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Effectiveness of Grassed Waterways in Reducing Runoff and Sediment Delivery from Agricultural Watersheds

P. Fiener and K. Auerswald*

ABSTRACT

Grassed waterways (GWWs) drain surface runoff from fields without gullying along the drainageway. Secondary functions include reducing runoff volume and velocity and retaining sediments and harmful substances from adjacent fields. Grass cover (sward)–damaging sedimentation in the GWW is commonly reduced by frequent mowing, but in doing so the effectiveness of the waterway relative to the secondary functions is reduced. Our objectives were to (i) evaluate whether the maintenance of a GWW can be reduced if on-site erosion control is effective, (ii) measure the effectiveness of such a GWW, and (iii) analyze the underlying mechanisms. A long-term (1994–2000) landscape experiment was performed in four watersheds, where two had GWWs for which maintenance was largely neglected. An intensive soil conservation system was established on all fields. Runoff and sediment delivery were continuously measured in the two watersheds with GWWs and in their paired watersheds that were similar, but without GWWs. Runoff was reduced by 90 and 10% for the two sets of paired watersheds, respectively. The different efficiencies of the GWWs resulted from different layouts (doubled width and flat-bottomed vs. v-shaped drainageway). The GWWs reduced sediment delivery by 97 and 77%, respectively, but the sward was not damaged by sedimentation. Grain sizes > 50 μm were settled due to gravity in both GWWs. Smaller grain sizes were primarily settled due to infiltration, which increased with a more effective runoff reduction. In general, the results indicated a high potential of GWWs for reducing runoff volume and velocity, sediments, and agrochemicals coming from agricultural watersheds.

Grassed waterways (GWWs) are a common erosion control practice in North American agriculture (Chow et al., 1999). They are broad shallow channels often located within large fields, with the primary function of draining surface runoff from farmland and preventing gullying along the natural drainageways (thalwegs) (Atkins and Coyle, 1977). To serve this function as effectively as possible, there is usually a selection of fast-growing grass sown in the GWW and it is mowed frequently to prevent sward-damaging sedimentation. This frequent mowing is necessary to reduce hydraulic roughness (e.g., Ree, 1949; Temple, 1999; Ogunlela and Makanjuola, 2000) because otherwise the GWW exhibits a high sediment trapping efficiency that may damage the sward and lead to ephemeral gullying.

Grassed waterways also reduce runoff volumes from agricultural watersheds due to their comparably high infiltration rates and the reduction in runoff velocity that prolongs the potential infiltration time. Reduction of runoff volume and velocity, sediment delivery, and also agrochemicals through GWWs has been investigated only in a few studies (e.g., Briggs et al., 1999; Chow et al., 1999; Hjelmfelt and Wang, 1997). Briggs et al. (1999), for example, found that GWWs in a laboratory experiment reduced runoff volume by an average of 47% and herbicide (isoxaben plus oryzalin and isoxaben plus trifluralin) residues by an average of 56% compared with nongrassed waterways. Hjelmfelt and Wang (1997) modeled a 5% total runoff volume reduction for a 34-ha watershed with a 600-m-long and 10-m-wide GWW.

A greater number of studies have dealt with the effects of relatively small vegetative filter strips (e.g., Schauder and Auerswald, 1992; Barfield et al., 1998; Chaubey et al., 1994, 1995; Schmitt et al., 1999; Zillgens, 2001). These studies, mostly plot experiments, have found a reduction of runoff volume ranging from 6% (Chaubey et al., 1994) to 89% (Schmitt et al., 1999), and a reduction of sediment delivery from 15% (Chaubey et al., 1994) to 99% (Schmitt et al., 1999). The variability of the results is based on differences in experimental setup, such as runoff volume input and precipitation on the vegetative filter strip, sediment concentration and grain size distribution, and the physical characteristics of the vegetative filter strip (e.g., slope, width, soil, grass composition, and density).

Taking into account the results of the vegetative filter strip studies, the layout and use of the common GWW is not optimal to reduce runoff volume and sediment delivery for several reasons. First, the layout, primarily the width, is only optimized to prevent gully erosion, with a minimum loss of agricultural land. Second, frequent mowing reduces hydraulic roughness and hence increases runoff velocity. Third, the usually frequent trafficking and mowing enhance soil compaction and hence reduce infiltration.

Our objectives were to (i) evaluate the long-term effects of a GWW on runoff and sediment delivery in a landscape-scale experiment, (ii) evaluate whether the maintenance of a GWW can be reduced without sward-damaging sedimentation if on-site erosion control is effective and runoff carries only a small sediment load, and (iii) analyze the effects of the layout on runoff and sediment delivery.

For this reason, a 650-m-long and 10- to 50-m-wide GWW was established in 1993 and a long-term measuring campaign was performed between January 1994 and December 2000. This GWW was divided into two parts: a lower part, where grass was sown and which was cut with a mulching mower once a year, and an upper part, where natural succession was allowed to occur for 8.5 years.

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Abbreviations: GWW, grassed waterway.

MATERIALS AND METHODS

Test Site

The test site was part of the Scheyern Experimental Farm of the Munich Research Association for Agricultural Ecosystems (FAM), which is located about 40 km north of Munich. The area is part of the Tertiary hills, an important agricultural landscape in central Europe. The test site covered an area of approximately 23 ha of arable land at an altitude of 454 to 496 m above mean sea level (48°30′50″ N, 11°26′30″ E). The mean annual air temperature was 8.4°C (for 1994–2000). The average precipitation per year was 804 mm (for 1994–2000) with the highest precipitation occurring from May to July (average maximum 116 mm in July) and the lowest occurring in the winter months (average minimum 33 mm in January).

