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Identification and regionalization of dominant runoff processes – a GIS-based and a statistical approach

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Abstract. In this study two approaches are presented to identify Dominant Runoff Processes (DRP) with respect to regionalization. The approaches are a simplification of an existing method to determine DRP by means of an extensive field campaign. The first approach combines the permeability of the substratum, land-use and slope of the basin in a GIS-based analysis. The second approach makes use of discriminant analysis of the physiographic characteristics of the basin and links it to the GIS analysis. The results of the developed approaches are maps, which identify dominant runoff processes and represent a spatial distribution of the hydrological behaviour of the soil during prolonged rainfall events. The approaches have been developed in a micro-scale basin (Germany). An additional meso-scale basin was introduced in which the two approaches were applied for quality control. The thus generated maps for the micro-scale basin were compared with an existing DRP map, which was derived with the existing method. The first approach showed a resemblance of 79% when compared to this map, whereas the second approach showed only a resemblance of 51%. The generated maps for the meso-scale basin were compared to DRP that were determined point wise according to the existing method. The first approach showed in this case a resemblance of 81%, whereas the second approach showed a resemblance of 68%. Therefore, the first approach is preferred to the second approach when accuracy, data input and calculation time are concerned.

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1 Introduction

Several aspects of runoff formation have been studied in micro-scale basins over the past years (e.g. Anderson and Burt, 1990; Scherrer, 1997; Buttle and McDonald, 2002; McDonnell, 2003; Scherrer and Naef, 2003; Weiler and Naef, 2003; Weiler et al., 2005). At the micro-scale (i.e. basins ranging in size from 1 km^2 to 10 km^2; Blöschl, 1996) runoff generation processes occurring at hill slopes and near-stream areas dominate basin response to rainfall (McDonnell, 1990; Montgomery, et al., 1997). In many cases several processes were observed to occur simultaneously at the same site, however, during prolonged precipitation often one process tends to dominate so that other processes can be neglected (Scherrer and Naef, 2001). Methods to identify the runoff processes on the plot and mirco-scale have been developed for example by Faeh (1997), Scherrer (1997) and Tilch et al. (2002, 2006). Tilch et al. (2002, 2006) developed a method to delineate hydrological response units (HRU) within a GIS environment using generally available data sets and expert knowledge. Each of the delineated HRUs is characterized by the same runoff source areas and the same dominating runoff generation processes. Faeh (1997) and Scherrer (1997) conducted sprinkling experiments in Switzerland on grassland hill slopes with varying slopes, geology and soils, recording soil-water level, soil-water content and soil-water tension. The outcome of this research formed the basis for developing process decision schemes, which reflect the complex nature of runoff formation eventually to determine the Dominating Runoff Process (DRP) on a soil profile (Scherrer and Naef, 2003).

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Table 1. Physiographic basin characteristics of the Zemmer subbasins Grundsgraben and Schleidweiler and the meso-scale basin Welschbillig, Germany.

		Land use				Substratum		Slope				
Basin	Area [km^2]	Urban [%]	Forest [%]	Grassland [%]	Arable land [%]	Permeable [%]	Impermeable [%]	0–3 [%]	3–5 [%]	5–20 [%]	20–40 [%]	>40 [%]
Grundsgraben	9.7	8	27	22	42	16	84	12	21	53	8	6
Schleidweiler	4.3	7	24	20	48	23	77	6	18	63	6	7
Welschbillig	40.5	5	26	29	40	16	84	8	14	62	12	4

These generated DRP-maps represent a spatial distribution of the hydrological behaviour of the soil during prolonged rainfall events. With such maps, areas relevant for the formation of floods can be identified and used to predict areas at risk of damage, for example pesticide loss or soil erosion (Schmocker-Fackel et al., 2007). However, the original method is time consuming and due to its heavy data load predominantly applicable at the lower micro-scale. Schmocker-Fackel et al. (2007) simplified the complex decision scheme of Scherrer (2006) but still requires data from detailed soil maps (1:5000) and from geological, land use and topographical maps. Since more often than not, detailed soil maps are lacking for meso-scale basins, the application of this approach becomes problematic. Peschke et al. (1999a) developed the WBS-Flab classification system for delineating runoff processes by using morphology, land use, stream network and detailed soil type information. However, as with Schmocker-Fackel et al. (2007) the same problem occurs when implementing this methodology to areas where detailed soil data is lacking.

A geo-statistical or statistical analysis of DRP without using detailed soil maps could provide insight into their regionalization potential. Since soil relief parameters are determinant for soil formation and for runoff generation (Ticehurst et al., 2007), they are considered crucial for soil and process mapping purposes. Besides other statistical and computational methods, discriminant analysis has been widely used to differentiate and characterise different spatial and soil process units (Sinowski and Auerswald, 1999; Kravchenko et al., 2002). One of the most important advantages of this linear statistical approach is the fact that all developed parameters are interpretable with parameters derived from known data. With this, it is possible to identify and quantify the differences and similarities of areas with common (hydrological) behaviour. GIS based approaches have been applied for digital soil mapping. Summaries regarding the current state of research about this topic are given in e.g. McBratney et al. (2003); Scull et al. (2003); Behrens and Scholten (2006). Flügel (1995) used physiographic basin properties such as topography, soils, geology, rainfall and land use to delineate HRU by a GIS analysis. Furthermore, the Hydrology Of Soil Types (HOST) classification of Great Britain enables the production of maps that indicate soils with similar hydrological behaviour (Boorman et al., 1995). HOST uses pedotransfer rules to estimate complex soil properties from existing, generally simpler, soil properties. These rules were used to derive the soil attributes for its classification system. The HOST approach was applied by Dunn and Lilly (2001) to transfer model parameters from one catchment to another.

The objective of this study is to develop two different approaches for identification and regionalization of dominant runoff processes (DRP) at the meso-scale based on the method of Scherrer and Naef (2003) without using detailed soil data. The two methods are: (i) a simple geo-statistical, or GIS-based, procedure based on land use, slope and permeability of the substratum, (ii) a stratified statistical approach based on a discriminant analysis of a large set of GIS-based derivatives. Both methods will be compared with each other to decide which approach is suited better to reflect the results of the original method in micro-scale and meso-scale basins. The purpose of these approaches is to simplify the complex method of Scherrer and Naef (2003). They should require less data sources (especially soil data), less field observations and have a simpler procedure for predicting the dominant runoff processes compared to the original method. This makes them not only applicable for larger areas, but also less time consuming.

