construction provides effective obstacles to overland flow, offering high water permeability through a stone body with various diameters, thus reducing the hydraulic velocity. There is usually also a high diversity of vegetation.

A number of these terraces are characteristic for the area of the Ore Mountains (Krušné hory), Adolfov, Fojtovice, Libouchec and the northern part of the Central Bohemian Uplands (Orlík and Verneřice).

The Libouchec experimental runoff area in the Knínice region in the Ore Mountains is well protected, and its terraces still provide good soil erosion control. This area was therefore selected as a case study area to test the differences in discharges between a steep slope that was not protected in the past and a slope protected by terraces. Using the infiltrometer measurements, it was found that the terraces at Knínice are more than 0.5–0.6 m in depth, and their upper edges are usually higher (by 0.10–0.30 m) than the neighbouring land.

Experimental area. The Knínice experimental runoff area (ERA) is one of the best-protected areas in the Ore Mountains as regards soil erosion. The reference system of terraces is effective and reliable. It is 8.80 ha in area, with 7 terraces and 6 field belts between them. The only drawback with this catchment is that it is ungauged. The geodetic measurements were carried out by the GMSS Trimble-type total station. The processing was executed using the Geodimeter 640 by the polar method, and the mapping was carried out within the Kokes system, version 1250 (Gepro, Prague, Czech Republic). The final mapping was amended in the Atlas system (Atlas, Prague, Czech Republic).

The average elevation of the catchment is 517.0 m, and the catchment ends not with a single outlet

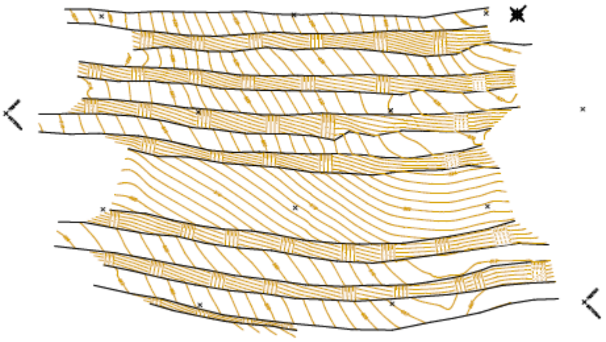

Figure 2. Situation of the experimental runoff area – 1:3000

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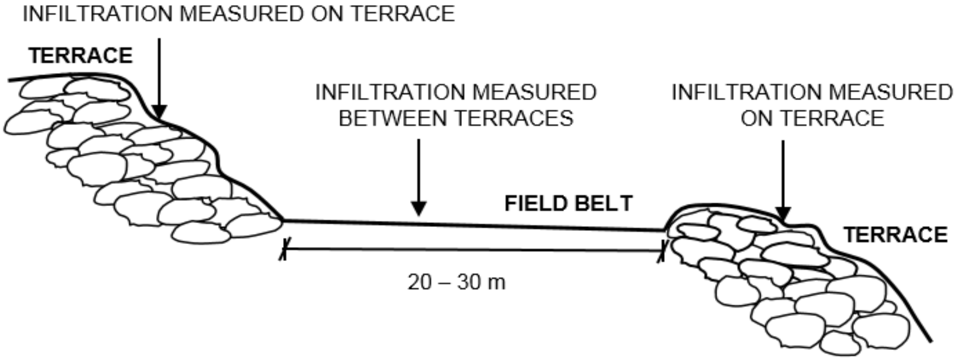

Figure 3. Scheme of terraces protecting field belts against soil erosion. Infiltration parameters are measured on both terraces and on field belts

profile, but with an open contour line profile which is about 400 m in width, transferring the surface runoff down to the rest of the catchment, where the slope is gentler. Slope J downstream within the catchment on arable land (nowadays permanent grassland) is $J_{PG} = 0.04$ to 0.12, and on the terraces the slope is $J_{TER} = 0.34$ to 0.61.

Figure 3 shows the principle of the longitudinal profile of a typical pair of terraces with one field belt between them. The complete longitudinal profile of the whole system of protective terraces is shown in Table 1. The width was rounded to 400.0 m, and the Manning roughness coefficient *n* was assessed to be 0.100 on the fields and 0.150 on the terraces (Fread 1989).

The climate in the catchment area is mild-warm and humid. The average annual temperature is between 6.5°C and 7.0°C, and the long-term annual precipitation varies between 650 to 750 mm. The geological structure of the study area is mainly of leistocene orthogenesis and quaternary stony and stony-loam sediments. The dominant soil type consists of mesotrophic to entropic Cambisols, which can be characterized as water-permeable silt loam and sandy loam.