On the test site the principles of integrated farming were applied in combination with an intensive soil conservation system in the fields (Auerswald et al., 2000). Field sizes ranged from 3.8 ha to 6.5 ha. The crop rotation consisted of potato (*Solanum tuberosum* L.), winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and winter wheat. This rotation allowed for the planting of a cover crop (mustard, *Sinapis alba* L.) before each row crop. Maize was planted directly without any tillage into the winter-killed mustard with a no-till planter. Potato was directly planted into ridges, which were formed before sowing the cover crop and therefore also covered with winter-killed mustard. Reduced tillage allowed the use of plant residues of maize and winter wheat as mulch cover and avoidance of soil compaction (Fiener and Auerswald, 2003).

The test site consisted of two small adjacent watersheds. The southern was 13.7 ha in size and had a GWW, while the northern was 9.4 ha in size and had none. The southern watershed could be divided into the subwatersheds E05 and E06, the northern into the subwatersheds E01, E02, and E03 (Fig. 1). The GWW in the southern watershed was established in 1993. In its upper part (subsequently referred as unmanaged GWW) natural succession without any maintenance occurred for 8.5 yr (watershed E06). Consequently, this area served more ecologically beneficial functions, for example, by improving biodiversity or acting as refuge for beneficial organisms (Fiener and Auerswald, 2003). The vegetation was dominated by fast-growing grasses (e.g., quack grass [*Elytrigia repens* (L.) Desv. ex Nevski], orchard grass [*Dactylis glomerata* L.], oat grass [*Arrhenatherum elatius* (L.) P. Beauv. ex J. Presl & C. Presl]), tall herbs (e.g., fireweed [*Epilobium angustifolium* L.], hemp-nettle [*Galeopsis tetrahit* L.], goose-grass [*Galium aparine* L.]), and a few woody plants (e.g., willow [*Salix* spp.], berries [*Rubus* spp.], rowan [*Sorbus* spp.]). This part of the GWW was 22 to 48 m wide, 290 m long, and 1.06 ha in area. Slopes were calculated from a digital elevation model with a 2- by 2-m grid. The average slope of the thalweg was 5.3%. The average slope and length of the side-slopes within the unmanaged GWW were 3.6% and 25 m, respectively. The layout (width) was not primarily a result of optimizing the drainage function, but resulted from improving the layout of the neighboring fields (Fiener and Auerswald, 2003). The eastern, lower part (subsequently referred as cut GWW), which was located in the subwatershed E05, was annually cut with a mulching mower at the beginning of August. Hence the vegetation was dominated by fast-growing grasses (e.g., quack grass, orchard grass, oat grass) and a few herbs (e.g., nettle [*Urtica dioica* L.]), but no woody plants. The size of the cut GWW was primarily a consequence of optimizing the drainage function. It was 10 m to 25 m wide, 370 m long, and 0.58 ha in area. The average slope of the thalweg was 4.1%. The average slope and length of the side-slopes was 2.6% and 13 m, respectively. The slopes were slightly flatter than the slopes of the unmanaged GWW. More significant was the difference in the cross-section of both GWWs, illustrated in Fig. 2 for two representative cross-sections midslope of each GWW. The unmanaged GWW had a broad, flat-bottomed thalweg, while a small gully, about 50 to 80 cm wide and 15 cm deep, could be found along the thalweg of the cut GWW. This gully was the result of runoff events that occurred shortly after sowing in the grass in 1993. Even though a dense sward had evolved within the following years, sedimentation was not sufficient to fill in the gully.

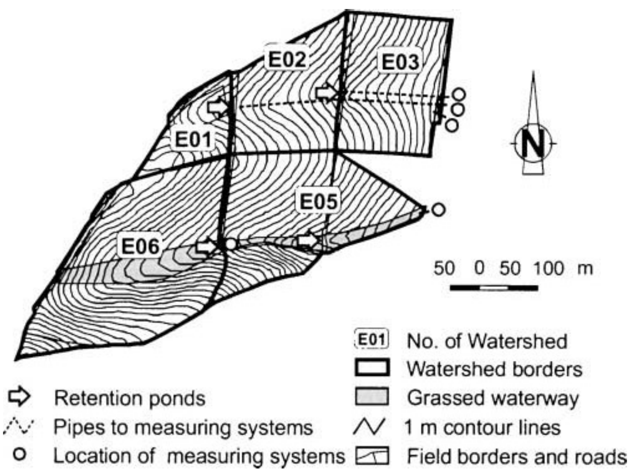

Fig. 1. Topography of the subwatersheds with and without grassed waterway; location of measuring system (flow direction from west to east).

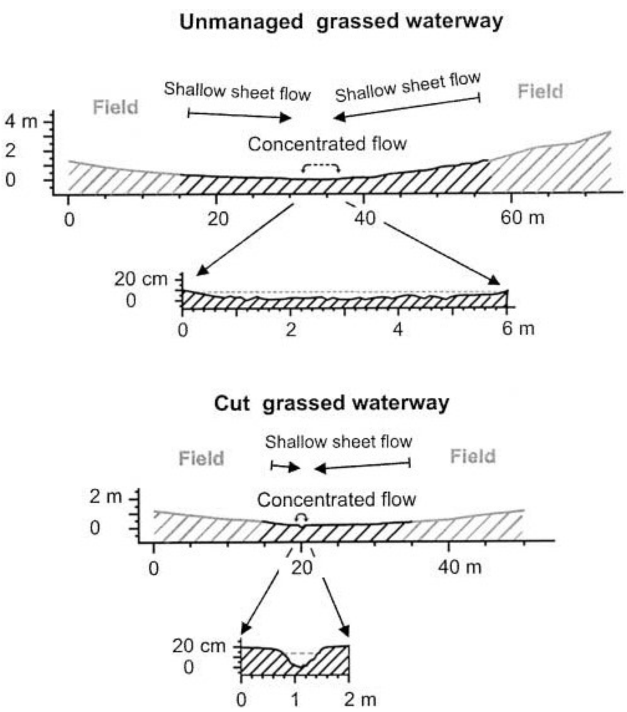

Fig. 2. Representative cross-sections of both grassed waterways; *y* axes twice inflated; dashed line represents water depth where concentrated flow occurs for a runoff rate of 6 L s^{-1} in both grassed waterways.

