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Man-made linear flow paths at catchment scale: Identification, factors and consequences for the efficiency of vegetated filter strips

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ABSTRACT

A vegetated filter strip (VFS) gains the best retention potential when surface runoff enters the strip as sheet runoff. However, surface runoff convergence may take place in linear flow structures long before approaching the river system. Limited information is available about the extent of these linear flow pathways and the factors that may influence their occurrence in the landscape. To better understand these effects, we carried out detailed field surveys in ten small headwater catchments in different climatic regions in Austria. Ditches and channels directly connected to the stream network were mapped. Surface flow pathways were calculated either with or without integrating the mapped structures. Effective placement of retention structures may also be influenced by the accuracy of digital elevation model (DEM) resolution. We therefore used three different DEMs with varying resolution. The catchment areas connected directly to the stream network via linear drainage structures were identified. In seven out of the ten catchments such unprotected areas (UA) were found. Their extent varied between 10% and 38% of the total catchment area. Factors influencing the extent of UA were length of the road network and annual precipitation. Without integrating the mapped linear structures, UA could not be detected in the broad-gridded DEMs. After integration of mapped linear structures, DEM resolution did not influence the calculated extent of UA. For our environmental setting, GIS-based design of placement of retention structures leads to considerable errors and should be verified by fieldwork.

1. Introduction

As a consequence of inappropriate management on agricultural land, sediments, nutrients and pollutants may easily reach surface waters and endanger water quality and biocenosis. Nutrient inputs due to soil erosion are now a major concern in landscape management issues. While nitrate leaching is one of the main risks for groundwater bodies, for surface waters phosphorus input is a major concern. Since the European Water Framework Directive (WFD) became effective in 2000, many Member States of the European Union have begun to develop funded landscape management programmes to reduce phosphorus input into surface waters, one of the major risks for stream and lake water quality. In Austria, the landscape management programme (ÖPUL) supports environmentally sustainable agricultural practices and is funding the installation of vegetated filter strips (VFSs) alongside permanent streams. In Austria, to be eligible for subsidy, a VFS is required to be parallel to the stream and have a fixed width of 50 m. The strip may be either abandoned completely or cut once a year.

VFSs are usually strips of cultivated or indigenous vegetation that provide erosion protection and filter nutrients, sediment or pollutants from agricultural runoff (Dillaha, Reneau, Mostaghimi, & Lee, 1989). Vegetated filter strips are a well-proven best management practice (BMP) to protect surface waters from sediment and nutrient pollution (Dorioz, Wang, Poulenard, & Trevisian, 2006; Hussein, Yu, Ghadiri, & Rose, 2007; Muñoz-Carpena, Parsons, & Gilliam, 1993). Sediment, nutrients and pollutants are filtered through the VFS; hence they improve water quality (Bhattarai, Kalita, & Patel, 2009; Mankin, Barnes, Harner, Kalita, & Boyer, 2006) and may also enhance bank stability (Lin, Chou, & Lin, 2002; Lin et al., 2004; McKergow, Weaver, Prosser, Grayson, & Reed, 2003). The main effect of a filter strip is a reduction in flow velocity, caused by an increased surface roughness. The decreased transport capacity of runoff generates sedimentation of soil particles. A second effect may also be an adsorption of soil colloids on plants. In general, two transport pathways from agricultural land to surface waters exist. Particulate-bound nutrients like phosphorus are transported mainly via sediment. Therefore removal mainly takes place through filtering of particulate matter. For soluble substances like nitrate, the main form of removal from runoff is due to either denitrification

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and/or plant uptake (Leeds-Harrison, Quinton, Walker, Sanders, & Harrod, 1999).

To test the effectiveness of such retention structures, plot and field-scale studies have been carried out (Hussein et al., 2007; Popov, Cornish, & Sun, 2006), with sediment input reductions of up to 87% (Duchemin & Hogue, 2009).

Various modelling studies have also been undertaken at the catchment scale (Burkart, James, & Tomer, 2004; Dosskey, Helmers, & Eisenhauer, 2011; Sahu & Gu, 2009; Xiang, 1996) and report positive effects on pollutant retention. However, there is considerable information on limitations of the effectiveness of VFSs. A key parameter in this respect seems to be the extent of runoff convergence when entering buffer strips. Whenever surface runoff converges into buffer strips there is a reduction of the retention capacity of the VFS (Bach, Fabis, Frede, & Herzog, 1994a, 1994b; Dillaha et al., 1989; Dosskey, Helmers, Eisenhauer, Franti, & Hoagland, 2002; Hay, Pittroff, Tooman, & Meyer, 2006; Leeds-Harrison et al., 1999; Verstraeten, Poesen, Gillijns, & Govers, 2006). Bach et al. (1994a) pointed out the difficulties of linear structures, like plough furrows and ditches, leading to a reduced filter effect whenever concentrated surface flow enters buffer strips. However, surface runoff may also be concentrated in ditches or channels that act as a linear flow path, in which case surface runoff may not enter a VFS at all. The Austrian environmental programme does not support VFSs along roadside ditches or channels; they are only funded alongside permanent stream systems. If surface runoff were concentrated in such linear flow lines (ditches, channels), water – together with suspended matter – would not enter a VFS at all and would drain directly into streams. Consequently, we hypothesized that subcatchment areas that are affected by such linear structures may be unprotected, even with VFSs installed alongside the permanent flow lines.

