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Influence of scale and land use pattern on the efficacy of grassed waterways to control runoff

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A B S T R A C T

Grassed waterways (GWWs) are established where runoff from arable land concentrates. They provide travel distances of some hundreds meters over hydraulically rough, flat-bottomed surfaces. Studies in small watersheds (<100 ha) have demonstrated a large reduction in runoff volume and peak discharge but it is unknown to who extent large watersheds (>1000 ha) also benefit from these effects, when land uses other than arable land also contribute and when travel time increases due to the increasing flow path length. We analyzed this by a modeling approach because controlled experiments can hardly be applied for large watersheds. Two summers, one prior to and one after small grain harvest, and one winter condition and recurrence times of 2, 10, 20 and 50 yr were taken into account. Land use was assumed to be either dominated by arable land (80%) or varying between sub-watersheds with arable land contributing only 45% on average. Under predominantly arable land use 2.3% of the total land was found suitable to be converted to GWWs, while for a diversified land use only 0.8% of the total land called for a GWW. For all conditions the efficacy of GWWs to reduce runoff volume and peak discharge decreased only slightly with increasing watershed size. Under arable land use and summer conditions-runoff volume was reduced by about 30% and peak discharge by about 40% with somewhat higher values for more frequent storms and lower values for rare storms. The efficacy was considerably lower under winter conditions and for a diversified land use where only a small proportion of GWWs was assumed. Runoff reduction was affected more and may drop below 5% under unfavorable conditions (low GWW percentage, winter, large events) while still a reduction in peak discharge of at least 15% was observed even under most of the unfavorable conditions despite a loss of land of only 0.8%. GWWs hence contribute considerably to flood control even in watersheds larger than 1000 ha and especially when summer floods are the main problem.

1. Introduction

Flooding of private properties and public infrastructure is a common problem in agricultural watersheds (Bielders et al., 2003). Several studies have been undertaken in the last decades pertaining to the occurrence of (muddy-) flooding and related damages in specific agricultural regions throughout Europe, i.e. South Downs in the UK (Boardman et al., 1994),

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the Pay the Caux in France (Papy and Douyer, 1991) and central Belgium (Bielders et al., 2003; Verstraeten et al., 2003).

To treat these problems grass has been widely used to control runoff and sediment delivery plot and field studies have been carried out to quantify sediment trapping and runoff control in vegetative filter strips (VFSs) (Chaubey et al., 1994, 1995; Barfield et al., 1998; Schmitt et al., 1999; Le Bissonnais et al., 2004; Syversen, 2005; Syversen and Borch, 2005). Depending on experimental setups the runoff reduction of the VFSs varied between 6% (Chaubey et al., 1994) and 89% (Schmitt et al., 1999). In most cases only low-volume sheet flow in the VFSs was tested and hence the results can hardly be extrapolated to VFS located along streams, where storm runoff enters as concentrated flow and leaves the grassed area again after some 10 m. Studies evaluating the effects of VFS on a watershed scale are rare and show a decrease in VFS efficiency with increasing scale, due to runoff concentration and bypassing of VFS (Verstraeten et al., in press).

In contrast to VFS, grassed waterways (GWWs) are established only where runoff concentrates and provide travel distances of some hundred meters. The efficiency of GWWs in reducing runoff has been investigated only in a few studies (Briggs et al., 1999; Chow et al., 1999; Fiener and Auerswald, 2003a,b, 2006). Briggs et al. (1999), for example, found a runoff reduction of 47% by a GWW in a laboratory experiment, but their experimental setup was similar to that of many VFS experiments. In a landscape experiment where potato production with commonly up-and-down slope cultivation was compared to combined terraces-GWW systems, the average runoff was reduced by 86% after establishing the terraces-GWW systems (Chow et al., 1999). Fiener and Auerswald (2003b) found a runoff reduction of 8% and 91% for two GWWs tested in a 8-yr landscape experiment. Moreover, there were some physically based modeling approaches dealing with runoff over grassed surfaces (Fiener and Auerswald, 2005; Deletic, 2001; Munoz-Carpena et al., 1999), whereby Fiener and Auerswald (2005) focused explicitly on the concentrated flow in GWWs. These authors found that the main GWW characteristics governing its runoff control efficiency were its length, a flat-bottomed cross-section, and the hydraulic roughness of the vegetation in dependency of flow depth.

The high efficacy found in these studies may be misleading, because in larger watersheds only some parts are suitable for the establishment of a GWW, thus decreasing the overall effect of the GWW. Furthermore, runoff travel time generally increases with increasing watershed size. A given increase in travel time caused by a GWW will thus lose relative importance with increasing watershed size. Despite the convincing results on the effects of GWWs on small (<100 ha) watersheds, large caveats exist regarding their effect on large (>1000 ha) watersheds. This would call for a long-term examination of their effect in large watersheds. That kind of controlled experiment (e.g., Loftis et al., 2001) is not always practical in larger watersheds due to high costs and the problem of finding a pair of similar watersheds which can be calibrated during a pre-treatment period. Therefore, modeling is the first choice. The difficulty arises that the modeling has to be able to handle a large, heterogeneous watershed, which calls for simplicity in the modeling approach, but on the other hand it has to be detailed enough to consider small landscape elements like GWWs and their determinants.

Here we use such a modeling approach to test the hypothesis that the efficacy of establishing GWWs changes with scale and with land use pattern.

2. Materials and methods

2.1. *Test site*

The Lauterbach watershed is located in North Rhine-Westphalia, Germany, about 10 km East of Bonn. The hilly area is part of the foothills of the Rheinisches Schiefergebirge (Rhenian Slate Mountains) and is draining into the river Sieg. The watershed covers an area of approximately 16.7 km^2 at an altitude of 69–321 m a.s.l. (50°44′N, 7°12′E). The mean annual air temperature, measured at a meteorological station about 15 km northeast of the watershed at 195 m a.s.l., was 10.2 °C (for 1993–2003). The average precipitation per year was 1027 mm (for 1993–2003) with the highest precipitation intensities per day occurring from May to October (maximum 52.4 mm d^{-1} occurring in June 1998).