Measuring Methods

In each subwatershed runoff and sediment delivery was measured for 7 yr between January 1994 and December 2000. The runoff was collected at the lowest point in the subwatersheds, which were bordered by small dams. From the dams runoff was transmitted via underground-tile outlets (15.6-cm-diameter pipes in E01 and E02; 29 cm in E03, E05, and E06) to the measuring systems. In the case of E01, E02, E05, and E06, the peak runoff rates were additionally dampened by a 4-cm effective opening width of the underground-tile outlets. Thus, the dams acted as small retention ponds (volumes: E01 = 420 m^3, E02 = 490 m^3, E05 = 340 m^3, and E06 = 220 m^3) (Weigand et al., 1995) (Fig. 1).

The measuring system was based on a Coshocton-type wheel runoff sampler (Fig. 3) similar to that used by Parsons (1954) and Carter and Parsons (1967). The system collected an aliquot of about 0.5% from the total runoff coming from the outflow pipes. The design of the outflow pipes did not achieve a subcritical flow as did the original system, which collected the runoff in an apron and lead it over an H-flume to the runoff sampler (Carter and Parsons, 1967). Therefore, the outflow at high rates in our setup could have overreached the wheel and resulted in an underestimation of runoff volume. This was avoided by using a relatively large-diameter wheel (61 cm) and by the runoff dampening of the retention ponds and the underground-tile outlets. The precision of the sampling wheel in combination with a supercritical flow coming from pipes was examined in a laboratory flume. For the 15.6- and 29-cm pipes the measured aliquot differed only slightly, in a range of ±10%, from the accurate value of 0.5% (Fig. 4), if the runoff rates ranged from 0.5 L s^{-1} to the maximum rate for each pipe of 8 and 16 L s^{-1}, respectively. For runoff rates smaller than 0.5 L s^{-1} the system overestimated the runoff volume (Fig. 4), but this error was neglected due to the small contribution of these runoff rates to total runoff volume.

During the first two years of the measuring campaign, the runoff aliquot was collected in 1- (E01, E02, E03, and E06) and 3.5-m^3 tanks (E05). The aliquot volume was measured and a sample was taken after each event, which was later dried at 105°C to determine the sediment concentration. In the case of large runoff events, where the tanks had to be emptied more than one time, the sampling was repeated before the clearing of each tank. After the first two years the tanks at E01, E02, and E06 were replaced by tipping buckets (volume = approximately 85 mL) at the outlets of the sampling wheels, which were connected to Model 3700 portable samplers (Isco, Lincoln, NE) that counted the number of tips and automatically collected a runoff sample after a defined runoff volume. All measuring systems were tested for function at least at the end of each runoff event. When an incorrect measurement was determined in one subwatershed, for example in case of frozen Coshocton wheels or overflowed tanks, we also omitted the measurement of its paired subwatershed.

Fig. 3. Coshocton-type wheel runoff sampler at the Scheyern Experimental Farm.

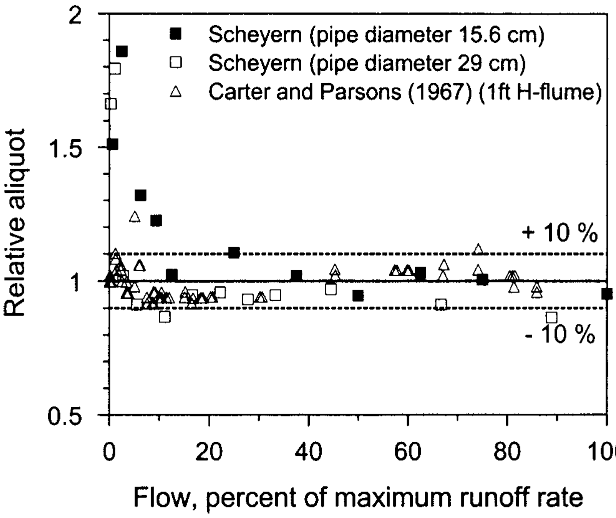

Fig. 4. Calibration data of the Coshocton-type runoff samplers used at the test side (wheel diameter = 61 cm, inflow from pipes, supercritical inflow possible) and by Carter and Parsons (1967) (wheel diameter = 61 cm, subcritical inflow from a 0.3-m [1-ft] H-flume); maximum runoff for the different pipes and the H-flume: 8 L s^{-1} for 15.6-cm-diameter pipe, 16 L s^{-1} for 29-cm-diameter pipe, and 54 L s^{-1} for the 0.3-m (1-ft) H-flume.

To be able to compare the sediment delivery from the subwatersheds, it was necessary to take the sediment deposition in the retention ponds into account. The sediment trapping efficiencies of the ponds in the watersheds E01 and E02 were evaluated in 1993 by using a grid of erosion pins laid over the pond bottoms (15 major events, which had flooded the ponds). Both ponds showed a similar annual sediment trapping efficiency of 59 and 54%, whereas the total sediment deposition differed noticeably (1.0 Mg ha^{-1} yr^{-1} for E01 and 11.6 Mg ha^{-1} yr^{-1} for E02). We concluded, therefore, that the long-term trapping efficiency was independent of the total sediment input and we assumed an average efficiency of 56% for the following years for all ponds. After 1993 erosion control by reduced-tillage techniques became more effective, and hence the input into the retention ponds decreased to less than 1.0 Mg ha^{-1} yr^{-1}. Therefore, the measurement of the deposited sediment after 1993 was impossible due to the small deposition depth. Even though the assumption of a sediment trapping efficiency of 56% seems to be justified, very small erosion events may result in little or no retention because only clay is transported, or alternatively complete retention if no runoff leaves the pond. In either case, however, these small events contribute very little to total sediment delivery. Total sediment delivery is governed by major events producing runoff rates and volumes, and sediment loads similar as in 1993. Henceforth we use the term *sediment delivery* for the sum of measured sediment transport across the lower field edge plus estimated sediment deposition in the ponds above the field edge.