To determine the quality of both approaches, their results will be compared to an existing reference DRP map (Schobel, 2005) that is constructed according to the method of Scherrer and Naef (2003) and provides the dominant runoff processes of a micro-scale basin. Furthermore, an additional (meso-scale) basin is introduced in which the two approaches will be applied. In the meso-scale basin the method of Scherrer and Naef (2003) was applied as well and its results will serve as a validation for the new approaches.

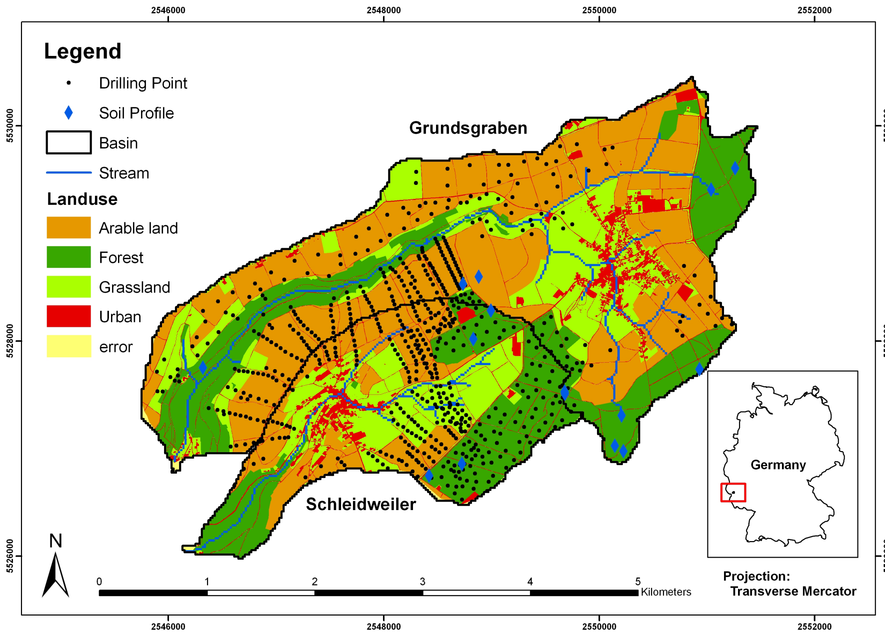

Fig. 1a. Land-use map of the micro-scale experimental Zemmer basin (Germany) with the 15 soil profiles and 728 drilling points used for the reference map of Schobel (2005).

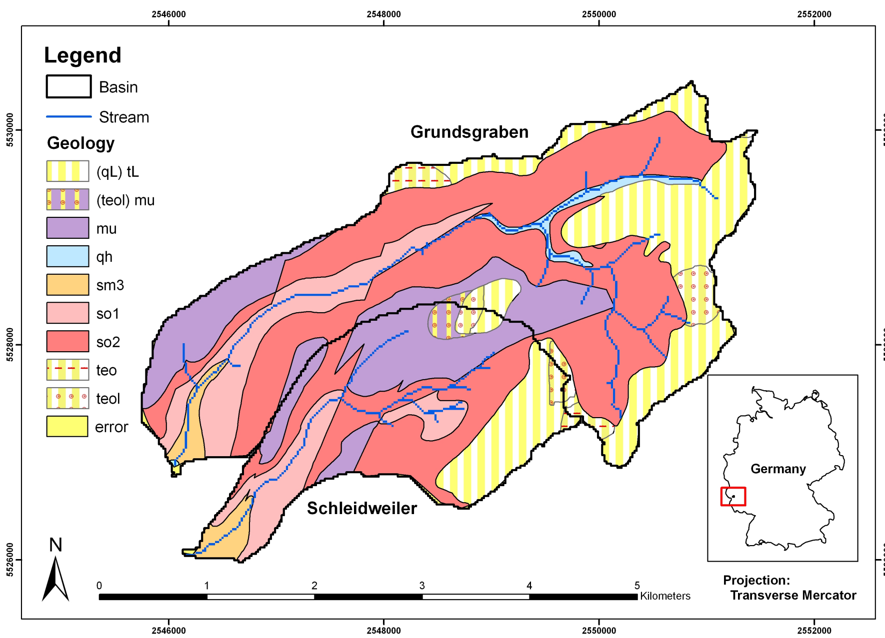

Fig. 1b. Geology-map of the micro-scale Zemmer basin (Germany) (Negendank and Wagner, 1988, adapted)*. *Explanation of abbreviations: (qL) tL=quaternary Loam; (teol) mu=local tertiary sand on limestone; mu=limestone; qh=quaternary sediments; sm=middle sandstone; so=upper sandstone; teo=local tertiary clay; teol=local tertiary sand.

2 Study area

The study area consists of the micro-scale experimental Zemmer basin and the meso-scale basin Welschbillig, both located in Rhineland-Palatinate, Germany. The physiographic basin characteristics, namely land use, permeability of the substratum and slope are given in Table 1. The research area of the Zemmer basin (Fig. 1a) comprises the subbasins of the

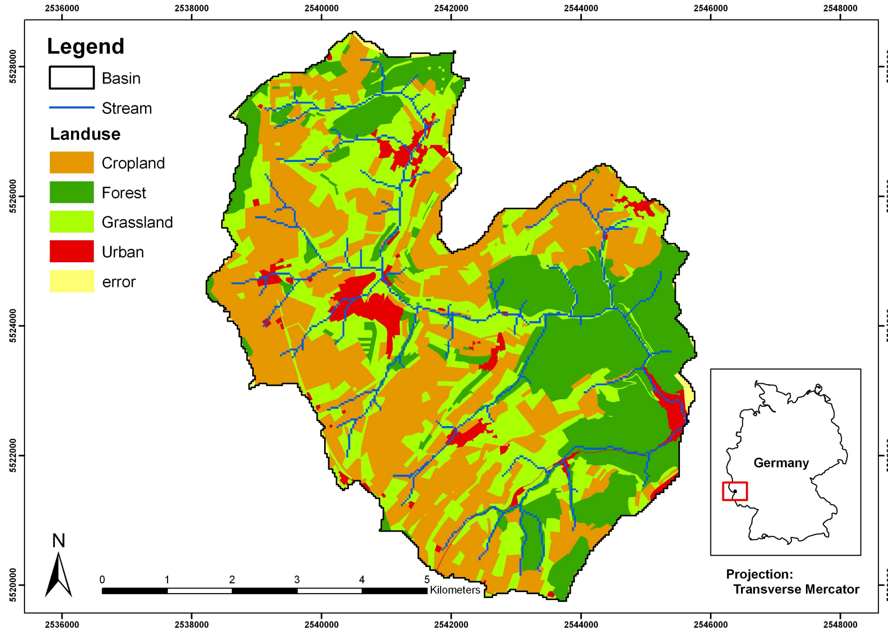

Fig. 2a. Land-use map of the meso-scale Welschbillig basin (Germany).