Due to its fertile, loess–containing silty and silty loamy soils and its proximity to the agglomeration of Cologne-Bonn, most of the area is intensively used for arable agriculture competing with expanding residential areas in the villages. On the steeper slopes mainly located in the Southern part of the watershed grassland, forests as well as settlements can be found (Fig. 1, Table 1). Small grains were cultivated on 69% of the arable land, dominated by wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.). On the remaining 31%, row crops were planted, mainly sugar beets (*Beta vulgaris* L.) and maize (*Zea mays* L.), as well as some potatoes (*Solanum tuberosum* L.).

2.2. *Modeling*

Runoff volume and peak discharge were modeled in 16 sub-watersheds (37–272 ha in size) according to a modified SCS curve number (CN) technique in combination with a runoff travel time estimation and the graphical discharge method (USDA-SCS, 1986). To simulate the runoff at three locations along the Lauterbach (Fig. 1, points A–C), describing composite watersheds of about 700–1700 ha, the runoff from the sub-watersheds was routed in the Lauterbach using Manning's equation. In more complex and sophisticated grid-based models, flow depth and flow velocity depends on the grid cell size used for modeling the watershed. In our case this approach is not satisfying, because the effect of GWWs must take into account the cross-section and roughness along the drainage line. Our approach, which is simpler in concept, allows focusing on GWWs as individual landscape structures, rather than an ill-defined subset of raster grid cells.

The standard SCS-CN approach (e.g., Mockus, 1972; USDA-SCS, 1986) was modified to take into account: (i) the seasonal variation in runoff generation in the draining fields, and (ii) the location of a GWW in a watershed as well as its high infiltration capacity and hydraulic roughness, which prolongs runoff travel time after the end of a rain event. The seasonal variability in runoff generation was introduced in the standard

Table 1 – Land use in the Lauterbach watershed and the Dissenbach sub-watershed determined from Landsat TM scenes of April and July 2003

Arable land		Grass land	Forests	Settlements and infrastructure
Small grains	Row crops			
Lauterbach watershed (=diversified land use)				
31%	14%	21%	14%	20%
Dissenbach sub-watershed (=predominantly arable land use)				
59%	21%	16%	0%	4%

CN-technique by taking the seasonal variability of soil cover and soil crusting into account (Van Oost, 2003) [Eq. (1)]:

$$CN = CN_{max} - \left(\frac{Cc}{100} \times c_1\right) + \left(\frac{Cr}{5} \times c_2\right) \quad (1)$$

where CN_{max} is the maximum CN derived from the USDA SCS handbook (1986), Cc the crop cover percentage, Cr the crusting stage (0 = no crusting, 5 = max crusting) and c_1 and c_2 are coefficients.

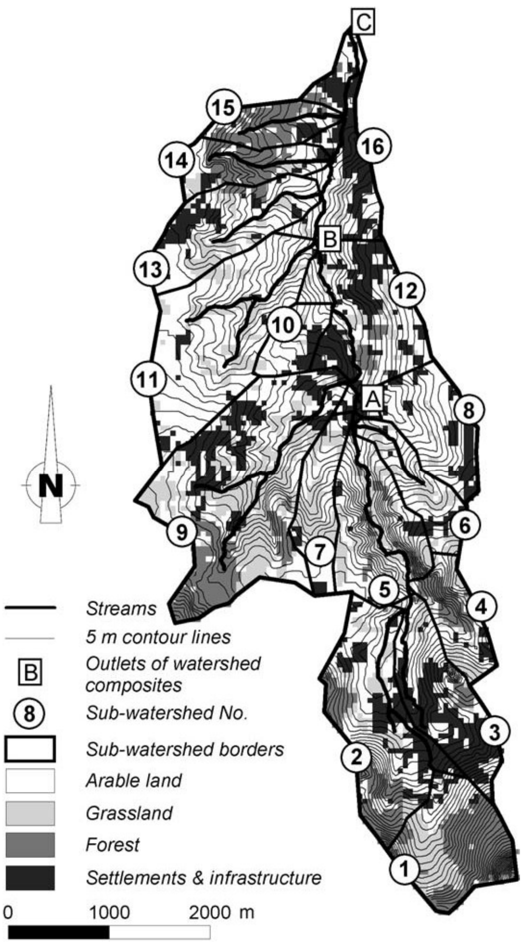

Fig. 1 – Topography and land use of the Lauterbach watershed; land use determined from Landsat TM scenes of April and July 2003; numbers indicate the different sub-watersheds, while letters (A–C) indicate points along the Lauterbach used to calculate runoff from a combination of the upstream sub-watersheds.