Table 1. Characteristics of the paired subwatersheds with (E05 and E06) and without (E01/02 and E02/03) a grassed waterway (GWW).

	Upper subwatersheds		Lower subwatersheds	
Characteristic	E01/02, no GWW	E06, unmanaged GWW	E02/03, no GWW	E05, cut GWW
Arable land, %	75	79	94	85
Set-aside areas, %	23	21	4	13
Linear structures along the field borders	8	3	4	3
At the divide of the watersheds	14	4	0	0
Along the watershed thalweg (i.e., GWW)	0	13	0	10
Field roads, %	2.0	0.7	1.3	2.1
Number of fields	2	2	2	3
Crop rotation†	WW–M–WW–P	WW–M–WW–P	WW–M–WW–P	WW–M–WW–P
Soil texture	silty loam	silty loam	silty loam	silty loam
Mean slope	7.1	9.3	7.3	9.0

† WW, winter wheat; M, maize; P, potato.

Comparability of Subwatersheds

Landscape elements like GWWs can only be fully examined in landscape experiments. Landscape experiments, however, are biased by the problem that no watersheds exist that are identical other than with respect to the landscape element to be tested. The differences in precipitation, topography, soils, land use, and hydrological properties should be as small as possible. Within the test site 22% of all rain events between 1994 and 1997 had spatial trends in rain depth. The median horizontal gradient in rain depth was 3.3 mm per 1000 m, the maximum horizontal gradient was 15.7 mm per 1000 m (Johannes, 2001). Even steeper trends were found for rainfall erosivity. The directions of the rain gradients were nearly equally distributed. Hence the spatial variation of rain properties could be neglected for this long-term observation of watersheds, which were only about 400 m wide and 500 m long. The considerable scatter in the rain data of shorter time periods may be attributed in part to these rain gradients.

A major prerequisite for the evaluation of effects of the GWW other than the prevention of gully erosion along the thalweg was to avoid gully erosion in the paired watershed without a GWW (E01–E03). This was achieved by constructing two retention ponds behind the field borders, drained via underground-tile outlets and 360- (E01) and 185-m-long (E02) pipes to the toe slope, where the runoff volume and sediment content were measured (Fig. 1). In the watershed with a GWW, runoff traveled on the soil surface because gullying was prevented by the sward. Consequently, the measured outflow of E05 was subtracted by the inflow from E06. To create otherwise identical conditions as in the watershed without a GWW, two retention ponds with underground-tile outlets also dampened runoff rates in the GWW (Fig. 1), but drained via the GWW instead of pipes. Thus, gully erosion was prevented in both watersheds between 1994 and 2000. This was confirmed by field observations.

The crop rotation in all subwatersheds was identical. Short-term differences in runoff and sediment delivery between the subwatersheds could result from the differences in the agricultural operations of the single fields and because the different fields occupied a different position within this rotation. The runoff and erosion behavior of the row crops, potato and maize, were especially different from that of winter wheat. Each of the subwatersheds E01, E02, and E03 belonged to a single field and was only covered by a single crop at a time. In contrast, the upper (E06) and lower (E05) subwatersheds with the GWW received runoff from different fields and hence different crops (Fig. 1). In E06, 47% of the arable area had an identical position in the crop rotation as the single field in E01, while 53% of the arable area was identical to the single field in E02. To account for this situation, the data measured in E01 were weighted with the factor 0.47, the data from E02 were weighted with the factor 0.53, and both combined to be compared with the data from E06. Thus, the distribution of wheat and row crops was identical also in individual years. In the following the weighted subwatersheds E01 and E02 are referred as subwatershed E01/02. In the lower subwatershed with a GWW (E05), 71% of the arable area was equivalent to the single field in E02 and 29% was equivalent to the single field in E03. Analogously to the upper subwatersheds, the data from E02 and E03 were weighted and summarized for the comparison with the data from E05. The weighted subwatersheds E02 and E03 are referred as subwatershed E02/03. The weighting did not only create an identical proportion of row crops and wheat in the paired subwatersheds with and without GWW, it also lead to a similarity of the pairs regarding other physical properties (Table 1).

To examine whether the integral response by the interacting factors may cause differences in runoff behavior, runoff volume was modeled with the USDA Soil Conservation Service curve number model (Mockus, 1972) for three different rains (Table 2). There was almost no difference between the paired watersheds in the calculated runoff volumes. Hence, it can be assumed that differences in measured runoff volume were a result of the GWWs.

In contrast to runoff volume, soil loss is strongly influenced by slope, which differed between the paired subwatersheds. The universal soil loss equation (USLE; Wischmeier and Smith, 1978) can be used to evaluate the relative influence of slope and other factors on soil loss. Instead of the USLE, the differentiating universal soil loss equation (dUSLE; Flacke et al., 1990; Kagerer and Auerswald, 1997) was used because it takes into account more precisely the influence of complex topography on the LS and P factors. The input data were derived from a detailed digital elevation model based on an

Table 2. Modeled runoffs of the paired subwatersheds with (E05 and E06) and without (E01/02 and E02/03) a grassed waterway (GWW) for different rains.

	Upper subwatersheds		Lower subwatersheds	
Rain depth	E01/02, no GWW	E06, unmanaged GWW	E02/03, no GWW	E05, cut GWW
		mm		
20	1	3	3	7
40	16	18	22	26
60	31	34	41	46

Table 3. Differentiating universal soil loss equation (dUSLE) factors for the paired subwatersheds with (E05 and E06) and without (E01/02 and E02/03) a grassed waterway (GWW).