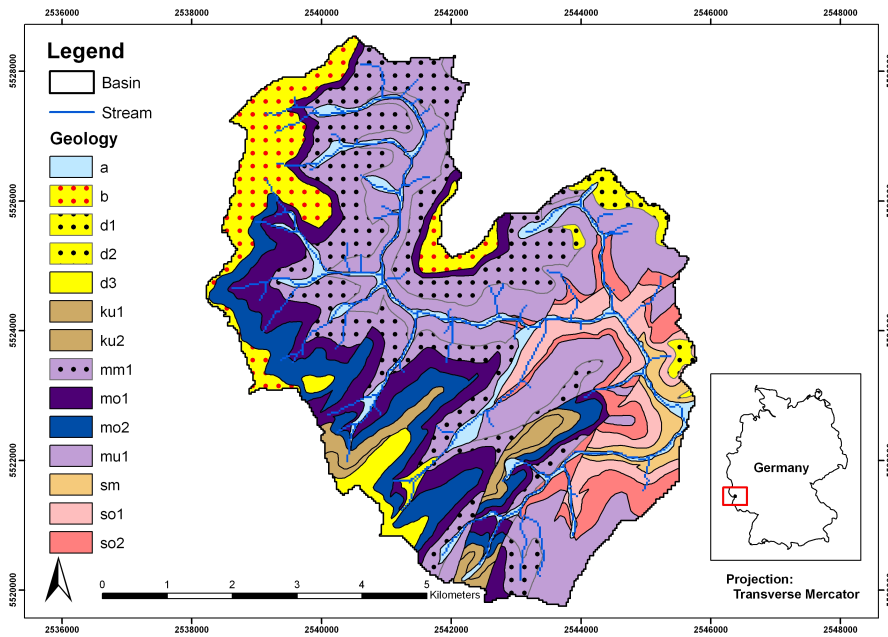

Fig. 2b. Geology-map of the meso-scale Welschbillig basin (Germany) (Negendank and Wagner, 1988, adapted)*, *Explanation of abbreviations: a=alluvial sediments; b=mixture of tertiary rubbles, sand and loam; d=different pliocene terraces; ku=lower keuper; mu=lower limestone; mm=middle limestone; mo=upper limestone; sm=middle sandstone; so=upper sandstone.

Grundsgraben basin and the Schleidweiler basin, situated in the southern part of the Eifel near the village of Zemmer.

The municipality of Zemmer consists of four small towns, three of which are situated on a plateau. The fourth sub-municipality lies in the "Kyll" valley and was subjected to repeated flooding in the past. Mesozoic sediments of the formations sandstone (*Buntsandstein*) and limestone (*Muschelkalk*) form thin surface layers covering the bedrock of Devonian schist (Fig. 1b). In higher elevated areas, this pattern is covered by tertiary sediments of the Ur-Mosel (ranging from yellow- red- brownish clays to sandy sediments and pebble) as well as by Pleistocene soliflunctional cover and loess (Walter, 1995). The in-situ loamy-sandy to loamy-clayey as well as clayey weathered rock of the upper sandstone has led to the Holocene formation of Leptosols, Regosols, Cambisols and Stagnic Cambisols. The areas of the lower limestone formation have weathered to a fine grained silty substrate (Meynen, 1967). Because of Pleistocene solifluidal relocation processes, the development of compacted and impermeable soil is widespread. From an agricultural point of view, these soils are only arable when meliorated (agricultural engineering for soil improvement, here: loosening the compacted (sub)-soil using special agricultural equipment) sufficiently (Schröder, 1983). The mean annual rainfall for this basin is about 800 mm/y.

The Welschbillig basin (Fig. 2a) is situated in the western part of Rhineland-Palatinate. The basin has a total area of 41 km^2 and is predominantly used for agriculture. The appearance of the basin is determined by arable- and grassland (69%). The lower parts of the watercourses towards the village of Kordel are forested (25%). Urban area is very low (4%). Regarding the geology, different specifications of limestone (*Muschelkalk*) predominate and red sandstone (*Buntsandstein*) can be found everywhere except near the village of Kordel (Fig. 2b). In higher areas, this pattern is covered by tertiary sediments of the Ur-Mosel (ranging from yellow- red- brownish clays to sandy sediments and pebble) as well as by Pleistocene soliflunctional cover and influenced by loess (Walter, 1995). The in-situ loamy-sandy to loamy-clayey as well as clayey weathered rock of the upper sandstone has led to the Holocene formation of Leptosols, Regosols, Cambisols and Stagnic Cambisols. The areas of the limestone formations have normally weathered to a fine grained silty substrate (Meynen, 1967). Because of Pleistocene solifluidal relocation processes, compacted and impermeable soils developed and are widespread throughout the whole basin. The mean annual rainfall for this basin is about 820 mm/y.

3 Methodology

The approach developed by Scherrer and Naef (2003) was based on large number of field- and sprinkling experiments (Faeh 1997; Scherrer 1997; Weiler and Naef, 2003). Scherrer and Naef (2003) used this research as a basis for developing process decision schemes to determine dominant runoff processes or DRP on a soil profile and occur after prolonged rainfall events. Several runoff processes can occur on one site, the dominant one being that which contributes most to runoff. Which process dominates depends on the site characteristics and the rainfall event. The processes thus derived are: Hortonian Overland Flow (D_{HOF}), Saturated Overland Flow (D_{SOF}), SubSurface Flow (D_{SSF}) and Deep Percolation (D_{DP}). The SOF and SSF processes are subdivided into D_{SOF1}, D_{SOF2} and D_{SOF3} and D_{SSF1}, D_{SSF2} and D_{SSF3} respectively. The numbers refer to the intensity with which the processes respond to rainfall, where 1 represents, relatively, the most abruptly changing flow reaction and 3 represents the most gradually changing flow response. The method incorporates climatic and physiographic characteristics and it has been applied successfully in Switzerland (Scherrer and Naef, 2003; Schmocker-Fackel et al., 2007). It is assumed that the new approaches developed in this study reflect changes in climate and physiographic characteristics, as is the case for the method of Scherrer and Naef (2003).