Field measurements. The procedure of the Richards equation (Kutílek and Nielsen 1994) and the Philip's solution for non-steady flow infiltration (Philip 1957) was used. The shortened Philip equation for the infiltration intensity v_f into the soil with saturated hydraulic conductivity K_s (mm/h) and sorptivity (mm/h$^{0.5}$), has the form:

$$v_f\,(t) = ½\ S \times t^{-1/2} + K_s \qquad (1)$$

Subsequently, parameters K_s and S were both computed, applying the method of the non-linear regression (Kovář et al. 2011, Štibinger 2011). Table 1 provides the values of the measurements of hydraulic conductivity K_s and also sorptivity S, measured four times each in four terraces and four fields. This table also shows the average values of K_s and S, and also provides the storage suction factor S_f (mm):

$$S_f = \frac{S^2}{2K_s} \qquad (2)$$

The final parameter values are given in Table 1. The average storage suction factor for fields is S_f = 28.0 mm, and for terraces is S_f = 20.0.mm. The K_s value for the terraces is about 4.3 times higher than for the field belts. The S value for the terraces is about 1.7 times higher than S value for the field belts.

Extreme rainfall assessment. The Knínice catchment uses the rainfall data from the Ústí nad

Table 1. Experimental runoff areas and the fragmentation of the Knínice catchment

Fields	length (m)	6.00	20.60	17.90	13.70	48.50	21.50	19.40	Σ 147.60
	slope (–)	0.04	0.07	0.06	0.04	0.12	0.05	0.04	
Terraces	length	11.30	10.70	13.90	10.40	12.40	10.70	3.70	Σ 73.10
	slope	0.36	0.43	0.37	0.45	0.35	0.34	0.61	

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Table 2. Measurement of soil hydraulic values: hydraulic conductivity K_s (mm/h); sorptivity S (mm/h$^{0.5}$), and storage suction factor S_f (mm) and average values on terraces and on fields

Number of measurement		1	2	3	4	Average
Hydraulic conductivity		29.0	32.0	26.0	33.0	30.0
Sorptivity	on terraces	34.2	33.5	32.6	38.0	34.6
Storage suction factor		20.2	17.5	20.4	21.9	20.0
Hydraulic conductivity		5.0	9.0	6.0	8.0	7.0
Sorptivity	on fields	17.0	22.4	19.4	20.3	19.8
Storage suction factor		28.9	27.9	31.4	25.8	28.0

Labem – Kočkov station, which is located 9 km away. This rain gauge provides daily rainfall data with a return period N = 2, 5, 10, 50 and 100 years, as shown in Table 3. Due to the small catchment area, the periods of critical rainfall duration were selected for time t_d = 10, 20, 30 and 60 min and a return period of N = 10, 20, 50 and 100 years. The DES_RAIN procedure (http://fzp.czu.cz/vyzkum) was used to compute the reduction in the daily rainfall depths $P_{t,N}$, (Kovar et al. 2011). This procedure is based on regional parameters a and c, which were derived using the methodology by Hrádek and Kovář (1994) with the results provided by Table 3, where $P_{t,N}$ is the maximum extreme rainfall depth (mm), less than 1 day duration and return period N years.

The value of one-day extreme rainfalls $P_{1d,N}$ was used from the published rainfall data records of the series from 1901 to 1980 (Šamaj et al. 1983). These short-duration extreme rainfalls were tested using the KINFIL rainfall-runoff model.

KINFIL rainfall-runoff model. The 3D KINFIL model accepts two parts of the hydrological process. The first part is infiltration of rainfall to create rainfall excess, and the second part is the overland flow production from rainfall excess and its transformation into a final runoff hydrograph. The model also has marginal results, e.g. hydraulic depths and velocities. It is physically based, and was been used since 2002 for simulating rainfall-runoff processes on gauged and ungauged catchments (Kovář et al. 2002). Since 2002, the model has been supplemented to simulate the hydraulic processes needed for shear stress values to compute erosion (Kovář et al. 2011).

Table 3. Maximum extreme rainfall depths $P_{t.N}$ of short duration in the station Ústí nad Labem (mm)

N (years)	$P_{t.N}$ (min)	t (min)			
		10′	20′	30′	60′
2	30.6	10.1	12.4	14.0	16.3
5	41.8	14.7	18.2	20.7	24.8
10	49.0	17.6	22.4	15.7	30.7
20	56.5	21.5	27.4	31.6	38.0
50	65.7	26.3	33.8	39.2	47.5
100	79.2	32.5	42.1	49.1	59.4

The rainfall excess r_e (t) is computed by subtraction from the extreme rainfall intensities i (t) of return period N in order to obtain the rainfall excess hyetograph r_e (t):

$$r_e (t) = i (t) - v_f (t) \tag{3}$$

This infiltration part of the KINFIL model is based on the infiltration theory of Green and Ampt, applying the concept of ponding time and the storage suction factor S_f by Morel-Seytoux and Verdin (1981) and by Morel-Seytoux (1982):

$$v_f = (\theta_s - \theta_t)\frac{d_{zf}}{dt} = K_s\left[\frac{z_f + H_f}{z}\right] \tag{4}$$