The value of c_1 is set to get a CN equal to the minimum CN for a given crop-soil combination when the crop cover equals 100% and c_2 is set to reach a CN equal to the value for a fallow soil surface when the crop cover equals 0%. The values of CN_{max}, c_1 and c_2 depend on the soil type and land use or cover, for the test site values are summarized in Table 2. In general, the CN values in the approach developed by Van Oost (2003) are only manipulated in the boundaries of the CN values used in the extensively tested original USDA SCS model. To examine the effects of GWWs for different watershed conditions two summer and one winter situation was modeled. The first summer modeling was carried out for typical July field conditions prior to the harvest of small grains (subsequently referred as summer prior to small grain harvest). For this situation an average soil cover of 80% and a crusting stage of 2.5 was assumed for all fields. The second summer model exercise represents the watershed conditions in August after harvest of small grains (subsequently referred as summer after harvest of small grains). In case of the August model runs again a soil cover of 80% and a crusting stage of 2.5 was assumed for the row corps. Following German agricultural statistics (INVEKOS inventory; Auerswald et al., 2003), on about 2/3 of the fields intercrops are planted after small grain harvest and therefore a soil cover of 60% and a crusting stage of 3 was adopted, while 1/3 of the harvested fields were assumed to be bare, hence for those a soil cover of 20% and a crusting stage of 5 was used. For the winter situation model runs were carried out with a soil cover of 10% and a crusting stage of 5. Moreover, for the summer events dry conditions with an antecedent moisture condition I (AMC I) were assumed and hence CNs from Eq. (1) were modified by Eq. (2). Analogously for wet conditions in the winter half-year the CNs from Eq. (1) were modified using Eq. (3) (Chow et al., 1988):

$$CN_{I} = 4.2 \frac{CN_{II}}{10 - 0.058 CN_{II}} \quad (2)$$

$$CN_{III} = 23 \frac{CN_{II}}{10 + 0.13 CN_{II}} \quad (3)$$

where CN_{I}, CN_{II} and CN_{III} were the CNs for AMC I, AMC II and AMC III, respectively. The two summer and winter conditions

Table 2 – Parameter values for CN_{max}, c_1 and c_2

Cover	CN_{max}	c_1	c_2
Row crops	88	6	3
Small grains	85	8	6

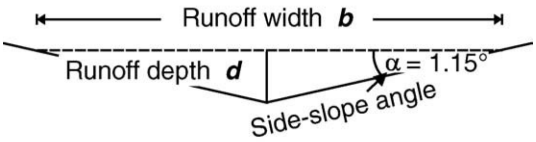

Fig. 2 – Idealized cross-section of modeled grassed waterways according to Fiener and Auerswald (2005).

thus covered about the whole range, which can realistically be expected as an average for a mesoscale watershed. Nevertheless, there might be more extreme conditions on single fields or small sub-watersheds, which were not addressed with the presented modeling exercise due to its focus on mesoscale effects of GWWs. Based on the calculated runoff volumes, peak discharge in all sub-watersheds was estimated according to SCS standard procedures (USDA-SCS, 1986), by calculating runoff travel time and using the graphical discharge method. We only modified the travel time estimation by replacing the empirical equation for shallow concentrated flow along drainage lines by the Manning's equation. For an idealized cross-section of a GWW (Fig. 2), Manning's equation can be rearranged as

$$q = \frac{1}{n} S^{1/2} \left(\frac{d}{2}\right)^{8/3} \frac{4}{\tan \alpha} \tag{4}$$

where q is the discharge ($m^3\,s^{-1}$), n the Manning's roughness coefficient ($s\,m^{-1/3}$) dependent on soil surface conditions and vegetative cover, S the slope along the drainage line, d the runoff depth (m), and α is the side-slope of the drainage line.

The average runoff depth ($d/2$) along the main drainage line of each sub-watershed was simulated for the different storms with the model. Therefore, the peak discharge mid-slope of each drainage line with a potential GWW was calculated and $d/2$ was derived from Eq. (4) and the idealized cross-section (Fig. 2). The idealized cross-section, with a side-slope α of 1.15° was adopted from field measurements (Fiener and Auerswald, 2003b) and a physically based modeling of concentrated runoff in GWWs (Fiener and Auerswald, 2005), which underline the importance of a flat-bottomed cross-section for GWW efficiency. Based on field experiences the width of the modeled GWWs was set generally to 15 m.

A dense vegetation of typical agricultural grasses, e.g. *Elytrigia repens* L., *Dactylis glomerata* L., *Arrhenatherum elatius* L., and herbs, e.g. *Epilobium angustifolium* L., *Galeopsis aparine* L., which are mowed only once a year or let to succession, was assumed in all simulations. They are typical for GWWs and measurements of hydraulic roughness carried out during field experiments can be adopted (Fiener and Auerswald, 2005). Provided vegetation in the GWWs is not flattened by high runoff velocities, a Manning's n of 0.35 $m\,s^{-1/3}$ (e.g., Jin et al., 2000; Fiener and Auerswald, 2005) was used. Where vegetation was flattened, values of 0.05–0.01 $m\,s^{-1/3}$ were assumed (e.g., Kouwen, 1992). To determine the runoff depth where a failure of vegetation can be assumed we adopted an approach developed by Kouwen and Li (1980), calculating a minimum critical shear velocity v_{crit} ($m\,s^{-1}$). This critical shear velocity depends on a combined effect of vegetation density, stiffness, and length represented by the flexural rigidity per square meter. The flexural rigidity was measured exemplarily for two grassed waterways, one let to succession the other mowed once a year (Fiener and Auerswald, 2006), applying a simple field test (Kouwen et al., 1981; Eastgate, 1969). From the critical shear velocity the critical runoff depth d_{crit} (m) was calculated:

$$d_{crit} = \frac{v_{crit}^2}{gS} \tag{5}$$

where g is acceleration due to gravity ($m\,s^{-2}$), and S is the slope along the drainage line of the tested GWWs.

Combining the critical shear velocities derived from 1 yr of bi-weekly measurements (2002–2003) at 21 locations within two GWWs in Bavaria (winter: average AVR $v_{crit} = 0.221\,m\,s^{-1}$, standard deviation S.D. = 0.023 $m\,s^{-1}$; summer: AVR $v_{crit} = 0.276\,m\,s^{-1}$, S.D. = 0.027 $m\,s^{-1}$) (Fiener and Auerswald, 2006), with the slopes along the drainage lines of the potential GWWs in the Lauterbach watershed allowed to estimate d_{crit}. For the winter half-year on average it was 0.10 m ranging from 0.14 m for gentle slopes (3.4%) to 0.05 m for the steepest slopes (9.8%). In the summer half-year the average was 0.15 m with a range between 0.23 to 0.08 m. According to these results we assumed in the modeling exercise that vegetation fails when average runoff depth in the GWWs exceeds 0.10 m in winter and 0.15 m in summer.