The data sources required for the method of Scherrer (2006) comprise 16 datasets: soil profiles; soil maps; topographical maps; geo-morphological maps; vegetation maps; geological maps; hydrological maps; geo-technical maps; geo-ecological maps; drilling points with soil description; infiltration tests; digital maps (ATKIS); forestry maps; agricultural land evaluation; remote sensing data and drainage plans (Scherrer, 2006). The field observations comprise measurements of 15 soil profile properties: vegetation cover; hydrophobic cover; slope; surface roughness; soil matrix; macroporosity; bulk density; soil sealing by rainfall; plough pan; thickness of the soil column; lateral flow paths and drainage; influence of groundwater/aquifer; depth of waterlogging; rate of water stagnation; permeability of the substratum (Scherrer, 2006). One should note that the results of the method of Scherrer and Naef (2003) (i.e. maps that indicate dominant runoff processes) have no direct relation with the quantitative aspects of hydrographs. The maps show a soil functional characterisation and the use of hydrometeorological data is not suited to validate either the results of the original method or the results of the approaches developed in this study.

Scherrer and Naef (2003) indicated the limitations of their approach as follows: Rains of low intensity infiltrate into the soil predominantly by matrix flow and the scheme presented does not apply to such conditions. The matrix-macropore system probably only becomes active during rainfall of higher intensities (Faeh, 1997). Field experiments emphasized the important role of the nature of the surface-topsoil interface infiltration and runoff formation. As this interface is more complex on arable land (soil compaction, surface sealing effects, etc.) and in forests than on grassland, special decision schemes are required for these other land use types. Hydrological data cannot be used to calibrate or validate the obtained dominant runoff processes.

The approaches presented in this study simplify the above-described method in such a way that it now can be applied in micro- and meso-scale basins without using the heavy data load that is necessary in the original method. The approaches are (i) geo-statistical (GIS-DRP) approach and (ii) statistical approach (CDA-DRP) for the delineation of dominant runoff processes with respect to regionalization and require three basic datasets in terms of permeability: simplified geological maps, digital elevation models and land use maps. Since

Table 2. The assumed dependency of the dominant runoff processes (DRP) on slope and permeability of the substratum for grassland, arable land and forest.

Slope [%]	Impermeable substratum Grass-and arable land	Impermeable substratum Forest	Permeable substratum Grass-, arable land and forest
0–3*	D_{SOF3}	D_{SOF3}	D_{DP}
3–5*	D_{SOF2}	D_{SSF3}	D_{DP}
5–20*	D_{SSF2}	D_{SSF2}	D_{DP}
20–40**	D_{SSF1}	D_{SSF2}	D_{DP}
>40**	D_{SSF1}	D_{SSF1}	D_{DP}

* According to Scherrer (2006); partly modified.
** According to Scherrer (2006) and Schüler (2006); partly modified.

the objective of this study is to develop approaches with a view to regionalization of DRP to areas where soil information is lacking, no soil characteristics were taken into account when developing the approaches. Moreover, this is the major point in which this study differs from Peschke et al. (1999a; 1999b), Scherrer and Naef (2003), Naef et al. (2007a, b) or Schmocker-Fackel et al. (2007).

The results of both approaches are compared to a reference map (Schobel, 2005), which was generated by means of the implementation of the method of Scherrer and Naef (2003). During an intensive field campaign in the micro-scale Zemmer basin the decision schemes of Scherrer (2004) were applied using 15 representative soil profiles containing information on soil type, soil structure and physical properties and an additional 728 soil drilling points for the determination of the DRP. Thus, the reference DRP map is the result of field data sampling as described in the methods proposed by Scherrer and Naef (2003) and Scherrer (2004). The comparison of both approaches with the reference map is therefore a comparison with the original method. The approaches then will be applied in a new basin with similar climate and physiographic properties (meso-scale basin Welschbillig, Germany) for regionalization purposes and offers the opportunity to detect methodological errors. In this meso-scale basin, the method of Scherrer and Naef (2003) and Scherrer (2006) has been applied point wise on 69 previously defined sites throughout the entire basin.

3.1 GIS-DRP (approach 1)

GIS-DRP makes use of a simplification of the procedure developed by Scherrer (1997), Scherrer and Naef (2003) and Scherrer (2006). The simplification assumes that the DRP are mainly dependent on slope and the permeability of the substratum. For the simplified approach only a DEM, a geological map and a land use map are required as data input. The first processing step is to generate the slope classes from the DEM (DEM available from the government of the Rhineland-Palatinate with a grid resolution of 20 m by 20 m) according to the original decision scheme for field campaigns to determine dominant runoff processes (Scherrer and Naef, 2003; Scherrer, 2006). Slope was calculated by means of the local pixel slope of two neighbouring pixels. Based on the DEM a GIS analysis is carried out to generate basin boundaries and the stream network.

As a second step, the geological substrata of the basins are classified. The classification is based on Zumstein et al. (1989), who classified the infiltration permeability of the substratum with respect to its lithology and geo-hydrological characteristics such as fractures and porosity obtaining eight different permeability classes. The classification of Zumstein et al. (1989) was adapted and simplified into two classes: permeable and impermeable. Hellebrand et al. (2008) applied this classification to regionalize winter storm flow coefficients. Regarding the determination of DRP on permeable substratum the decision schemes of Scherrer (2006) are followed. Regarding the determination of DRP on impermeable substratum, partly the decision schemes of Scherrer (2006) and modifications for forested areas from Schüler (2006) is used. The geological map used for the basins was the 1:25 000 scale map of the south Kyll-Valley (Negendank and Wagner, 1988).

As a last step, the permeability layer is linked to the slope classes and the existing land use map to determine a dominant runoff process for each of the polygons. Table 2 lists the DRP dependency for forest, grass- and arable land with respect to slope and permeability as assumed in this study and used for the GIS analysis. Besides these previously defined criteria, a few additional assumptions have to be made and applied in the analysis. For urban areas, the DRP is supposed to be D_{HOF}, independent of permeability and slope according to the method of Scherrer and Naef (2003) and Scherrer (2006). Along the stream network on both sides of the stream a D_{SOF1} area is assigned, which represents the riparian zone.

GIS-DRP is applied to the Zemmer and Welschbillig basin resulting in so-called GIS-DRP maps for both basins. The GIS-DRP map of the Zemmer basin is compared to the reference map (Schobel, 2005) for quality control. The GIS-DRP map of the Welschbillig basin is compared to the results of the method of Scherrer and Naef (2003) available in this basin for validation purposes.