The left-hand side of Eq. (4) expresses the Darcy principle for the infiltration process v_f (t), while the right-hand side of the equation reflects the Green-Ampt theory (Rawls and Brakensiek 1983). The Darcy principle was used by many authors (e.g. Morel-Seytoux and Verdin 1981). In Eq. (4), $(\theta_s - \theta_t)$ the difference between the saturated soil moisture content and actual content (–), z_f is the depth of the infiltration front, and z is the vertical ordinate (both in m). K_s is the hydraulic conductivity (m/s), and H_f is the capillary suction on the infiltration front (m).

The second part of the KINFIL model is the overland flow component, using the kinematic equation (Kibler and Woolhiser 1970, Beven 2006):

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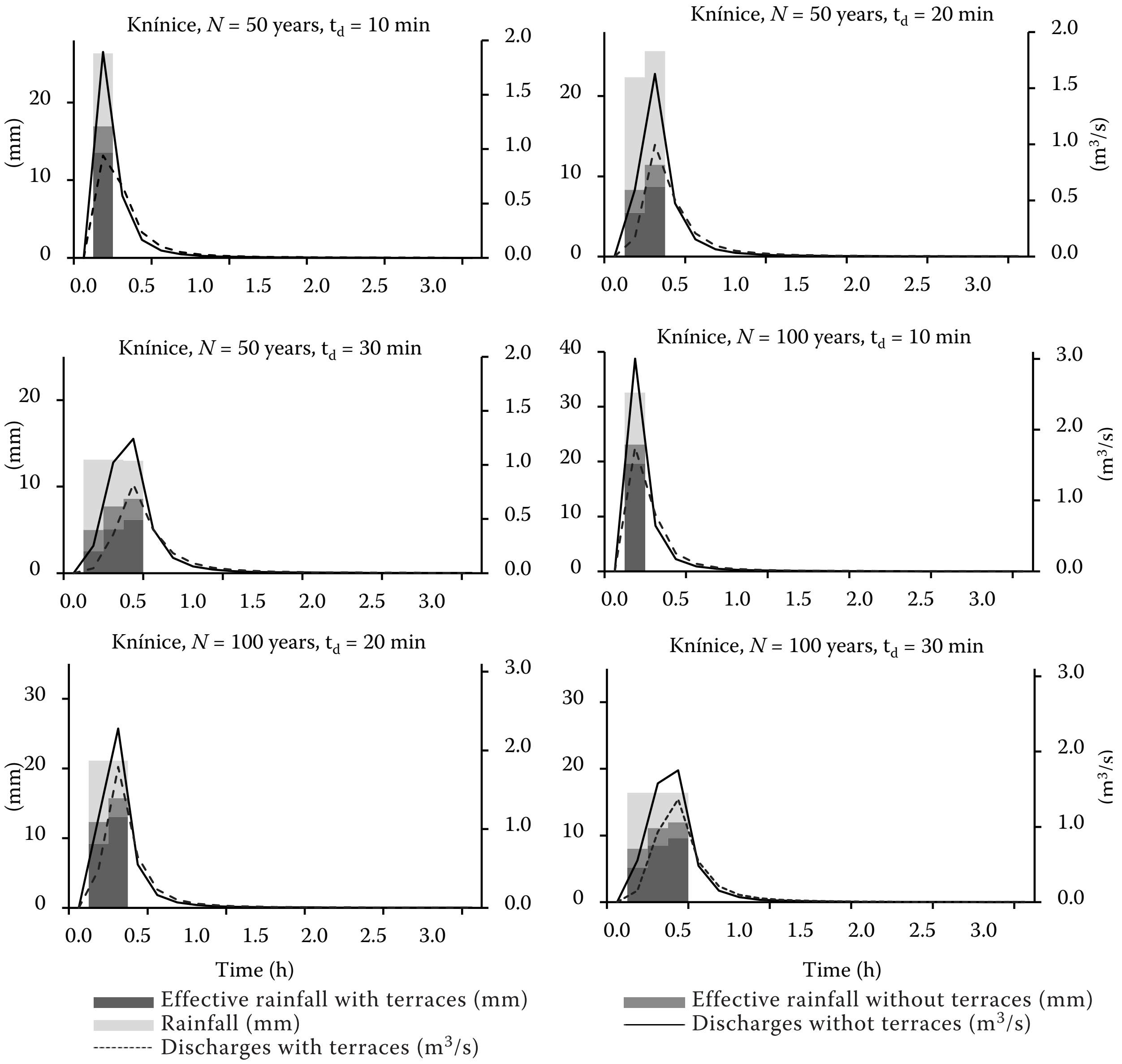

Figure 4. Hydrographs comparison on the Knínice catchment with a terrace infiltration function and without it, for extreme rainfalls of various return periods *N* (years) and time periods t_d (min)

$$\frac{\partial y}{\partial t} + \alpha \,.\, m \,.\, y^{m-1} \,.\, \frac{\partial y}{\partial x} = r_e(t)$$

Where: r_e (t) – rainfall excess intensity (m/s); *y*, *t*, *x* – ordinates of the depth of water, time and position (m, s, m); α, m – hydraulic parameters.