Though the problem is clear, surprisingly little information is available regarding the extent of unprotected subcatchment areas within a watershed. Dosskey et al. (2002), for example, made a broad study into concentrated flow paths through riparian buffers, but did not consider fields that drained into ditches. Various studies on VFS designs are based on desktop analysis of data (Lin et al., 2004; Xiang, 1996). Xiangmei, Xuyang, and Minghua (2008) reviewed the major factors influencing the efficacy of vegetated buffers on sediment trapping. While buffer width, slope, area ratio and rainfall are discussed, concentrated surface runoff or linear flow pathways were not mentioned as limiting the effectiveness of a VFS.

Hydrological processes are dependent on various factors like scale, topography, soil heterogeneity or subsurface flow through preferential flow paths. In addition, they may be modified by anthropogenically induced features like roads, tile drains, culvert systems and land use (Lazzarotto, Stamm, Prasuhn, & Flühler, 2006). Linear flow structures may appear together with roads of any size. As suggested in various studies (Forman & Alexander, 1998; Jones, Swanson, Wemple, & Snyder, 2000; Wemple, Swanson, & Jones, 2001), road networks may have a great influence on hydrological patterns of a landscape. Furthermore, roads affect ecosystems and landscape fragmentation (Liu et al., 2008). Roads very often go along with open or partly open roadside ditches; they then work as linear flow pathways, concentrating surface runoff. Thus, surface runoff from agricultural land can flow directly into surface waters without being filtered by a VFS. We therefore hypothesized a relationship between the length of road network in a catchment and the size of unprotected area (UA), which we defined as subcatchments affected by man-made linear flow pathways like ditches and channels. Linear flow paths may also occur as a Thalweg situation, which can be seen as geomorphologically built landscape structures, not as a man-made factor on which the authors focused in this study.

Design and dimensioning of VFSs is frequently done using automated GIS procedures (Lin et al., 2004; Xiang, 1996) using best available data. One of the most important data inputs for designing VFSs is the DEM. The placement of environmentally beneficial VFSs will certainly depend on the accuracy and availability of the DEM. Previous studies have compared DEMs of different spatial resolution in order to determine topographic indices, catchment characterization variables or soil erosion (Hancock, 2005; Sørenson & Seibert, 2007; Thompson, Bell, & Butler, 2001; Vaze, Teng, & Spencer, 2010; Zhang, Chang, & Wu, 2008). It would seem logical that higher-resolution DEMs would improve results. However, while Vaze et al. (2010) suggested that high-resolution data or re-sampled high-resolution data concerning watershed boundaries should be used whenever possible, Hancock (2005) reported a sufficient DEM resolution of 10 m for various catchments. Hence, the appropriate DEM resolution seems to be dependent on the scientific purpose of the study, and the scale on which it is based. This study operates on small headwater catchments (65–422 ha). Within such catchments, linear flow pathways are often very small structures and may be hard to determine by a coarse resolution DEM. However, employment of high-resolution DEMs would be linked to high work space demands and long computing times. In order to evaluate the necessity of a high-resolution database for such catchments, three different grid-based DEMs were used for calculating flow paths.

For routeing flow pathways within catchments, multiple flow algorithms as well as single flow algorithms are used. Comparative studies indicate advantages for multiple flow algorithms (Jones, 2002; Martz & Garbrecht, 2000; Turcotte, Fortin, Rousseau, Massicotte, & Villeneuve, 2001). According to these studies, multiple flow algorithms are particularly suitable in flat areas where single flow algorithms exhibit problems with routeing the surface runoff through plains and sinks. Single flow algorithms, on the other hand, have the advantage of needing lower computing power and less work space. In the present study, multiple and single flow algorithms were applied to evaluate possible effects for our sites.

To summarize, the main objectives of this study were (a) to identify the extent of anthropogenically caused linear flow pathways in headwater catchments that may prevent surface runoff from flowing into the VFS, (b) to discuss problems of automated desktop analysis of VFS design in headwater catchments and (c) to identify parameters that may cause linear flow pathways within headwater catchments.