3.2 CDA-DRP (approach 2)

CDA-DRP for predicting DRP is a statistical approach where the main derivatives of a DEM are combined to generate canonical components of the different DRP. This method is widely used e.g. in remote sensing, vegetation science and hydrology (e.g. Matthew et al., 1994; Sinowski and Auerswald, 1999; Dobos et al., 2000; Seeger et al., 2004; Liu et al., 2008), including also the analysis of relief parameters. The classification of the unknown areas based on the derived canonical components leads to the prediction of DRP.

In the present study, the micro-scale Zemmer basin is used as training area where the discriminant functions are built. Afterwards, these functions are applied to the meso-scale Welschbillig basin. The topography of both basins was based on a DEM (resolution 20 m by 20 m, provided by the government of Rhineland Palatinate) and a set of derivatives generated within the GRASS GIS 6.3.cvs (GRASS Development Team, 2008) environment: slope (degrees), profile curvature (in slope direction), tangential curvature (curvature parallel to the contour line), flow path length and flow path density. Additionally, the topographical index as well as the steepness (S) and slope length (LS) factors were also calculated. The S and LS factors were defined with the r. watershed command in GRASS GIS 6.3.cvs (GRASS Development Team, 2008). The procedures are based on McCool et al. (1987) for the S-factor and Weltz et al. (1987) for the LS-factor. The terrain attributes are transformed into principal components (GRASS GIS command i.pca), which are themselves the basis for the calculation of the canonical components (i.cca) of the DRP of the Zemmer catchment. The DRP of the meso-scale Welschbillig basin are then predicted through the application of the maximum likelihood classification algorithm (i.maxlik) provided in GRASS GIS 6.3.cvs (GRASS Development Team, 2008).

Approach 2 is applied to the Zemmer and Welschbillig basin resulting in so-called CDA-DRP maps for both basins. The CDA-DRP map of the Zemmer basin is compared to the reference map (Schobel, 2005) for quality control.

4 Results

The reference DRP map of the Zemmer basin by Schobel (2005) is given in Fig. 3; Table 3 lists the percentages of the DRP processes of the basin. The map reflects the dominant runoff processes of the micro-scale Zemmer basin after the method of Scherrer and Naef (2003) and Scherrer (2004). The dominant process is D_{SSF2} and occurs mainly between the crest of the hill and its steeper slope on all land use types. The occurrence of D_{DP}, mostly classified on the steeper parts of the basin and allotted in one continues part, can directly be connected to the geology (Fig. 1b). The rest of the processes show a more dispersed distribution.

4.1 Results GIS-DRP

Figure 4a shows the results of GIS-DRP: the GIS-DRP map of the Zemmer basin. Percentages of the respective processes obtained by means of the GIS-DRP map are listed in Table 3. The main dominant runoff process is represented by D_{SSF2} (45%) followed by D_{DP} (14%) and D_{SOF2} (10%). The similarity between the GIS-DRP map and the reference map (Schobel, 2005) was 79%. Additionally, 6% of the processes determined with GIS-DRP differed only in one process class.

The main difference between the GIS-DRP map and the reference map was found for areas of the upper sandstone formation. This could be related to imprecise geological data input (e.g. the *upper Buntsandstein 2* is composed by a permeable and an impermeable layer), which is not differentiated in the geological map. The D_{SSF1} for arable land resulting from the newly introduced slope class 20–40% further weakened the similarity of the GIS-DRP map with the reference map. In order to remain as close as possible to the methodology of Scherrer and Naef (2003) this was tolerated. Near-stream areas also showed differences between the two maps. The width of the riparian zone, which produces D_{SOF1}, could not be determined with the basic settings of the GIS-DRP. By classifying the riparian zone automatically as D_{SOF1} this problem can be solved, with the width now depending on the relief and its location within the stream network. For larger streams, this classification gave good results, however, for headwaters and accumulation in depressions no proper classification was achievable. The differences between the GIS-based generated D_{SOF1} areas and the D_{SOF1} areas in the reference map of Schobel (2005) are only conditionally based by the resolution of the DEM. Part of the Scherrer and Naef (2003) methodology is the application of aerial photography and topographical maps. In combination with an intensive field campaign, this offers the possibility for the implementer of the original method to delineate exactly the D_{SOF1} areas in the riparian zone, far better than any GIS-based approach using even a very detailed DEM.

4.2 Results CDA-DRP

The combination of input parameters into canonical components showed that the components based on a combination of (i) LS- and S-factor, (ii) LS-factor and slope and (iii) slope, topographical index and flow density contributed most to the discrimination of the DRP. For the permeable substratum, the

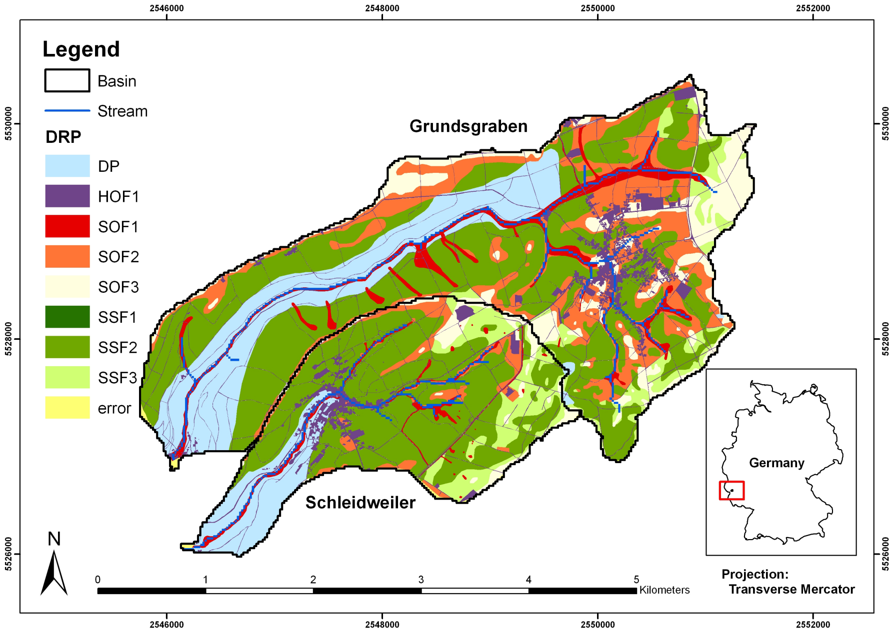

Fig. 3. Reference map of the dominant runoff processes of the Zemmer subbasins Grundsgraben and Schleidweiler as derived by Schobel (2005).