To take into account the high infiltration capacity and the location of the GWWs within the sub-watersheds, we estimated the amount of runoff infiltrating into the GWWs. In cases of runoff generation in the fields but not in the GWWs, the total runoff volume of the sub-watersheds was reduced by the difference between initial abstraction of the CN-model and rain amount in the GWWs. Moreover, the GWWs prolong runoff after the end of a rain event compared to drainage lines without GWW, hence afterflow infiltration also increases. Based on extensive field observations and experiments with concentrated flow in two ca. 300 m long GWWs (Fiener and Auerswald, 2003b, 2005) we assumed 1/2 h additional afterflow infiltration per 100 m GWW length along the drainage line. As this occurs mainly in the area of concentrated flow of the GWWs, only half of the GWWs area was taken into account for afterflow infiltration. An infiltration rate of $5 \times 10^{-6}\,m\,s^{-1}$ was assumed typical for saturated colluvial soils found along drainage lines (e.g., Blume et al., 2002).

The modeled peak discharge of each of the 15 sub-watersheds was routed to the outlet of the Lauterbach watershed using the Manning's equation assuming board-full runoff within the Lauterbach (USDA-SCS, 1986). Therefore, information about the cross-section was derived from field surveys and from data of local water authorities.

2.3. *Modeled land use*

To simulate runoff and peak discharge reduction under different boundary conditions 24-h rains with a recurrence time of 2, 10, 20, and 50 yr were applied. The 24-h rains were used under the focus of mesoscale watersheds, which typically show a similar time of runoff concentration. The rain amounts for the Lauterbach watershed were taken from regionalized maps of the National German Weather Service (DWD) presented in

Table 3 – Size of 24-h rainstorms at the test site in winter (October–April) and summer (May–September); data adopted from Bartels et al. (1997)

Recurrence time (yr)	24-h precipitation (mm)	
	Winter (January)	Summer (July/August)
2	30.1	41.2
10	36.3	61.3
20	38.9	69.9
50	42.4	81.3

an 8.5 km × 8.5 km grid (Bartels et al., 1997). The higher rain intensities per day measured at the meteorological station Northeast of the watershed between May and October (for 1993–2003), were confirmed by the DWD maps. Therefore, different rain intensities for the summer and winter half-year were used (Table 3).

For the field management in the watershed we assumed that all fields were planted in slope direction and no cover crops, e.g. mustard (*Sinapis alba* L.), were cultivated for soil-conservation during winter. This results in a conservative estimate of the GWWs runoff control because a smaller inflow due to water-conservation measures in the watershed would increase effectiveness (Fiener and Auerswald, 2005).

In general the model was tested under two land use settings to evaluate the runoff control effectiveness of potential GWWs in the mesoscale Lauterbach watershed. (1) A land use dominated by arable land, which allows to establish GWWs along all drainage lines. The proportion of different agricultural land uses of this setting was taken from the Dissenbach sub-watershed (Watershed no. 11 in Fig. 1, Table 1), which is dominated by arable land. Subsequently, this land use setting is referred as predominantly arable land use. This land use was designed to determine whether there is a scale effect in runoff control moving from small agricultural watersheds, where measurements of GWW efficiency exist, to a mesoscale watershed. (2) The existing land use pattern differing between sub-watersheds was used and GWWs were established only along drainage lines where arable fields are located. Hence, the potential GWWs were widely limited to the Northern part of the watershed (Fig. 3). This land use is subsequently referred as diversified land use. Comparing both land use settings allows distinguishing between land use and scale effects in case of up-scaling the efficiency in runoff control of GWWs.

In both land use settings 15 m wide GWWs were assumed along drainage lines draining at least 5 ha. The locations of the GWWs were determined using a 50 m × 50 m digital elevation model (DEM) and calculating an artificial stream network for all sub-watersheds draining at least 5 ha with an algorithm included in a the USDA Soil & Water Assessment Tool interface AVSWAT (Di Luzio et al., 2002) for Arc View 3.2 (Esri Inc., Redlands, California). Moreover, the length and slope of each potential GWW was calculated from the DEM and was used individually for modeling runoff travel time in each sub-watershed. Thus, two land use settings (predominantly arable/diversified), three surface conditions (summer before and after harvest, winter) and four rain recurrence conditions (2, 10, 20, 50 yrs) were evaluated for the 16 sub-watersheds and three locations along the main watercourse.

3. Results

3.1. *Area demand*

Under the predominantly arable land use only one sub-watershed did not allow to establish a GWW due to a steep (>10%) main drainage line. In the other sub-watersheds the GWWs occupied between 1.3% and 4.2% of the land, with an average for the whole Lauterbach watershed of 2.3% or 37.7 ha (Table 4). The individual length of the GWWs varied from 140 to 1680 m.

Under diversified land use GWWs were mainly established in the northern part of the watershed (Fig. 3), which is dominated by arable land. While in seven sub-watersheds no GWW was modeled, GWWs occupied between 0.2% and 3.6% of the other sub-watershed areas. Within the total Lauterbach watershed 0.8% (12.5 ha) of the area was converted to GWWs (Table 4). The length of the GWWs varied from 120 to 1360 m.