2. Materials and methods

2.1. Site description

Ten small headwater catchments (65–422 ha) in Northern Austria were studied (Fig. 1). They are situated in the Weinviertel region (5), the Mostviertel region (3) and the Innviertel region (2). They were chosen to obtain a representative lateral cut through intensive agricultural regions in Austria, north of the Alps. The northern part of Austria is the main area used for intensive agriculture; the main crops are wheat, barley and maize. Hence, this part of the country has a landscape that exhibits the highest anthropogenic influence in Austria. Table 1 gives the main characteristics, catchment size (ha^{-1}), mean annual precipitation (P), mean annual temperature (T) and mean slope gradient (S), mean field size (mF) of arable land and permanent river network (pRN) of the catchments. Land use was divided into arable land, forest and others (which includes urban areas and water bodies). The location of the ten headwater catchments studied covers the full climatic diversity of Austrian agriculture north of the Alps. Fig. 1 illustrates the location of the ten headwater catchments investigated.

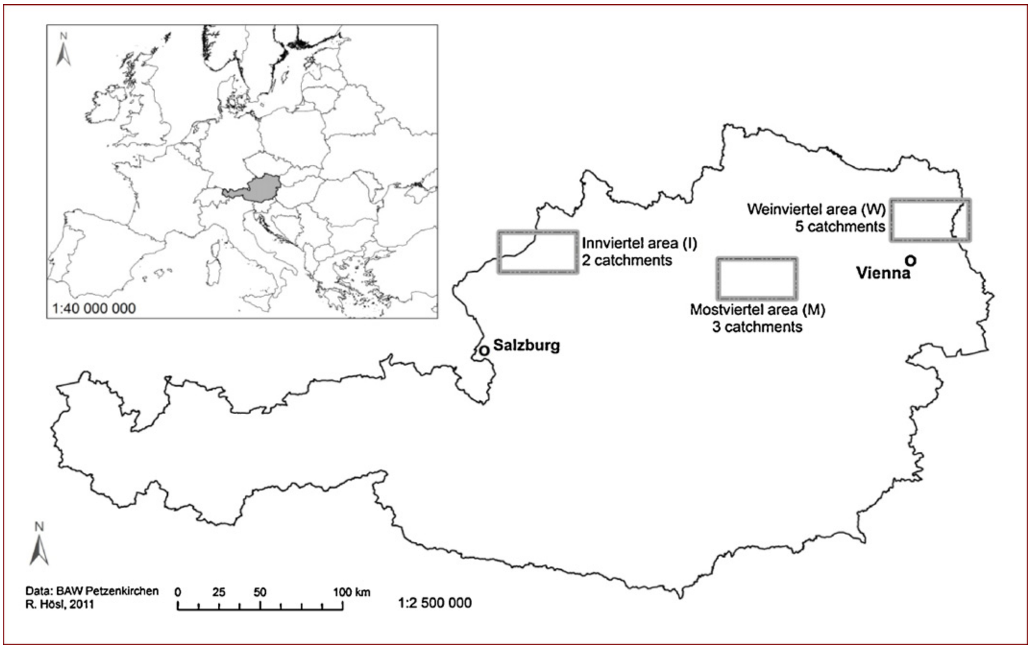

Fig. 1. Location of the headwater catchments studied in Austria.

2.1.1. Weinviertel region

The Weinviertel region is situated in the northeast of Lower Austria; it belongs to the geological unit of the Vienna Basin, which is filled with tertiary sediments. The sediments are covered with loess, the parent material of the present soils. Typical soils are Cambisols, Chernozems and Lithosols (WRB). The five study catchments are situated between 150 and 360 m above sea level (a.s.l.) and have a hilly relief with mean slopes between 3.7 and 5.9°. Mean annual temperature is 9.5 °C and mean annual rainfall is 520 mm (mean average 1971–2000, ZAMG, 2010). About 90% of the five catchments are used for agriculture, typical crops being wheat, barley and sunflower. The remaining 10% are forest, fallow land and areas of settlement.

2.1.2. Mostviertel region

The three selected headwater catchments in the Mostviertel region are located in the foothills of the Alps, which have been formed by tertiary sediments. Typical soils are Cambisols and Planosols (WRB). The catchments are situated between 255 and 390 m a.s.l. and have a mean slope gradient between 6.1 and 8.6°. Mean annual temperature is 9.1 °C and mean annual precipitation is 750 mm (ZAMG, 2010). About 80% of the area of the catchments is used for agriculture, the main crops being barley, maize and wheat. The remaining parts are forest and areas of settlement.

2.1.3. Innviertel region

Two of the headwater catchments studied are situated in Upper Austria, within the Innviertel region. This area was formed by tertiary sediments. Typical soils are Gleysols, Regosols, Cambisols and Planosols (WRB). The elevation of the catchments ranges from 380 to 500 m a.s.l., with a mean slope gradient between 7.0 and 7.4°. Mean annual temperature is 8.3 °C and mean annual precipitation is 950 mm (ZAMG, 2010). About 90% of this region is used for intensive agriculture; typical crops are wheat, maize, barley and rape. The remaining area is forest and areas of settlement.