This equation describes non-steady flow, approximated by a kinematic wave on a plane or a cascade of planes or segments. It is computed using the finite differences scheme (Lax and Wendroff 1960). The upper boundary condition of the Lax-Wendroff scheme is *y* (*x*, 0) = 0 for all values of *x*. Figure 4 shows the view of the longitudinal profile, and Table 2 provides the measured parameters. This system puts emphasis on the geometry of the planes, their slopes and the hydraulic roughness conditions.

RESULTS AND DISCUSSION

The simulation by the KINFIL model was implemented for all events in the return periods of

Table 4. Major rainfall parameters and runoff hydrograph peaks on the Knínice catchment without terraces and with terraces

N (years)	Duration time t_d (min)	Rainfall depth (mm)	Effective excess (mm)		Hydrograph peak (m^3/s)	
			without terraces	with terraces	without terraces	with terraces
10	10	17.6	8.38	5.31	0.60	0.19
	20	22.4	8.71	4.08	0.61	
	30	25.7	8.39	2.78	0.52	0.08
	60	30.7	5.21	0.18	0.23	0.06
20	10	21.5	12.18	8.89	1.11	0.45
	20	27.4	13.49	8.23	1.09	0.41
	30	31.6	13.90	7.07	0.85	0.31
	60	38.0	11.19	2.32	0.43	0.09
50	10	26.3	16.94	13.52	1.89	0.94
	20	33.8	19.78	14.17	1.63	0.99
	30	39.2	21.30	13.77	1.24	0.82
	60	47.5	20.00	8.28	0.69	0.33
100	10	32.5	23.12	19.65	3.00	1.75
	20	42.1	28.03	22.27	2.28	1.79
	30	49.1	31.12	23.26	1.75	1.37
	60	59.4	31.62	18.41	0.99	0.66

their duration t_d = 10´, 20´, 30´, and 60´ for the basic scenario without terraces and with terraces, to see how much they reduce the overland flow discharges. The sub-catchment areas were fragmented to reflect the fact that each field belt has one biotechnical protective measure in the form of a terrace. The geometric dimensions of the terraces correspond to the real situation. The final results are shown in Table 4 and Figure 4.

The highest values of the hydraulic variables are on N = 100 years rainfall with 10 min duration when the depth of overland flow is about 0.2 m, hydraulic velocity 0.34 m/s and the shear stress is about 42.0 Pa.

There are a few hydrological models that can simulate infiltration and overland flow processes on agricultural bench terraces (e.g. Amore et al. 2004, Zhao et al. 2000, Aksoy and Kavvas 2005). A simpler geomorphological system of erosion control usually provides better modelling (Maidment 1992). The terrace system at Knínice is a good example. An analysis of the effects of terrace configuration on peak flow, and on the delay to peak flow on an undisturbed hillslope can also provide information leading to improved land management (e.g. Hallema and Moussa 2014, Vetter et al. 2014).

In conclusion, slope terraces have distinct hydrophysical characteristics that are different from the characteristics of field belts where there is permanent grassland growing between them. The area of the field belts in the Knínice study area is about 2/3 of the 8.80 ha sub-catchment and the rest of the area is taken up by terraces. One third of the farmer's arable land has to be taken out of agricultural productions. As a result of their favourable infiltration characteristics, the terraces act as biotechnical infiltration and erosion control measures for decreasing the overland flow. They may also have an important influence on the water regime during dry seasons.

Simulations using the KINFIL model proved that due to the favourable infiltration characteristics of the soils in the Knínice catchment, the hydraulic depth of the overland flow for gross rainfall with return periods of N = 2 and 5 years is insignificant

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(Table 4). The discharges caused by rainfall with a return period of $N = 10, 20, 50$, and 100 years could be harmful if there were no terraces. In the most critical runoff Q_{100} (10´), the discharges are reduced by the terrace system from a value of 3.00 m^3/s to a value of 1.75 m^3/s (i.e. by 42%).

However, if the plots of permanent grassland were to be transformed into arable land for growing field crops, there would surely be inadequate protection, due to the changes in the critical shear stress of soil that is not covered by permanent grassland.

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