Under predominantly arable land use the GWW area was about 3-times larger than the area commonly recommended for vegetative filter strips beside third order streams, which would be 2 m × 10 m × 6700 m (13.4 ha) in case of the Lauterbach. Under diversified land use the GWW area was smaller

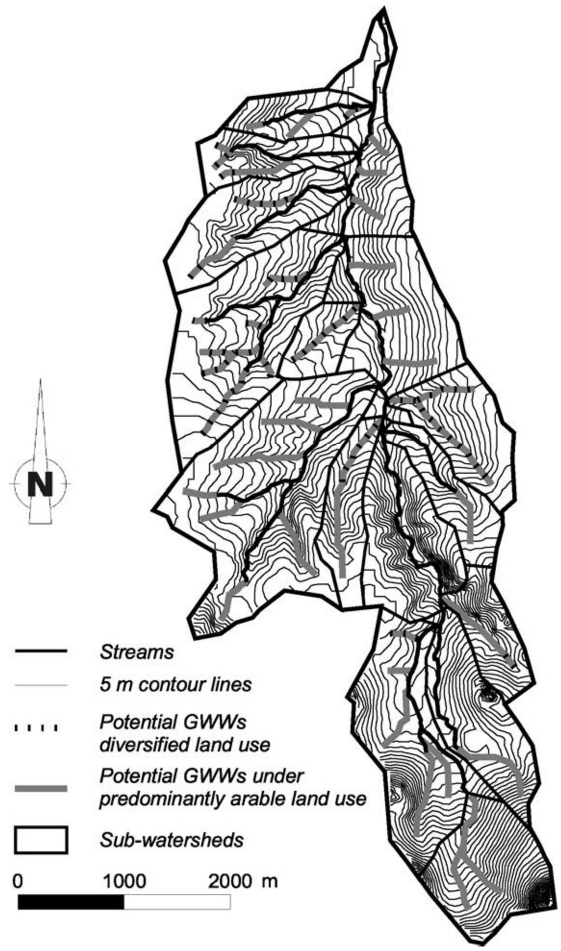

Fig. 3 – Potential grassed waterways (GWWs) in the Lauterbach watershed under predominantly arable land use in all sub-watersheds and diversified land use.

Table 4 – Area of sub-watersheds (nos. 1–16) and composite watersheds (Fig. 1, points A–C); length and area of potential GWWs for the modeled land use

Watershed no.	Watershed area (ha)	Diversified land use		Predominantly arable land use	
		GWWs length (m)	GWWs area (%)	GWWs length (m)	GWWs area (%)
1	108.4	0	0.0	1802	2.5
2	267.3	294	0.2	4481	2.5
3	102.2	0	0.0	873	1.3
4	52.9	229	0.7	984	2.8
5	115.7	0	0.0	0	0.0
6	55.6	0	0.0	550	1.5
7	59.6	730	1.8	1674	4.2
8	79.5	1922	3.6	1922	3.6
9	272.3	0	0.0	3982	2.2
10	36.9	849	3.5	849	3.5
11	194.0	2833	2.2	2833	2.2
12	144.0	0	0.0	1314	1.4
13	102.2	825	1.2	1178	1.7
14	54.8	524	1.4	1107	3.0
15	45.4	189	0.6	705	2.3
16	87.4	0	0.0	899	1.5
A	653.4	1253	0.3	10364	2.4
B	1380.2	6857	0.8	21264	2.3
C	1670.1	8395	0.8	25153	2.3

than the commonly recommended area for the vegetative filter strips along the Lauterbach.

3.2. *Effect during summer runoff*

Inflow volumes mid-slope of the GWWs in case of 50-yr summer storms after small grain harvest, which produce in general larger inflows than prior to small grain harvest, ranged between 1100 and 6310 m^3 for the predominantly arable land use with maximum inflow rates from 0.08 to 0.28 $m^3 s^{-1}$. Therefore, the average runoff depths of 0.06–0.10 m were always below the critical runoff depth of 0.15 m in summer, and hence no vegetation failure is expected. In addition, no failure of vegetation is expected for summer storms under diversified land use.

Runoff reduction by GWWs is generally governed by storm size and GWW area (Figs. 4 and 5, left). Under predominantly arable land use, in case of the smallest modeled runoffs (10-yr summer storm prior to small grain harvest), their effect in the different sub-watersheds ranged from 19% (sub-watershed no. 12, 1.4% GWW area, runoff reduction 1714 m^3) to 88% (sub-watershed no. 7, 4.2% GWW area, runoff reduction 3296 m^3), while for the largest runoffs (10-yr winter storm) it was between 3% (sub-watershed no. 16, 1.5% GWW area, runoff reduction 524 m^3) and 21% (sub-watershed no. 7, runoff reduction 2783 m^3). Compared to the runoff reduction efficiency of 91% determined for a 7.8 ha watershed under soil-conservation agriculture, with a 1.07 ha grassed waterway similar in cross-section and vegetation (Fiener and Auerswald, 2003b), the modeled efficiencies were clearly smaller, but seemed to be reasonable due to the smaller GWW area proportion, the larger watershed sizes and the conventional agriculture, which both increase inflow volumes.

For the total Lauterbach watershed runoff reduction was 2.6-times more efficient under predominantly arable land use (Fig. 4, left), which allowed GWWs on 2.3% of the watershed area, than under the diversified land use (Fig. 5, left), where GWWs occupied 0.8% of the area. Runoff reduction by GWWs in mesoscale watersheds is prominent in case of summer storms, which produce little runoff due to high soil cover and low crusting.

Compared to runoff reduction the efficiency of GWWs to lower peak discharge decreased less with storm size (Figs. 4–5, right). An exception was the 10-yr summer storm prior to small grain harvest, where peak discharge was strongly affected by a runoff reduction >60% in some sub-watersheds.