2.2. Digital elevation models (DEMs)

We tested three different digital elevation models. The DEM with the highest accuracy was derived from airborne laserscan data with a spatial resolution of 1 m (DEM 1 m). The general accuracy of an airborne laserscan varies, accuracy of height is ±15 cm, accuracy of position is ±30 cm (Land OÖ, 2011). This DEM was then used to generate a re-sampled DEM with a spatial resolution of 10 m (DEM

Table 1
Catchment characterization: region, size (ha^{-1}), mean annual precipitation (P), mean annual temperature (T), slope (S), mean field size ($mF\ ha^{-1}$), permanent river network (pRN) and land use within the ten catchments investigated.

No.	Catchment	Region[a]	ha^{-1}	P (mm)	T (°C)	S (°)	mF (ha^{-1})	pRN (m)	Land use (%)		
									Arable	Forest	Others[b]
1	Kleinebersdorf	W	228	520	9.5	5.3	1.1	2232	91	3	6
2	Lachsfeld	W	338	520	9.5	4.5	1.6	3410	92	1	7
3	Weidenbach	W	422	520	9.5	3.7	0.8	2913	80	1	19
4	Götzendorf	W	287	520	9.5	5.9	1.2	2420	88	4	8
5	Ebenthal	W	89	520	9.5	4.3	1.1	2462	92	2	6
6	Maihof	I	141	950	8.3	7.4	3.3	3825	82	12	6
7	Asböckbach	I	270	950	8.3	7.0	2.9	7254	83	10	7
8	Seitengraben	M	65	750	9.1	6.1	1.6	643	95	0	5
9	Hauptgraben	M	106	750	9.1	6.8	1.7	945	67	27	6
10	Grub	M	262	750	9.1	8.6	1.2	4457	76	21	3

[a] W, Weinviertel region; I, Innviertel region; M, Mostviertel region.
[b] Urban area, water bodies.

10 m). In addition to these laserscan-derived DEMs, an elevation model derived from aerial photographs with a spatial resolution of 10 m (DHM 10 m) was used. Its accuracy of height varies between ±2 m and ±5 m (Land OÖ, 2011).

The three DEMs used represent different databases, which require different computing times and work space: from the most accurate DEM 1 m, which has high work space demand, to the coarser re-sampled DEM 10 m derived from the laserscan, to the broad-gridded DHM 10 m, which has short computing times and less work space demand. Hereby we try to answer the question which DEM can produce most accurate results on which working complexity.

2.3. Field mapping and road networks

During a detailed field mapping campaign, linear structures with an anthropogenic origin (ditches and channels) were mapped. The headwater catchments were inspected, and all visible inflows from channels and ditches were traced upstream and mapped.

As mentioned in various studies (Croke, Mockler, Fogarty, & Takken, 2005; Forman & Alexander, 1998; Jones et al., 2000; Wemple et al., 2001), road networks may influence hydrological patterns in a catchment. The mean average size of the agriculturally used land of an Austrian farm is about 19 ha (hectares). The agricultural landscape is therefore characterized by many small tracks used by farmers to approach their fields. For calculating road network density, an existing digital road map was used and verified by aerial photographs. Paved roads, as well as unsealed roads and small field tracks, were taken into account.

Ditches may occur near almost every road or track to drain road systems. Surface runoff from adjacent farmland is frequently concentrated in ditches alongside these tracks. These ditches are directly connected to surface waters, and surface runoff from fields flows unfiltered through VFSs into the stream. We use the term ‘channel’ here for partially subsurface ditch systems, or channelled ditches, which mostly occur near roads and tracks. These man-made structures all act as linear flow pathways for surface runoff and were considered by field mapping. However, the environmental subsidy programme in Austria does not support VFSs alongside these structures.

Thalweg situations were accounted for by two different mechanisms. When a Thalweg situation appeared but no linear feature was part of the Thalweg, flow was routed automatically along the Thalweg until either (a) the Thalweg drained into a man-made ditch or (b) the Thalweg drained into a stream. In the first case, the area was identified as unprotected (UA); in the second case, there would also be a certain concentration of flow along the Thalweg. However, these structures usually do not exhibit the same flow characteristics as linear flow paths, and they therefore were not considered.

Micro-relief created by different tillage techniques may also influence surface runoff (Dosskey et al., 2002; Takken, Govers, Steegen, Nachtergaele, & Guérif, 2001). Micro-relief is supposed to have much less influence within the scope of our study, because we focused on (a) the importance of linear flow structures located outside field boundaries (actually the connection between fields), and (b) permanent features of a landscape.