	Upper subwatersheds		Lower subwatersheds	
dUSLE factors	E01/02, no GWW	E06, unmanaged GWW	E02/03, no GWW	E05, cut GWW
R factor, N h^{-1}	69	69	69	69
Mean K factor, Mg h ha^{-1} N^{-1}	0.35	0.39	0.42	0.49
Mean LS factor	1.51	3.30	1.63	4.07
Mean C factor	0.06	0.06	0.08	0.07
Mean P factor	0.86	0.84	0.81	0.81

intensive geodetical survey and a geostatistically interpolated K factor map, based on soil properties measured in a 50- by 50-m grid. The 23.6-ha total area was resolved into 17 841 cells with homogeneous slope, soil, and cropping conditions for the soil loss calculations. The modeling revealed that only the LS factors of the dUSLE differed significantly (Table 3), which reflects the different slope gradients of the paired subwatersheds. The LS factor was greater in both subwatersheds with GWWs (E05 and E06).

Due to the extensive validation of the USLE that had been performed on this landscape (e.g., Schwertmann et al., 1987; Becher et al., 1980) it was assumed that the USLE was suitable and particularly that the LS factor accounted for the difference in topography (Auerswald, 1986). Hence, the dUSLE predictions were used to adjust the measured sediment deliveries from E05 and E06 by dividing the measured values through the ratio of the LS factors of the paired subwatersheds.

RESULTS AND DISCUSSION

During the seven-year monitoring period, 237 events produced runoff and sediment transport in at least one of the subwatersheds. A failure of one of the measuring systems was determined for 2.5% of all measurements. In 100 cases, one of the subwatersheds without a GWW (E01/02 and E02/03) produced runoff while the paired ones with a GWW (E06 and E05) did not, indicating that during smaller events the GWW completely absorbed the runoff from the adjacent fields. In the unmanaged GWW (E06) this happened more often (n = 62) than in the annually cut (E05) (n = 38). In 15 cases, one of the subwatersheds E06 and E05 produced runoff while the paired ones did not. In contrast to the opposite cases, this happened more often in E05 (n = 11) than in E06 (n = 4).

The average annual runoff and sediment delivery in the upper subwatersheds was 3 mm and 16 kg ha^{-1} in E06 compared with 34 mm and 312 kg ha^{-1} in E01/02. In the lower subwatersheds it was 26 mm and 172 kg ha^{-1} in E05 compared with 29 mm and 303 kg ha^{-1} in E02/03 (Table 4). In total, the unmanaged GWW removed about 1.7×10^4 m^3 of runoff and 37 Mg of sediment between 1994 and 2000 and the cut GWW removed 1.2×10^3 m^3 and 24 Mg, respectively. Averaged over the whole area the unmanaged GWW accumulated about 2.2 mm and the lower about 2.5 mm of sediment during this seven-year period, if a soil density of 1.5 Mg m^{-3} was assumed. In the year of the highest accumulation (1994) this amounted to 0.8 and 1.3 mm, respectively. Even if the accumulation occurred on only half of the area of the GWWs, this was still low enough that the vegetation was not damaged and that the drainage function would remain effective for a long time. Given that the on-site erosion control is as effective as in our case, GWWs will not be damaged if the maintenance is reduced to a minimum or even neglected.

The amount of runoff and sediment transport in individual events occurring during the seven years ranged over more than six orders of magnitude, hence the data were compared on a log basis (Fig. 5 and 6). To avoid neglecting those events in which one of the subwatersheds produced no runoff, comparisons were based on monthly totals. The unmanaged GWW reduced monthly runoff and sediment delivery from E06 considerably in almost all cases (Fig. 5) compared with E01/02. The overall high variability presumably resulted from deviations in the cropping conditions between the subwatersheds and the spatial gradients in single rain properties. In total, the unmanaged GWW reduced runoff and sediment delivery by 90 and 97%, respectively (Table 4).

The cut GWW was less effective (Fig. 6) than the unmanaged. For small monthly runoff and sediment

Table 4. Annual runoff and soil delivery in the paired subwatersheds with (E05 and E06) and without (E01/02 and E02/03) a grassed waterway (GWW).

	Runoff				Sediment delivery†			
	Upper subwatersheds		Lower subwatersheds		Upper subwatersheds		Lower subwatersheds	
Year	E01/02, no GWW	E06, unmanaged GWW	E02/03, no GWW	E05, cut GWW	E01/02, no GWW	E06, unmanaged GWW	E02/03, no GWW	E05, cut GWW
	mm				kg ha^{-1}			
1994	40	6.3	34	11	791	22 (10)	965	341 (136)
1995	40	3.3	32	22	198	17 (8)	148	79 (31)
1996	10	0.3	13	59	78	13 (6)	79	130 (52)
1997	16	0.1	21	9	213	0.5 (0.2)	133	48 (19)
1998	20	0.9	26	11	100	6 (3)	218	251 (101)
1999	67	11.1	45	49	299	40 (18)	244	229 (91)
2000	44	2.2	34	24	507	16 (7)	335	123 (49)
Average	34	3	29	26	312	16 (7)	303	172 (69)
Total	237	24	205	184	2187	114 (52)	2122	1201 (480)

† Values in parentheses adjusted according to the ratio of the LS factors of the differentiating universal soil loss equation (dUSLE).

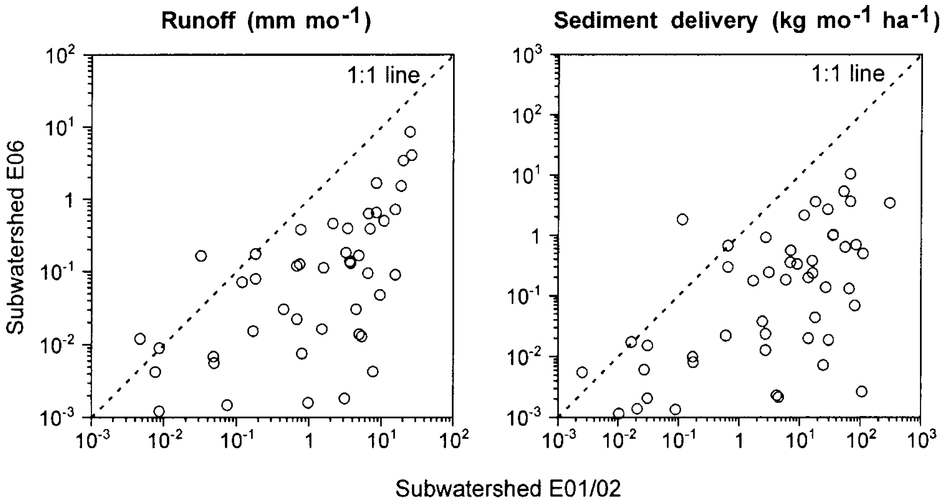

Fig. 5. Comparison of monthly runoff and sediment delivery of the upper subwatersheds between 1994 and 2000 (E06 with an unmanaged grassed waterway, E01/02 without).