Under predominantly arable land use the GWWs reduced peak discharge for the largest applied storms in summer (50-yr storm) between 30% (sub-watershed no. 16, storm after small grain harvest) and 59% (sub-watershed no. 8, storm prior to small grain harvest) (Fig. 4, right). For the total Lauterbach watershed peak discharge was at least reduced by 41% in case of predominantly arable land use and by 16% for the diversified land use (50-yr summer storm after small grain harvest). In general, there was only a minor difference in peak discharge reduction between the modeled summer storms prior and after small grain harvest, because the additional inflow after small grain harvest was relatively small.

3.3. *Effect during winter runoff*

The modeled winter events produced generally more runoff than the summer storms of equal recurrence time, even if applied summer storms are larger (Table 3). This results from insufficient cover and increased crusting on arable land in winter.

Inflow volumes mid-slope of the GWWs ranged from 1430 to 8170 m^3 for 10-yr winter storms under predominantly arable land use, depending on sub-watershed size and GWW proportion. Taking into account gradient and length of the drainage lines simulated maximum inflow rates were 0.18–0.61 $m^3 s^{-1}$. Calculated average runoff depth for this storm size varied between 0.07 and 0.13 m. Due to high inflow rates and reduced flexural rigidity of the vegetation in winter, the average runoff

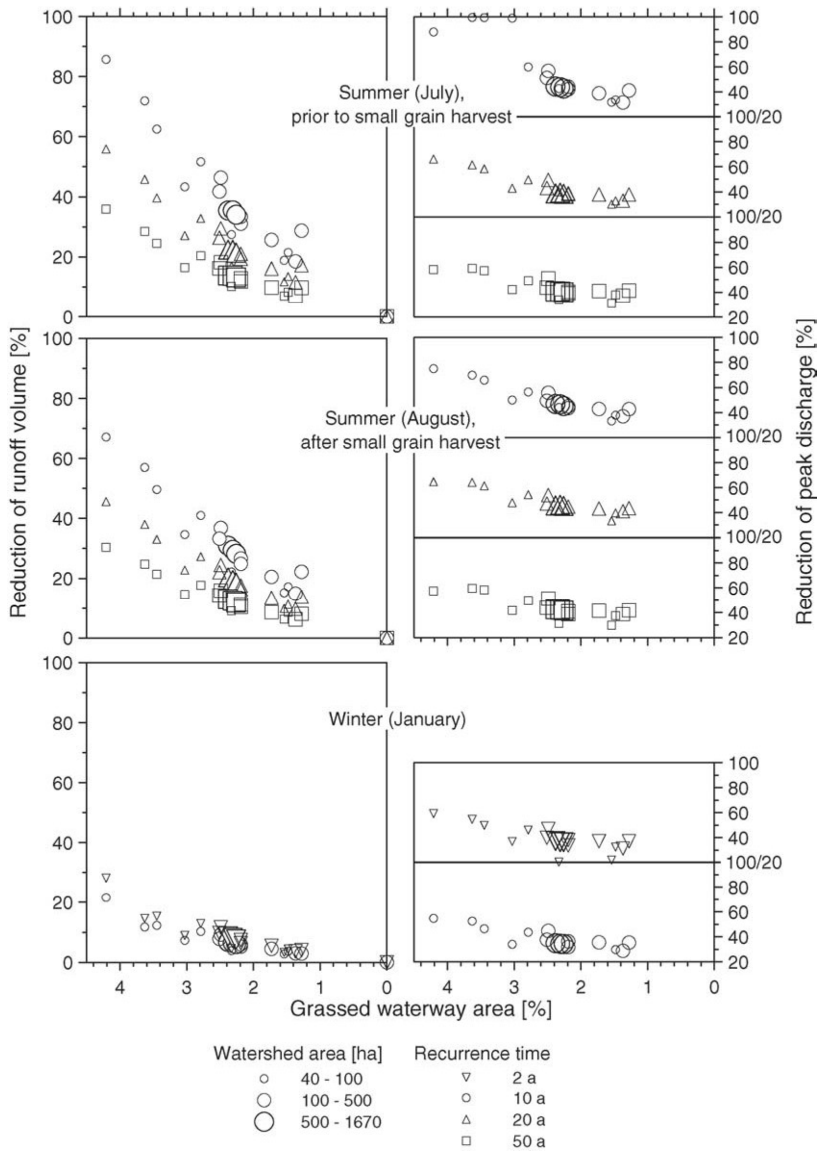

Fig. 4 – Modeled reduction of runoff volume (left) and peak discharge (right) for 24-h storms for a predominantly arable land use; grassed waterways assumed in all sub-watersheds except no. 5, where the drainage line was steeper than 10%; note for summer storms recurrence times of 10–50-yr (no runoff in case of 2-yr storms), while for winter events recurrence times of 2–10-yr are presented; winter storms >10-yr are excluded due to unknown vegetation behavior.

depth for the 10-yr storms in case of the predominantly arable land use exceeded the critical runoff depth of 0.10 m in 5 of the 16 sub-watersheds. For the 2-yr storm this happened in one case. High runoff depths were mainly modeled in sub-watersheds with long GWWs draining relatively large areas (e.g., sub-watershed no. 1 or 7), hence in case of the diversified land use the vegetation failed only in four sub-watersheds for the 10-yr winter storm. An average maximum runoff depth, which exceeds the critical runoff depth, will not automatically lead to a total failure of a GWW in increasing runoff travel time, because these high rates will not occur along the total drainage line and only after some time. Moreover, a GWW will still prevent gully erosion and the concentration of runoff within the gully by maintaining a flat-bottomed cross-section of the flow path. To take such a failure into account a more sophisticated spatially and temporally distributed model dealing with concentrated flow and gully erosion along the drainage lines would be necessary and the behavior of the vegetation after being once bent to the ground must be known. With the conceptual approach presented here this is impossible and hence winter storms with a recurrence time >10-yr were excluded due to an increasing uncertainty because of unknown vegetation behavior. However, with a GWW management that increases flexural rigidity, e.g. by allowing succession of woody plants, a better performance during winter and rare storms can be expected although experimental evidence is missing.