2.4. Implementing mapped structures into GIS

After field mapping, identified linear structures were implemented into the different DEMs using GIS (ESRI, ArcGIS 9.3). To ensure correct automated routeing of the implemented linear structures, elevation of the stream network and mapped flow structures were artificially decreased. This so called ‘stream burning’ can be suitable for reducing problems with areas of low relief, wetland/lake complexes or stream junctions (Kenny & Matthews, 2005).

Surface flow paths were then calculated with implemented mapped linear structures (Advanced) and without these structures (Regular). This was performed by using standard GIS functions (fill, flow direction, flow accumulation). While the ‘Advanced’ calculation is supposed to reflect the real hydrological situation in the studied catchments as best as possible, the ‘Regular’ calculation depicts an automatically calculated surface runoff routeing without any knowledge of field conditions. Finally, subwatersheds that drained via linear flow paths (i.e. unprotected) into permanent flow lines (brooks or rivers) were identified and their size calculated. This was done for both the ‘Advanced’ and ‘Regular’ calculation variants. Fig. 2 illustrates such a situation by using the ‘Advanced’ calculation method. A headwater catchment in the Weinviertel region is shown. The area given as UA (10%) is the subcatchment, which drains unprotected through the VFS directly into the stream due to identified linear flow structures (black arrows). Ditches alongside roads (white lines) where no flow structures were identified are connected to communal sewage plants. By using the ‘Regular’ calculation method no UA was detected.

2.5. Flow routeing algorithms

To test the effect of flow algorithms for routeing surface runoff within the watershed, two different algorithms were applied. One of them, the D8 Algorithm of O’Callaghan and Mark (1984), directs flow completely from the starting pixel into one of eight neighbouring pixels. The second algorithm applied was the so-called D-Infinity (D-Inf) algorithm of Tarboton (1997). The D-Inf directs flow from the starting pixel into two neighbouring cells, thus it belongs to the group of multiple flow algorithms. For applying the D8 and D-Inf algorithms, the software package TauDEM (Terrain Analysis Using Digital Elevation Models; Tarboton, 2008) was used.

3. Results and discussion

3.1. Algorithms

A comparison between the D8 and D-Inf algorithm was made for the five catchments located in the Weinviertel region.

Table 2 shows the unprotected areas (UA) for each of the different approaches based on the DEM 1 m. A comparison between the D8 and D-Inf algorithm resulted in a difference of more than 10% in only one catchment. For all other catchments the differences were much smaller or no differences could be found between the different algorithm methods. Multiple flow algorithms, like the D-Inf, are often proposed for areas with low slopes, where they seem to be superior to the D8 algorithm (Jones, 2002; Martz & Garbrecht, 2000; Turcotte et al., 2001). Our test regions, however, exhibit moderate slope angles between 4 and 7°. The rationale for choosing these areas was the obvious connection between slope and erosion on agricultural land. The results therefore suggest that, although the D-Inf algorithm provides higher complexity, it will not lead to more realistic results at the watershed scale, whenever studies focus on surface runoff and associated features. Consequently, we decided only to use the D8 algorithm for further evaluations in the additional regions investigated (M and I).

3.2. Unprotected areas (UA)

Comparing the ‘Regular’ with the ‘Advanced’ approach (Table 2) reveals that for seven out of ten catchments, identification of existing linear pathways leads to significant differences in the evaluation of unprotected catchment area. Between 10 and 38% of the total catchment area was found to be unprotected by using