Table 3. Distribution of DRP: Results for both applied approaches for the micro-scale Zemmer basin and the meso-scale Welschbillig basin, Germany.

DRP [%]	Zemmer Reference map (Schobel 2005)	Zemmer Approach 1 (GIS-DRP)	Zemmer Approach 2 (CDA-DRP)	Welschbillig Approach 1 (GIS-DRP)	Welschbillig Approach 2 (CDA-DRP)
D_{HOF}	8	8	8	6	6
D_{SOF1}	5	6	3	8	6
D_{SOF2}	13	10	7	9	5
D_{SOF3}	9	8	10	6	7
D_{SSF1}	0	3	0	5	0
D_{SSF2}	43	45	32	54	35
D_{SSF3}	6	5	26	3	24
D_{DP}	15	14	13	8	17
Error	1	1	1	1	0

topographical index was the most important input parameter. The remaining four canonical components were very similar for all DRP. Figure 4b shows the results of CDA-DRP: the CDA-DRP map of the Zemmer basin. Percentages of the respective processes are listed in Table 3. The similarity between the CDA-DRP map and the reference map (Schobel, 2005) was 51%. The low performance of the CDA-DRP map when compared to the reference map could be attributed to the fact that approach 2 systematically confounded DRP. The cross tabulation of the DRP obtained via the reference map with the DRP obtained via approach 2 showed that both D_{SOF1} and D_{SOF2} had only weak retrieval rates (26% for D_{SOF1} and 19% for D_{SOF2}, respectively), 24% of the D_{SOF1} area was classified as D_{SSF2} and 44% of the D_{SOF2} area was

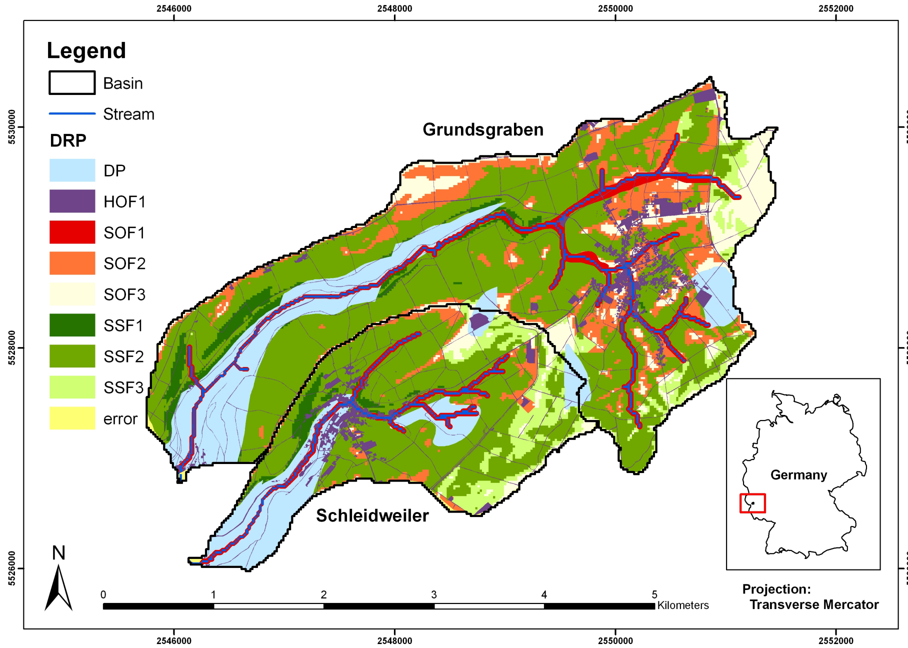

Fig. 4a. GIS-DRP map of the dominating runoff processes for the Zemmer subbasins Grundsgraben and Schleidweiler.

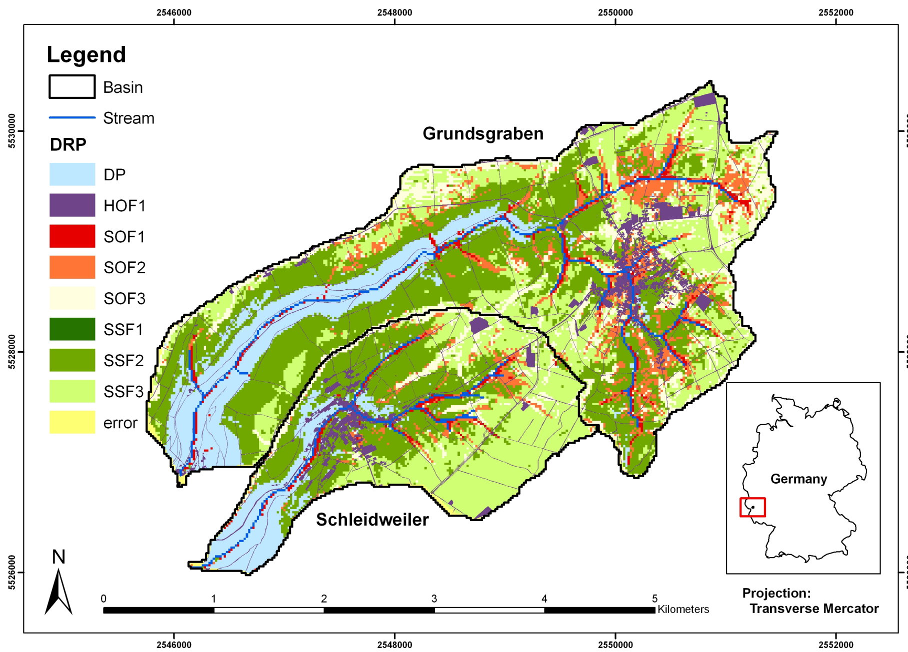

Fig. 4b. CDA-DRP map of the dominating runoff processes for the Zemmer subbasins Grundsgraben and Schleidweiler.

classified as D_{SSF3}. The latter mix up of classifications was contributed to the topographical index, which was within the determinant factor combinations of the mentioned DRP. The weak classification of D_{SOF1} was the result of an unspecified combination of all the topographical factors. This was caused due to the fact that the determination of D_{SOF1}, mainly occurring in the riparian zone and thalwegs, for the reference map was done by observational means (aerial photography and during the drilling campaign). CDA-DRP cannot use this information by default and therefore gives a bad performance regarding this process. Furthermore, 32% of the D_{SOF3} area classified with CDA-DRP turned out to be D_{SSF3} according