Under predominantly arable land use, in case of 2-yr winter storms, the runoff reduction efficiency of the GWWs in the different sub-watersheds ranged from 3.3% (sub-watershed no. 16) to 28.1% (sub-watershed no. 7), while for the 10-yr storms it was between 2.8% and 21.6% (Fig. 4, left). For the total Lauterbach watershed runoff reduction was about 2.5-times more

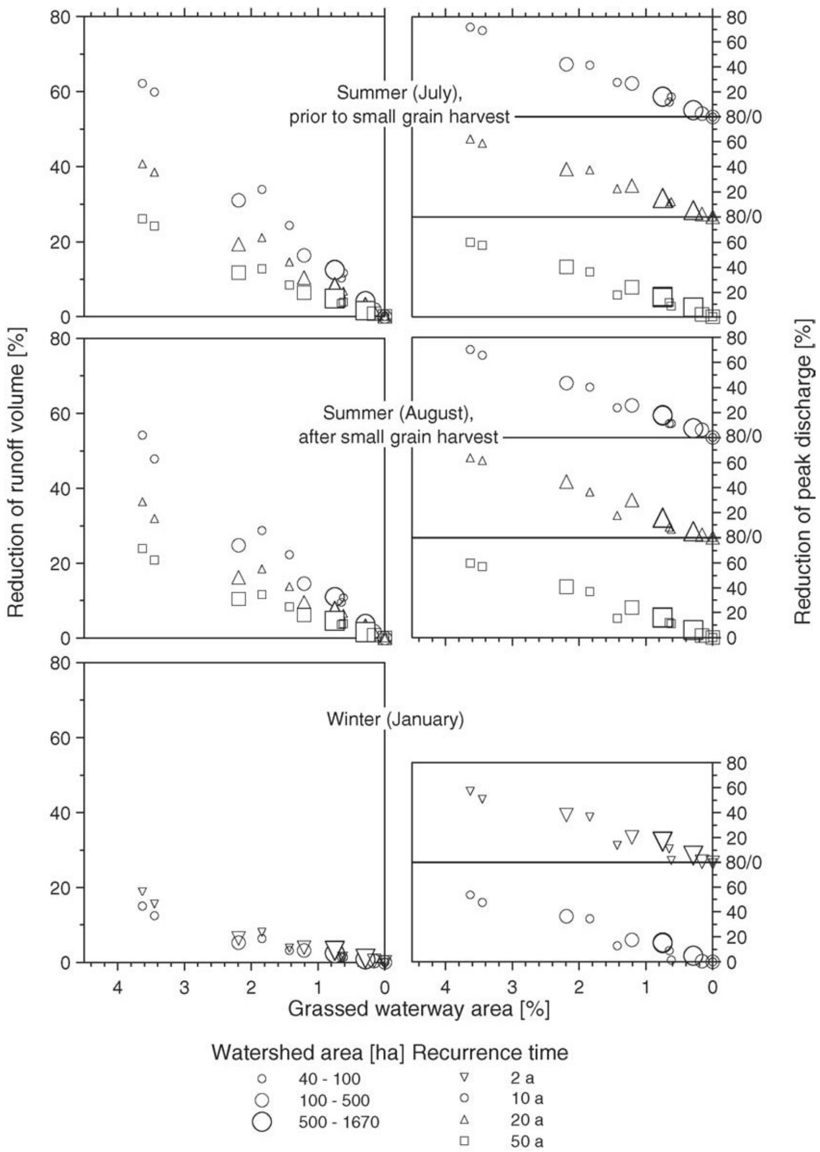

Fig. 5 – Modeled reduction of runoff volume (left) and peak discharge (right) for 24-h storms for a diversified land use; grassed waterways assumed where ever possible due to topography and land use; note for summer storms recurrence times of 10–50-yr (no runoff in case of 2-yr storms), while for winter events recurrence times of 2–10-yr are presented; winter storms >10-yr are excluded due to unknown vegetation behavior.

efficient under predominantly arable compared to diversified land use (Figs. 4 and 5, left).

Similar to summer events, peak discharge decreased less with increasing storm size (Figs. 4 and 5, right). Under predominantly arable land use GWWs reduced peak discharge for the largest applied winter storm (10-yr storm) between 19% (sub-watershed no. 15) and 55% (sub-watershed no. 7). In case of the 10-yr storm peak discharge in the total Lauterbach watershed was reduced by 34% for predominantly arable land use and by 15% for diversified land use.

3.4. *Influence of watershed size*

Increasing watershed size had no remarkable effect on runoff reduction as long as GWW area did not change with increasing watershed size. While the total watershed corresponds to the average GWW area, small sub-watersheds may have higher or lower proportions of GWW, which in turn will affect runoff reduction without being a scale effect.

The correlation between GWW area and efficiency in peak discharge reduction was less pronounced than for runoff volume reduction, because shape of watershed as well as length and slope of the main drainage line, where the GWW was established, are also important. In general, the GWWs reduced peak discharge in the predominantly arable mesoscale watershed effectively, again with no effect of scale. During summer storms in the Lauterbach watershed the peak discharge decreased at least 40% (9.2 m s^{-1} without, 5.6 m s^{-1} with GWW, 50-yr storm), for all applied events.

4. Discussion

Assuming that the average field conditions applied for the modeling are representative focusing on the GWWs efficiencies in a mesoscale watershed, it can be concluded that GWWs can be an effective measure to reduce flooding on this scale. On the scale of sub-watersheds the effects of single GWWs might differ considerably because of the large influence exhibited by an individual field of a distinct state. There might be a flooding on this small scale, reported in several studies after heavy summer storms (e.g., Verstraeten and Poesen, 1999) although already on the mesoscale summer events seem to be easier to control than winter events when all fields produce more runoff and infiltration capacities in the GWWs are small.