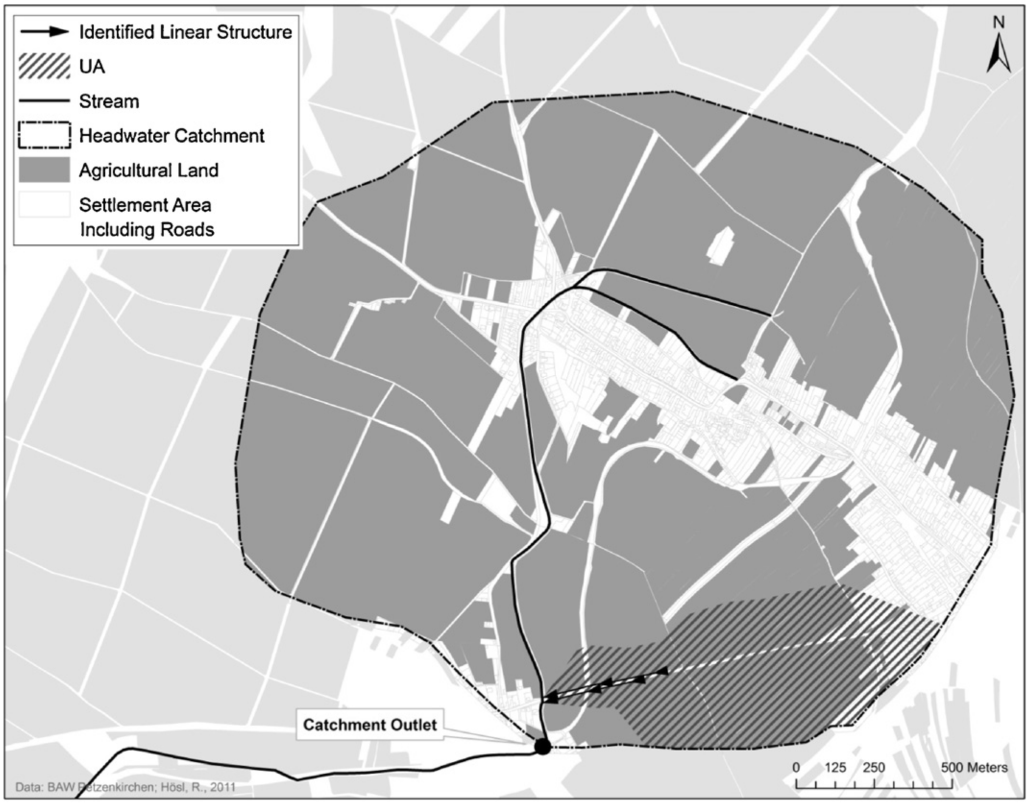

Fig. 2. Headwater catchment in the Weinviertel region. Identified linear structures and unprotected areas (UA) by using the Advanced calculation method and DEM 1 m.

the 'Advanced' approach (DEM 1 m). The differences detected amounted to up to 29% of the catchment area. Within the remaining three catchments (Lachsfeld, Hauptgraben, Götzendorf), no linear flow pathways were found, thus these catchments would potentially be 100% protected by implementing VFSs alongside brooks or rivers. Other management structures that buffer nutrients, sediments and pollutants could also be considered, such as wetlands, retention basins or constructed floodplains. However, in the ten headwater catchments investigated no such structures could be found. Moreover, the national subsidy programme of Austria (ÖPUL) does not take into account such landscape components.

When the 'Regular' approach was applied, in seven catchments no UA was detected at all (Table 2). For the remaining three catchments, 3–18% of the total catchment area was found to be an UA. This suggests that a purely GIS-based design of filter strip placement (here done with the 'Regular' method), as used for instance by Lin et al. (2004) or Xiang (1996), may lead to significant errors.

Table 2
Unprotected areas (UA) for different catchments obtained by employing the D8 and D-Inf algorithm, either calculated with integrated linear structures (Advanced) or without linear structures (Regular) and three different databases used.

No.	Region[a]	Size (ha)	UA (%)	D8		D-Inf	
				Regular	Advanced	Regular	Advanced
1	W	228	DEM 1 m	18	38	19	38
			DEM 10 m	0	37	0	37
			DHM 10 m	0	39	0	39
2	W	338	DEM 1 m	0	0	0	0
			DEM 10 m	0	0	0	0
			DHM 10 m	0	0	0	0
3	W	422	DEM 1 m	0	10	0	9
			DEM 10 m	0	1	1	1
			DHM 10 m	0	11	1	11
4	W	287	DEM 1 m	0	0	0	0
			DEM 10 m	0	0	0	0
			DHM 10 m	0	0	0	0
5	W	89	DEM 1 m	6	16	7	29
			DEM 10 m	0	13	1	13
			DHM 10 m	0	13	0	13
6	I	136	DEM 1 m	0	29	–	–
7	I	260	DEM 1 m	0	18	–	–
8	M	65	DEM 1 m	0	11	–	–
9	M	106	DEM 1 m	0	0	–	–
10	M	262	DEM 1 m	3	22	–	–

[a] W, Weinviertel region; I, Innviertel region; M, Mostviertel region.

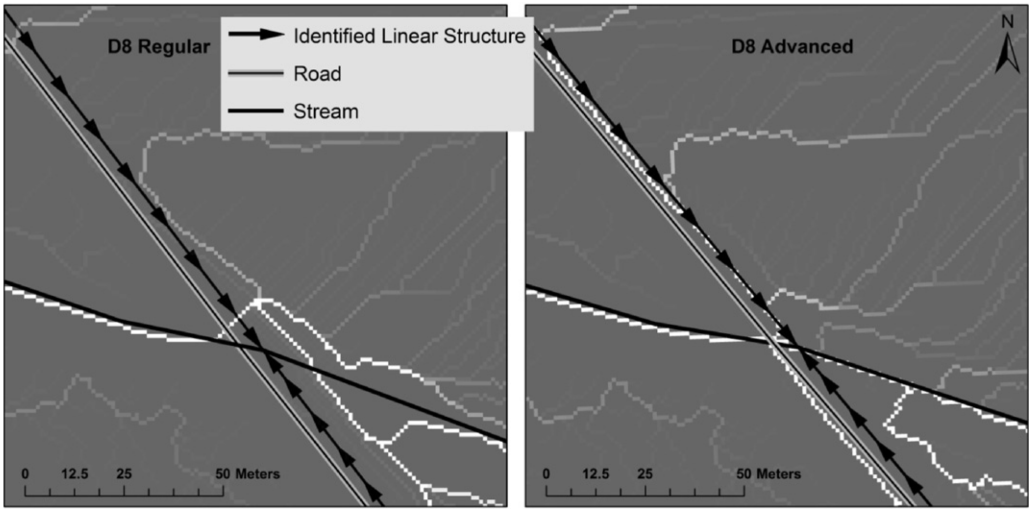

Fig. 3. Surface runoff routeing; D8 Regular and D8 Advanced; Database DEM 1 m.