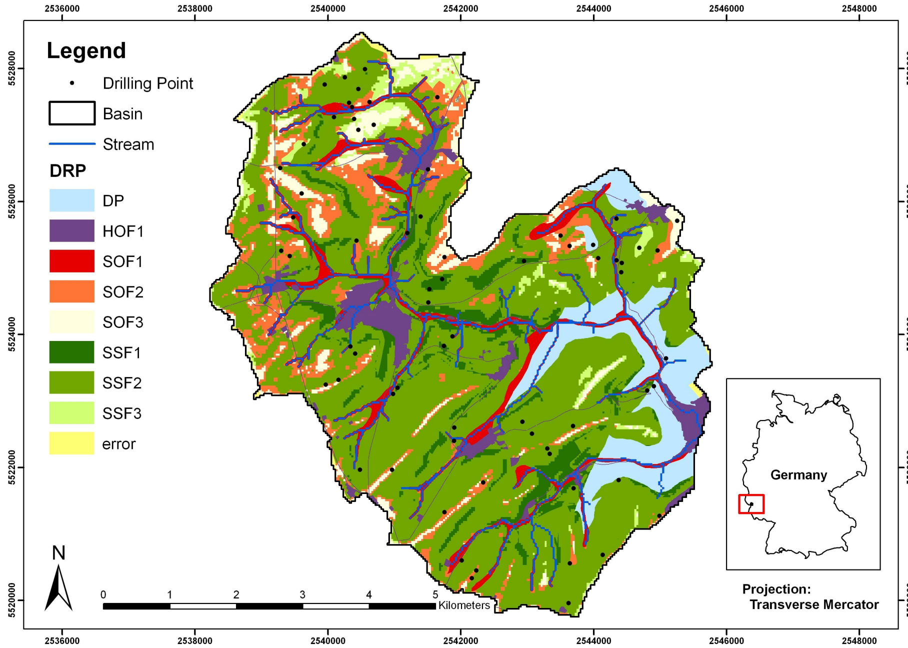

Fig. 5a. GIS-DRP map of the dominating runoff processes for the meso-scale Welschbillig basin.

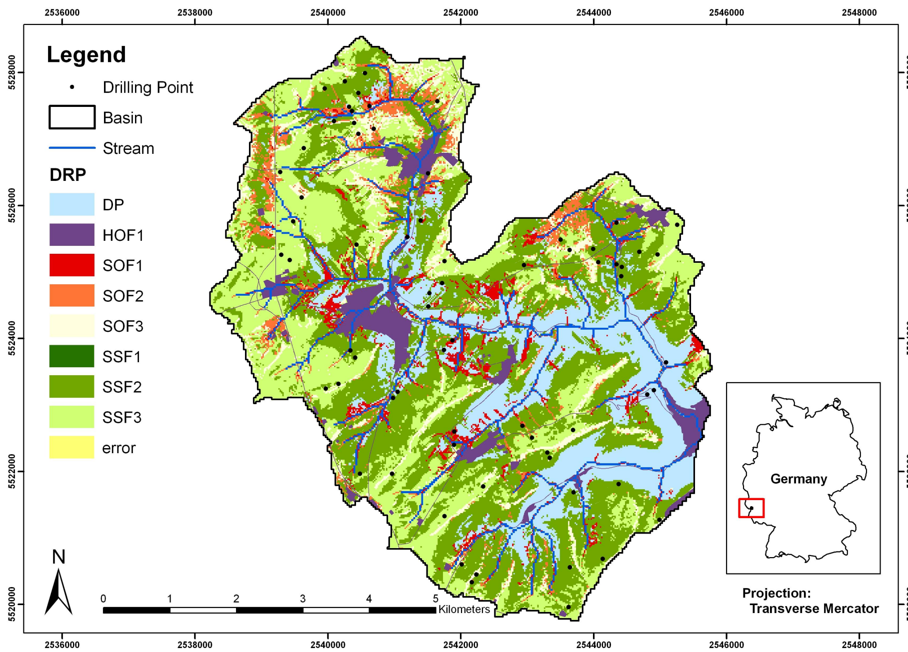

Fig. 5b. CDA-DRP map of the dominating runoff processes for the meso-scale Welschbillig basin.

to the reference map. Here again, the topographic index was the determining factor for the mix up of DRP areas. The last process that showed a considerable classification mistake was D_{SSF2}, 29% of its area was confounded with D_{SSF3}.

4.3 Quality control of GIS-DRP and CDA-DRP

Figure 5a shows the results of the GIS-DRP map of the meso-scale Welschbillig basin. Percentages of the respective processes obtained by means of the GIS-DRP map are listed in Table 3. Of the GIS-DRP-areas 81% gives a corresponding fit to the mapped DRP, which have been determined during a field campaign according to the decision schemes of Scherrer (2006). As for the micro-scale Zemmer basin the main DRP occurring is D_{SSF2} (54%). Furthermore, the processes are spatially clearly divided, D_{DP} is only found at the eastern part of the basin, while in the northern part the incidence of $D_{SOF1,2,3}$ increases compared to the southern part. Of the 19% wrongly classified DRP, 12% was due to a false attribution of process intensity within the subsurface flow and saturated overland flow process groups (e.g. D_{SOF3} into D_{SOF2} and D_{SSF2} into D_{SSF3}). The remaining 7% of the wrongly classified DRP was attributed to a mix-up of D_{SOF3} instead of D_{SSF2} (6%) and of D_{DP} instead of D_{SOF2}(1%). The first kind of error is considered by Naef et al. (2007a) as not so grave and can be attributed to differences in the accuracy of the calculation of slope based on the available DEM and the field observations. The latter kind of errors is regarded to be grave. However, as for the micro-scale Zemmer basin, this could be attributed to the low resolution of the available geological map.

Figure 5b shows the results of the CDA-DRP map of the meso-scale Welschbillig basin and gives a 68% corresponding fit to the mapped DRP. Percentages of the respective processes obtained by means of the CDA-DRP map are listed in Table 3. D_{DP} (17%) was identified mainly in the eastern part of the basin and on those areas that have steep slopes, whereas D_{SSF3} (24%) was found mainly on the higher planes. The mid slope areas in between are classified mainly with D_{SSF2} (35%). As with the micro-scale Zemmer basin, a mix of DRP occurred in the Welschbillig basin. The wrongly classified 32% could mainly be attributed to mistaking the saturated overland flow process with the subsurface flow process. The consequent mistaking of one DRP for another through the application of CDA-DRP could be attributed to a low occurrence of some of the DRP on the impermeable substratum (e.g. 0% for D_{SSF1}; 5% for D_{SOF1}; 6% D_{SSF3}) in the training basin. This puts a considerable constraint on the statistical analysis since there were simply not enough differentiated training data for an optimal analysis.