deliveries (<0.9 mm and <0.2 kg ha^{-1}) the subwatershed E05 produced even higher values than its paired neighbor E02/03. This was presumably caused by a field road (slope approximately 12%, length approximately 100 m, width approximately 3 m) dominating the runoff generation of small rains. For larger monthly runoff and sediment deliveries the effect of the GWW dominated in most cases. Hence, total runoff and sediment delivery were 10 and 77% lower, respectively (Table 4).

Mechanisms of Runoff Volume Reduction in the Grassed Waterways

In general, runoff volume is reduced when adjacent fields produce runoff while the rain intensity does not exceed the infiltration rate in the GWW itself. The amount of runoff volume reduction depends on (i) the size of the area where runoff from the adjacent fields overflows the GWW (effective area), (ii) the difference between rain volume and infiltration volume plus surface storage capacity in the GWW, and (iii) the infiltration volume after the rain caused by the runoff time lag between inflow and outflow. According to De Ploey (1984), the runoff after the rain event is termed afterflow.

For further calculations we assumed similar infiltration rates and surface storages per unit area for both GWWs and that the ratio between effective area and total area was similar. Infiltration and surface storage during the rain is then 1.8 times larger in the unmanaged GWW than in the cut GWW.

The runoff time lag can be calculated from flow velocity v according to Manning (1889) taking into account the characteristics of the side-slopes and the thalwegs using the equation:

$$v = (1/n) \times R^{2/3} \times S^{1/2} \quad [1]$$

where R is the hydraulic radius (m), S is the slope (tan α), and n is the roughness coefficient (Manning's n; s m$^{-1/3}$). Manning's n for unsubmerged sod-forming grasses ranges from about 0.15 to 0.35 s m$^{-1/3}$ (e.g., Ree,

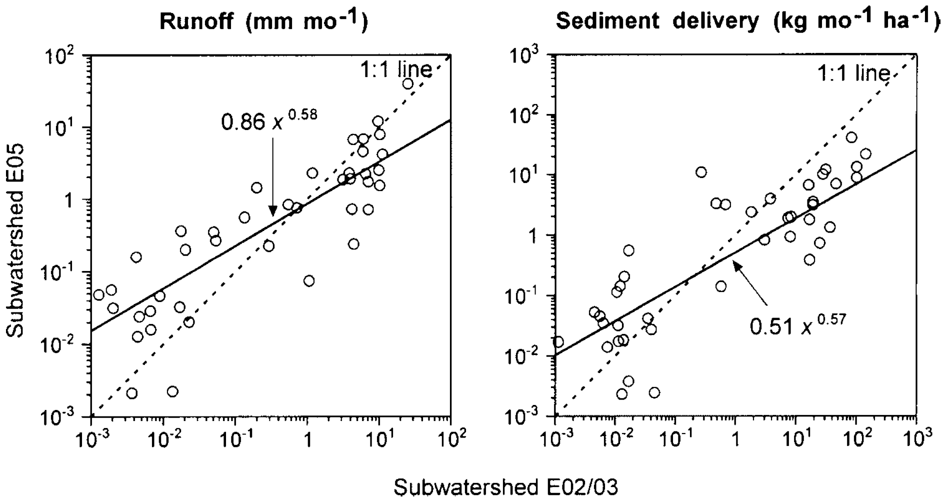

Fig. 6. Comparison of monthly runoff and sediment delivery of the lower subwatersheds between 1994 and 2000 (E05 with a cut grassed waterway, E02/03 without).

1949; Ogunlela and Makanjuola, 2000) depending on species composition, sward density, grass stem heights, and runoff properties. For both GWWs, a typical Manning's n for dense swards of 0.3 s $m^{-1/3}$ (e.g., Ree, 1949) was used. Effects of annual cutting around 1 August in the cut GWW were neglected because the grasses already had developed stiff stems by August and after cutting, the grasses on the side-slopes and along the thalweg were still higher (approximately 10 and 25 cm, respectively) than the expected maximum runoff depth (approximately 3 and 15 cm, respectively).

For the shallow sheet flow on the side-slopes, the hydraulic radius R can be approximated by the runoff depth h (m). For a constant $h = 10^{-2}$ m, the predicted runoff velocity of 2.6×10^{-2} m s^{-1} in the unmanaged GWW is similar to 2.2×10^{-2} m s^{-1} in the cut GWW. Taking into account the differences in side-slope lengths, the time lag in the unmanaged GWW is 1.6 times larger than in the cut GWW. Together with the larger area of the unmanaged side-slopes, we can expect 2.5 to 3.0 times more afterflow volume reduction from the doubled length of the unmanaged side-slopes. The large total area of the side-slopes in the unmanaged GWW compared with the cut GWW can explain much of the greater effectiveness of the unmanaged GWW.