In addition, subsidy programmes within the European Union which fund placement of filter strips only alongside permanent flow lines to reduce nutrient input are likely to be considerably biased.

Table 3 shows data comparing catchment size (ha^{-1}), road network length per hectare (Road m ha^{-1}), mapped linear structures per ha of study area (mLS m ha^{-1}), mean field size (mF m ha^{-1}) and UA in hectares and percent. Available data suggest that there is no linear relationship ($r^2 = 0.17$) between the length of the mapped linear structures and the extent of UA. A ditch or a channel just a few metres long could still drain a significant part of a catchment.

Fig. 3 shows a typical situation and illustrates the differences in flow path generation when using the 'Regular' and 'Advanced' method and the D8 algorithm. The irregular white/grey lines show the calculated flow paths according to the respective algorithm. The whiter the cells, the bigger the contributing area above this raster cell. According to the illustration, the 'D8 Advanced' can reproduce the hydrological situation better, owing to implemented mapped linear flow paths. The illustration for 'D8 Regular' shows the result of an automated desktop analysis in which no mapped structures were included. The calculation shown was made with DEM 1 m and depicts an example for visualization.

3.3. DEMs

The effects of different spatial resolution of DEMs on topographically environmental questions have been investigated by various authors (Hancock, 2005; Sørenson & Seibert, 2007; Thompson et al., 2001; Vaze et al., 2010). These studies did not include existing linear pathways in their evaluation. We therefore used the variants 'Regular' and 'Advanced' to test the effects of DEM resolution on the identification of unprotected subcatchment areas in the Weinviertel region (Table 2).

For both coarse grids tested (DEM 10 m and DHM 10 m), the 'Regular' variant did not indicate any unprotected subcatchments. In contrast to this, the 'Advanced' method detected UA in three out of five catchments. A comparison of the 'Advanced' variants between DEM 10 m and DHM 10 m reveals almost no differences, with the exception of one catchment. Calculation using either D8 or D-Inf did not give any differences. Results obtained suggest that the influence of existing linear flow structures is much higher than the effect of grid size and type of data (whether derive from laserscan or from aerial photographs). A high-resolution DEM may certainly reproduce stream networks better than a coarse DEM; however, if field mapping is considered, a DEM resolution of 10 m was sufficient for calculating flow pathways.

3.4. Factors influencing UA

To identify parameters that might be influencing the extent of UA, various parameters were calculated (Table 3): the road network length per hectare (Road m ha^{-1}) of the ten headwater catchments investigated, mean field size (mF) and the length of the mapped linear structures per hectare (mLS) are given in Table 3. As mentioned in various studies (Croke et al., 2005; Forman & Alexander, 1998; Jones et al., 2000; Wemple et al., 2001), road networks may influence the hydrological situation in a catchment. Furthermore, road networks may also affect landscape ecology and landscape functions. Mean field size was also included in a statistical analysis as a factor thought to be reflecting the agricultural landscape structure of the three different regions (W, M, I) tested.

Correlations (Spearman) between Road and UA ($r^2 = 0.19$) and mF and UA ($r^2 = 0.08$) were insignificant.

The study sites investigated represent the full climatic range of Austrian agricultural land north of the Alps. To account for this range, we included two site-specific parameters: mean annual rainfall and mean slope gradient. Annual rainfall is not to be understood as a primary explanatory variable in itself, but as a surrogate (with the advantage of being easily accessible) of a climatic situation which reflects the land-forming capacity of climate. The same applies for mean slope gradients of the ten catchments (see Table 1), as higher slopes are found in areas with higher annual rainfall.

We conducted a stepwise regression analysis with the variables UA, mean slope gradient, annual rainfall and Road (mF was discarded); this resulted in a r^2 of 0.64. Regression analyses considering Road, mLS and annual rainfall lead to $r^2 = 0.78$.