5 Discussion

Although a basin of 14 km^2 was available with a very detailed map of DRP, not enough training data were on hand for appropriate statistical analysis, which indicated a major setback of CDA-DRP compared to GIS-DRP when the former approach was applied in the Welschbillig meso-scale basin. Clearly, GIS-DRP is preferred to CDA-DRP when accuracy, data input and calculation time are concerned.

GIS-DRP provides acceptable results without making use of detailed and numerous data sources mandatory for the application of the method of Scherrer and Naef (2003) and Scherrer (2006). It is therefore less time consuming and very well suited to be applied not only in micro-scale basin but also in meso-scale basins. However, when enough data is available, the method of Scherrer and Naef (2003) and Scherrer (2006) is still preferred to the GIS-DRP method in the lower micro-scale or at the plot scale, since it provides much more detailed results. Facing a mapping exercise at the meso-scale, more often than not, the basin area is not covered entirely with the necessary information to apply the method of Scherrer and Naef (2003) and Scherrer (2006). A literal application of this method at this scale becomes then difficult; GIS-DRP could serve as an alternative at this scale for delineating DRP.

The results of Schmocker-Fackel et al. (2007) showed that at 67% of their study sites (2 basins; 1.7 km^2 and 2.1 km^2 respectively), the automatically determined processes agreed with the results of the detailed examination of the soil and the sprinkling experiment data. For 31%, either the process (24%) or the storage class (7%) were correct. In only one case did both process and storage class differ. Problems occurred mainly in the differentiation between the saturated overland flow process and the subsurface flow processes. GIS-DRP gave similar results concerning the performance and error sources. However, GIS-DRP has an advantage compared to the approach of Schmocker-Fackel et al. (2007), since they still need soil maps with a scale of 1:5 000 to obtain results.

Peschke et al. (1999a) developed the WBS-Flab-System (equipollent XPS-System, Peschke et al., 1999b) to delineate dominant runoff processes at micro- and meso-scale basins. Basically, this approach and GIS-DRP are similar in their results (DRP – even though different specifications of DRP are given), but, as for Schmocker-Fackel et al. (2007), detailed information about soils are taken into account in the WBS-Flab/XPS-System (Peschke et al., 1999a, b). The approach of Tilch et al. (2002, 2006) was developed for areas with the same slope genesis (Tilch et al., 2002, 2006). Based on the genesis of the hillslope material a regionalization approach was developed which delineates the spatial structure and the lithological variance of the quaternary drift covers. Therefore this approach has a limited application character (Tilch et al., 2006). GIS-DRP was developed in a middle mountain region in western Germany, where among land use and topography the permeability of the substratum served as input parameters. This information can be easily obtained in other regions as well and therefore, in principle GIS-DRP can be applied. However, a field campaign remains necessary to check results and thus the regionalization potential of GIS-DRP is object of further study. Regarding the British HOST classification systems (Boorman et al., 1995), among pedotransfer functions in combination with soil maps, discharge data is needed to obtain its 29 classes. This is major point in which HOST differs from GIS-DRP, since the latter cannot use discharge data to confirm results. However, when discharge data is lacking GIS-DRP is still applicable.

6 Conclusions

The objective of this study was to identify dominant runoff processes with a respect to regionalization. Two approaches were developed and their results compared to an existing dominant runoff processes reference map of a micro-scale basin and pointwise to reference points in a meso-scale basin. The first approach (GIS-DRP) constituted the emulation of a simplified derivation of runoff processes, using a modified approach of evaluating permeability of substratum in combination with slope and land use classification. The second approach (CDA-DRP) used the derivatives of a DEM as variables defining the different dominating runoff process areas. For this purpose, a canonical discriminant analysis was used to build the model for derivation of homogeneous process areas.

GIS-DRP was able to specify the DRP for the experimental micro-scale Zemmer basin with an acceptable level of accuracy. Furthermore, when GIS-DRP was applied in a meso-scale basin for quality control purposes, the level accuracy remained the same and no methodological errors were detected. This indicated that GIS-DRP could very well be used as an alternative to extensive measurement campaigns in order to define dominant runoff processes. The remaining uncertainties were attributed to the low resolution of the DEM, the coarseness of the geological map and the misinterpretation of the deep percolation process (D_{DP}) and the saturated overland flow process (D_{SOF1}) in the riparian zone. Therefore, the accuracy of GIS-DRP may deteriorate with decreasing detail of DEMs and geological maps.

CDA-DRP showed clearly a strong dependency of the generated DRP on the topography of the Zemmer basin, but gave a lower performance than GIS-DRP when its results were compared to the reference map. The error source of CDA-DRP was the wrong classification of DRP when its results were compared to the reference map. When CDA-DRP was applied to a meso-scale basin the performance remained low. An adaptation of CDA-DRP to obtain better results was not possible due to a lack of enough training data. Since some parts of the training data were obtained by field surveys and expert knowledge systematic errors when using CDA-DRP were unavoidable. Therefore, CDA-DRP turned out to be not very suited for regionalization purposes.

Summarizing, the first approach (GIS-DRP) is preferred to the second approach (CDA-DRP) when accuracy, data input and calculation time are concerned. It is the fastest method with an acceptable accuracy. Training errors are avoided in the GIS-DRP-approach, since it does not use any statistical operations. This approach could serve well as an addition to the method of Scherrer and Naef (2003) and Scherrer (2006) to identify dominant runoff processes in micro and meso-scale basins, especially in those areas where necessary information (e.g. soil maps, soil profiles), is lacking. However, small field campaigns according to the method of Scherrer and Naef (2003) and Scherrer (2006) will always be necessary for verifying the results when the GIS-DRP-approach is applied. The magnitude of such a field campaign stands in no proportion to the amount of field data necessary when applying the method of Scherrer and Naef (2003) and Scherrer (2006). The obtained dominant runoff processes maps by means of GIS-DRP could conversely be used for modelling purposes, either to delineate the manifestation of certain soil properties in a distributed way, or to adapt model concepts. This remains the subject of further study.

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