Compared with the side-slopes, the area of concentrated runoff was small in both GWWs. Nevertheless, it was of special importance because in the area of concentrated runoff, afterflow, and hence infiltration, last the longest time. Its size and the time lag of concentrated runoff depend on the thalweg properties (length, slope, cross-section, and hydraulic roughness) and the runoff rates. Runoff rate, Q (m^3 s^{-1}), is related to runoff velocity, and area of runoff cross-section, A_{cs} (m^2), as:

$$Q = vA_{cs} \qquad [2]$$

The hydraulic radius for concentrated flow is:

$$R \approx A_{cs}/W \qquad [3]$$

Combining Eq. [1], [2], and [3] yields:

$$Q = (1/n) \times S^{1/2} \times A_{cs}^{5/3} \times W^{-2/3} \qquad [4]$$

According to Eq. [4], the runoff widths W (m) of the concentrated flow along the thalweg can be derived for representative cross-sections (Fig. 2), if Q, n, and S are given. For runoff rates between 10^{-3} and 6×10^{-3} m^3 s^{-1} (equivalent to rains in both watersheds between 10 and 50 mm) the runoff widths in the unmanaged GWW are approximately eight times larger than in the cut GWW. Hence, the area of concentrated flow in the unmanaged GWW (290 m long) is about 6.3 times larger than in the cut GWW (370 m long). Applying Eq. [2], the runoff velocities at the representative cross-sections (for $Q = 10^{-3}$ to 6×10^{-3} m^3 s^{-1}) range from 3.2×10^{-2} to 5.2×10^{-2} m s^{-1} in the unmanaged and 6.0×10^{-2} to 10.3×10^{-2} m s^{-1} in the cut GWW. Given this 1:2 ratio in concentrated runoff velocity, time lag along the (shorter) unmanaged GWW is about 1.6 times larger than in the cut GWW. Combining this with the 6.3-times-larger area of concentrated flow on the flat-bottomed unmanaged GWW, 10 times more afterflow volume can infiltrate during concentrated runoff on the unmanaged GWW compared with the cut GWW. In general, it appears that the flat-bottomed cross-section and the larger area of the unmanaged GWW were the main reasons for its higher runoff volume reduction compared with the cut GWW. Differences in management between the GWWs seem to be less important.

Mechanisms of Sedimentation in the Grassed Waterways

Sedimentation is mainly controlled by (i) a decrease in transport capacity caused by reduced runoff velocity, (ii) the sieving of particles by dense vegetation and litter, and (iii) the infiltration of sediment-laden runoff.

Decrease in Transport Capacity Caused by Reduced Runoff Velocity

The sediment settling can be estimated according to Stokes equation (Eq. [5]) (Deletic, 2001) for laminar runoff conditions. These can be assumed for the side-slopes of the GWWs (Reynolds number of 200 and 170, respectively, for $n = 0.3$ s $m^{-1/3}$, $h = 10^{-2}$ m), but not in the area of concentrated flow (Reynolds number > 500 for $n = 0.3$ s $m^{-1/3}$, $h > 2.5 \times 10^{-2}$ m):

$$v_s = [2r^2g(d_s - d_w)]/9\eta \qquad [5]$$

where v_s is the settling velocity (m s^{-1}), r is the radius of grains (m), g is the gravitational acceleration (m s^{-1}), d_s is the density of particles (kg m^{-3}), d_w is the density of water (kg m^{-3}), and η is the dynamic viscosity of water (kg m^{-1} s^{-1}). For a particle density of 2.65 Mg m^{-3} for sand and 1.90 Mg kg m^{-3} for wet aggregates, a 10°C water temperature, and a constant water depth on the side-slopes of 10^{-2} m, particles larger than medium silt (>63 μm) will settle in both GWWs, while clay will not. A slightly higher effectiveness of the unmanaged GWW was predicted for particles in the size of fine silt and clay (Table 5). In general, sediment settling will increase less than flow path length. This nonlinear relationship corresponds to the findings of other authors. Schmitt et al. (1999), for example, observed only small additional sedimentation effects by doubling the width of vegetated filter strips from 7.5 to 15 m.

Sieving of Particles by Dense Vegetation and Litter

The grain size that can be removed by sieving is given by the size of the pores with water flow. From Hagen–Poiseuille's law (Hillel, 1998):

$$v_p = Jr_p^2/8\eta \qquad [6]$$

where v_p (m s^{-1}) is the average flow velocity through a pore, J is the pressure gradient (Pa m^{-1}), and r_p is the average pore radius (m), r_p can be calculated by using the estimated runoff velocities in the GWW, assuming a constant water depth and hence a pressure gradient J equivalent to slope gradient and a 10°C water temperature. The computed effective pore size is greater than 1750 μm in all parts of both GWWs. Consequently, this mechanism can be neglected because particles larger

Table 5. Computed settling of different grain sizes on the side-slopes of the two grassed waterways (GWWs).

	Sands settled		Aggregates settled	
Particle size	Unmanaged GWW	Cut GWW	Unmanaged GWW	Cut GWW
μm	%			
>100	100	100	100	100
>50	100	100	90	55
>2	26	16	–	–
>1	7	4	–	–
>0.5	2	1	–	–

than 1750 μm will settle within the first centimeters of the side-slopes.

For changing water depths caused by barriers along the flow paths, J increases locally and hence r_p locally decreases. A more effective sieving can then be expected. It will be counteracted, however, by the capillary pressure, which must be exceeded by the water pressure above the barrier for water flow to occur through the barrier. The smallest effective pore size in this case can be calculated from capillary forces:

$$h_c = 2\sigma \cos \alpha/\rho g r_c \qquad [7]$$

where h_c is the capillary rise (m), σ is the surface tension (kg s^{-2}), α is the contact angel between liquid and solid (approximately 0° between water and soil particles), ρ is the density of the liquid (kg m^{-3}), and r_c is the radius of the capillary (m). For a pressure head of 5×10^{-2} m above the average runoff depth and a 10°C water temperature, only particles larger than 500 μm are sieved at the lowest point of the barrier, which is not submerged. This may slightly enhance the sediment trapping efficiency of the GWWs, but sieving generally contributes very little to their effectiveness.