Fig. 4 shows the extent of UA versus mLS, for regression analyses we obtained $r^2 = 0.17$. Further analysis revealed that this was due to two extreme results (marked with (a) and (b) in Fig. 4). Fig. 4(a) refers to catchment 8 'Seitengraben', where a roadside ditch was connected via two subsurface ditches directly to the stream. Hence comparably long mLS (13.7 m ha^{-1}) lead to only 11% UA. In contrast, at Fig. 4(b) (which refers to catchment 6 'Maihof'), a rather short mLS (0.7 m ha^{-1}) led to almost 30% UA, meaning that a short ditch may also drain a considerable part of a catchment. Removing these extremes would result in a considerable linear regression. However, situations like (a) and (b) certainly occur in anthropogenically influenced landscapes and should not be removed. These

Table 3
Specific catchment parameters: mean Road Length per hectare (Road m ha^{-1}), mapped linear structures per hectare (mLS ha^{-1}), mean field size (mF ha^{-1}), and unprotected areas (UA) in hectare and percentage, based on DEM 1 m.

No.	Region[a]	ha^{-1}	Road (m ha^{-1})	mLS (m ha^{-1})	mF (ha^{-1})	UA (ha^{-1})	UA (%)
1	W	228	76	8.0	1.1	87	38
2	W	338	61	0.0	1.6	0	0
3	W	422	71	1.8	0.8	42	10
4	W	287	54	0.0	1.2	0	0
5	W	89	73	5.3	1.1	14	16
6	I	136	52	0.7	3.3	39	29
7	I	260	39	3.8	2.9	46	18
8	M	65	31	13.7	1.6	7	11
9	M	106	37	0.0	1.7	0	0
10	M	262	38	6.3	1.2	58	22

[a] W, Weinviertel region; I, Innviertel region; M, Mostviertel region.

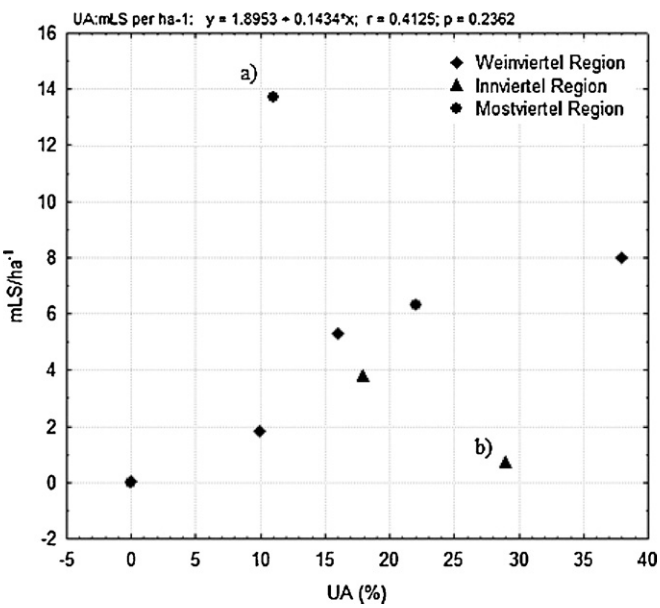

Fig. 4. Unprotected areas (UA) versus mapped linear structures (mLS) for the catchments in the different regions (W, M, I) studied.

examples also demonstrate the high variability of results that may be obtained when identifying linear structures.

Field mapping will certainly not always be affordable or practicable. Nevertheless, considering easily available data like road networks and taking into account site-specific variables like slope gradient or annual rainfall may support decisions about the necessity of additional field surveys when planning activities related to VFSs.

4. Conclusion

In only three out of the ten catchments studied, no man-made linear flow paths were detected by field mapping. For these three catchments, it could be assumed that all incoming runoff would potentially flow through VFSs (when implemented). All other catchments were affected by ditches or channels that concentrate surface runoff before entering a potential VFS, thus leading drainage water directly and unfiltered into surface waters. Moreover, the amount of unprotected areas was up to 38%, which indicates that the dimension of the problem is not of minor importance. On the other hand, this also suggests that inclusion of linear flow paths by field surveys is an essential tool for effective placement of filter strips. Whenever this is neglected, for instance in subsidy programmes or automated desktop analyses, considerable errors in calculated effectiveness are likely to occur.

Results both on small effects of the different DEM resolutions compared to large effects of linear flow path detection and the comparison of different flow routeing algorithms also highlight the importance of conducting field surveys to identify linear flow structures over data availability and routeing technique. At present, considerable efforts are being made worldwide to produce high-resolution airborne laserscan DEMs. Using this information in watershed modelling still needs enormous investments in computing time, whereas our results show that results of equal accuracy may be obtained when additional field information is available.

Although we established a relationship between UA, annual precipitation and length of road network, we suggest using such a relationship only in support of the decision to carry out additional fieldwork. The results show that although the occurrence of UA is dependent on the occurrence of linear flow pathways, it is not constrained by their length. Therefore a short ditch may also drain a substantial part of a catchment, thus leading to a large area that would potentially be unprotected by VFSs. Flexibility in placement of VFSs in subsidy programmes is therefore needed.

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