In summer, the effects of prolonging runoff travel time and hence to reduce peak discharge, may even increase for short rains as they are typical for heavy summer storms. Also, the prevention of gully erosion will reduce the damages of local (muddy) floods in summer. Even if these heavy storms occur in late spring or autumn (due to the general large storm sizes between May and October) when the fields produce more runoff, the GWWs should stay effective due to the high flexural rigidity of the vegetation in this period. In the winter half-year the GWWs were less effective in reducing peak discharge for storms with a recurrence interval larger than 2-yr (Fig. 4). The reasons were the higher inflow rates even in case of smaller storms and the reduced flexural rigidity, which allows only a critical runoff depth of about 0.1 m without vegetation failure. The results in case of the 10-yrs storm (Fig. 4) may even over estimate the GWWs effectiveness because partly a failure of vegetation can be expected. In general, in winter intensive rains often lasts for more than 1 day and hence the prolonging of runoff travel time is less prominent for a decrease of peak discharge. Nevertheless, there will be still a GWW effect by preventing gully erosion, which without GWW increases the connectivity between source of runoff and watershed outlet.

For the total Lauterbach watershed, the peak discharge reduction under present diversified land use was significantly smaller than for the predominantly arable land use but reduction was still remarkable although only some sub-watersheds had GWWs. In total the minimal reduction of peak discharge by establishing GWWs under diversified land use ranged between 15% (23.2 $m^3 s^{-1}$ without, 19.7 $m^3 s^{-1}$ with GWW, 10-yr winter storm) and 17% (2.8 $m^3 s^{-1}$ without, 2.3 $m^3 s^{-1}$ with GWW, 10-yr summer storm). Establishing GWWs only in the sub-watersheds with arable dominated land use still had a remarkable effect on peak discharge in the mesoscale watershed. It is obvious that this effect is smaller than in single sub-watersheds, which were optimal for GWW establishment, because in nearly half of the Lauterbach sub-watersheds no GWWs and in only three the optimal GWW set-up could be implemented (Table 5).

In general, the modeling exercise showed that peak discharge reduction by GWWs only slightly decreased with increasing watershed size from tens to thousands of hectare, as long as a predominant arable land use allows introducing GWWs in most drainage lines. The heterogeneity of flow pathways acts to desynchronize and thereby attenuate runoff

Table 5 – Modeled runoff for different 24-h rainstorms for winter (January) and summer (July, August) events; winter storms >10-yr not simulated due to unknown vegetation behavior

Storm recurrence time (a)	Runoff for predominantly arable land use (mm)						Runoff for diversified land use (mm)					
	Winter		Summer, prior to small grain harvest		Summer, after small grain harvest		Winter		Summer, prior to small grain harvest		Summer, after small grain harvest	
	Without GWW[a]	With GWW	Without GWW	With GWW	Without GWW	With GWW	Without GWW	With GWW	Without GWW	With GWW	Without GWW	With GWW
2	16.3	15.1	1.2	0.0	1.5	0.0	14.4	13.8	1.0	0.0	1.2	0.0
10	21.6	20.4	6.5	4.3	8.3	6.0	19.4	19.0	6.2	5.4	7.2	6.4
20	–	–	9.7	7.6	12.1	9.8	–	–	9.3	8.6	10.5	9.8
50	–	–	14.7	12.8	17.7	15.6	–	–	14.1	13.4	15.7	15.0

[a] GWW, grassed waterway.

peak volumes also on the large scales. In contrast the efficiency decreases from small sub-watersheds dominated by arable land use to a mesoscale watershed with a more heterogeneous land use. For the present diversified land use the effect of reducing peak discharge on the mesoscale is governed by some sub-watersheds in the North of the Lauterbach watershed. Therefore, the proper management of those is of major importance for mesoscale efficiency of the GWWs. Due to our results a reduction of GWWs efficiency in reducing peak discharge is mainly caused by an increasing percentage of land use not suitable for an establishment of GWWs but not by an increase of scale. The increase in the proportion of runoff bypassing the grassed area with increasing watershed size, as it was found for vegetated filter strips (Verstraeten et al., in press), should be small because of their location close to the source of runoff production and their general design to handle concentrated runoff. Nevertheless, it must by recognized that similar efficiencies of GWWs than those presented can only be expected if they are properly designed and managed. Especially, to keep their vegetation in good condition and to shape and maintain their cross-sections flat-bottomed is of major importance (Fiener and Auerswald, 2005).

5. Conclusions

The hypothesis that the efficacy of GWWs changes with scale and with land use could be verified. The decrease with scale was small, however, which was especially evident for a predominantly arable land use. Even for watershed sizes up to 1700 ha, GWWs are an efficient control of peak discharge. In contrast, the effect of land use is strong. The efficacy of GWWs is low where land use and storm size produce high amounts of inflow into the GWWs. This is especially critical in winter because then hydraulic roughness of the grass cover will drop due to a reduced flexural rigidity under these conditions. Nevertheless, even in case of a failure of vegetation GWWs will increase runoff travel time by preventing gully erosion causing a concentration of runoff and an increase in runoff velocity. The efficacy in runoff reduction is also low, where the whole area produces only very little runoff like in forested watersheds because then runoff only occurs for storms, which also produce runoff on the GWW itself. The highest efficacy, however, can be expected in watersheds of small-patterned arable land use typical for many European landscapes. Such landscapes, which suffer most from adverse off-site effects of erosion, would benefit most and over the whole range of scales tested from the installation of GWWs.

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