Infiltration of Sediment-Laden Runoff

For infiltration-induced sedimentation, two contrasting situations can be identified. The sediment reduction is equivalent to runoff volume reduction if inflow from the fields occurs after the rain event (rain shorter than runoff time lag in the fields). In contrast, sediment-laden runoff from the fields will be diluted by rain on the GWW if inflow and rain occur simultaneously (long-lasting rain, relatively negligible time lag). Even if the GWW itself produces runoff, some sedimentation will then result from the infiltration of the diluted runoff. The change in sediment concentration (SC) by runoff dilution can be calculated according to Eq. [8]:

$$\mathrm{SC_{gww}} = \mathrm{SC_{in}} \frac{R_{in}}{R_{in} + P} = SC_{in} \frac{aPA_f/A_{gww}}{aPA_f/A_{gww} + P} \qquad [8]$$

After rearrangement, the equation is:

$$\frac{SC_{gww}}{SC_{in}} = \frac{aA_f/A_{gww}}{aA_f/A_{gww} + 1} \qquad [9]$$

where $\mathrm{SC_{gww}}$ is the sediment concentration at the GWW outlet (g L^{-1}), $\mathrm{SC_{in}}$ is the sediment concentration at the inflow from the fields (g L^{-1}), R_{in} is the total inflow

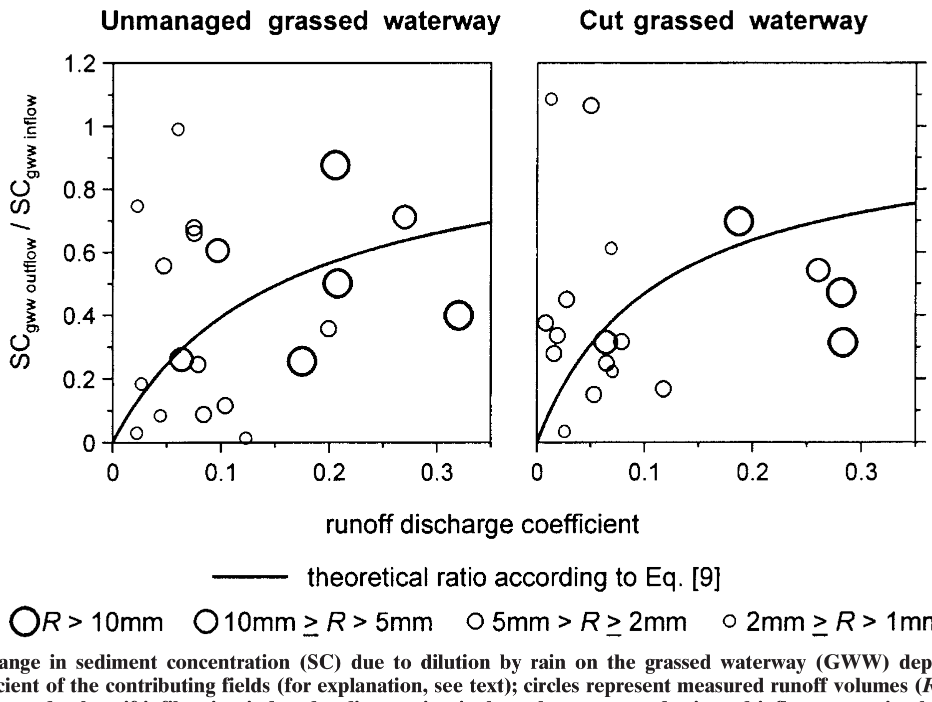

Fig. 7. Relative change in sediment concentration (SC) due to dilution by rain on the grassed waterway (GWW) depending on the runoff discharge coefficient of the contributing fields (for explanation, see text); circles represent measured runoff volumes (R); lines represent the theoretically expected values if infiltration-induced sedimentation is the only process and rain and inflow occur simultaneously.

volume per area of the GWW (mm), P is the rain depth (mm), and a is the discharge coefficient in the fields (runoff volume from fields/rain depth; mm mm^{-1}). Given that the SC_{in} can be approximated by the SC in the outflow of subwatersheds E01/02 and E02/03, the prediction with Eq. [9] can be compared with the measured ratios (Fig. 7). It can be expected that measured SC ratios should be below the theoretical ratio because of the two other mechanisms of SC reduction. In fact, that was not always the case when for small runoff events (discharge coefficients < 0.1) inflow and rain on the GWW did not appear simultaneously. Thus, for about half of the small runoff events, the measured SC ratios were higher than expected, but were still lower than 1 because of the sediment settling. For larger runoff events (discharge coefficients > 0.1) with roughly simultaneous inflow and rain, the measured SC ratios met the expectations and were mostly smaller than the pure dilution effect. It can be concluded that infiltration-induced sedimentation in a GWW is an important process reducing sediment delivery even if runoff volume is not reduced where rain intensity exceeds infiltration capacity of the GWW.

CONCLUSIONS

Our long-term landscape experiment indicated a high potential of a grassed waterway (GWW) to reduce runoff and sediment delivery from an agricultural watershed, without a loss in the drainage function of the GWW. Due to intensive on-site erosion control in the fields it was possible to neglect maintenance in the GWW without sward-damaging sedimentation.

The performance of a GWW to reduce runoff volume depends strongly on the length of the side-slopes and the shape of its cross-section in the area of concentrated flow. The two-times-longer side-slopes and the flat-bottomed thalweg of the unmanaged GWW were the major reasons for its higher runoff volume reduction (90%) compared with the cut GWW (10%).

The performance of a GWW to reduce sediment delivery depends mainly on the sediment settling due to a decreased runoff velocity and the infiltration of sediment-laden runoff. The mechanism of sediment sieving can be neglected. Infiltration-induced sedimentation is larger than runoff volume reduction. Sediment settling takes place primarily during sheet-flow on the side-slopes, where Reynolds numbers are small (<200). Most of the settling is expected to occur in the first few meters of the grass filter. Hence, the two-times-longer side-slopes in the unmanaged GWW induced only a small additional settling of sediment. Consequently, the different sediment trapping efficiency of the two GWWs was primarily caused by differences in infiltration-induced sedimentation.

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