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Prioritizing Small-Scale Water Retention Measures Through Spatial Differentiation of Dominant Runoff Processes

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Abstract

In order to mitigate the negative effects of heavy rainfall events, natural water retention measures (NWRM)—such as hedges, erosion control strips, vegetated drainage channels, wooded strips, retention basins and ditch pockets—have gained renewed attention as an effective climate adaptation strategy. To identify potential areas for NWRM, this study applied and methodologically expanded an existing approach for identifying dominant runoff processes (DRPs) to an agricultural sub-catchment in the Weserbergland region of Germany. The DRP were determined using a Geographic Information System (GIS) and validated through field surveys. Potential areas for water retention within the same runoff process classes were identified for three defined objectives: improving infiltration, extending flow paths, and redirecting runoff to surrounding areas. Spatial differentiation was achieved using accumulated catchment area and overland flow distance. The watershed is predominantly characterized by surface runoff (Hortonian Overland Flow). Field validation confirmed the DRP classification for around two-thirds of the study area, with deviations occurring predominantly on arable land. Supplementing the DRP approach with a topographic analysis allowed for further differentiation, focusing on small, topographically defined sub-watersheds. The identified areas offer significant potential for interventions. Combined with supplementary data, analyses of the water network and the involvement of local stakeholders, the resulting potential map provides a solid basis for planning smaller-scale water retention measures.

Keywords: climate adaptation; dominant runoff process; geographic information systems (GIS); natural water retention measures (NWRMs); spatial prioritization; decision support

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Academic Editor: Andrea Petroselli

Received: 16 June 2026
Revised: 9 July 2026
Accepted: 20 July 2026
Published: 22 July 2026

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1. Introduction

As a result of global warming, significant changes in extreme weather events are to be expected [1]. This is also linked to the assumption that there will be an increase in heavy rainfall events in the future [2–4]. Heavy rainfall events lead to rapidly rising water levels and, consequently, flooding, mass movements and soil erosion. These are also known as pluvial floods, as they can occur far from streams [5]. Flooding caused by heavy rain has the potential to cause significant damage. Under unfavorable conditions, flash floods might even occur. However, the potential risk must be assessed on a case-by-case basis, taking into account precipitation patterns, topography, and land use [6].

Whilst damage in built-up areas mainly affects buildings and infrastructure, in agriculture, heavy rainfall events primarily result in crop failures [7]. Furthermore, soil erosion is also exacerbated by heavy rainfall events [8]. In the context of agriculture, this results in the erosion of fertile soil, accompanied by the loss of nutrients and humus. Furthermore, the soil is deposited elsewhere, where it usually has to be removed at considerable cost. The flooding caused by heavy rainfall is not confined to watercourses but also occurs on slopes. Conventional flood protection measures may therefore prove ineffective in some circumstances, and protection strategies cannot be directly applied. This raises two overarching questions for decision-makers: (1) what measures should be taken to reduce the risk of pluvial flooding and flash floods, and (2) where the optimal locations for preventive measures are.

With regard to preventive measures, approaches aimed at predicting events more accurately have been further developed [9–11]. In addition, contingency plans were evaluated [12–14]. In urban areas, nature-based solutions (NbS) for rainwater management have increasingly come into focus and their use and effectiveness are examined in detail in the context of climate change adaptation [15–18]. NbS is an "umbrella term" that encompasses approaches such as ecosystem-based disaster risk reduction and ecosystem-based management [19,20]. The agricultural and forestry sectors are also addressing the question of how water retention across the landscape can be promoted [21,22] and a wide range of guidance documents and measure catalogues are now available [23,24]. Complementary to these preventive and management-oriented approaches, other studies have focused on understanding the underlying causes and mechanisms of such events. As an example, past events in Braunsbach were analyzed to better understand their origins, mechanisms, and progression [25].

Various studies have also addressed the question of where the optimal locations for interventions are. Multi-criteria analysis is often used, typically in combination with a Geographic Information System (GIS). A comprehensive overview of current spatial allocation optimization tools is provided in [26], and further approaches can be found in [27–29]. Overall, it can be said that GIS-based multi-criteria analyses primarily focus on urban areas [30]. The approach taken in [31] is an exception, where the authors have developed a GIS-based framework for the systematic identification and selection of NbS at the catchment level. The analysis was conducted on a regional scale; it therefore serves primarily as a basis for strategic prioritization rather than as concrete planning support at the mesoscale.

In contrast to the multi-criteria approach, other methods combine hydrological models with an optimization process. In Belgium, a study assessed how strongly individual sites influence total downstream runoff under different land use changes and rainfall events [32]. However, changes in land use are associated with a significant demand for land, which depends strongly on the specific measure and local conditions. This poses a practical challenge, as documented for large-scale flood retention measures in Germany [33]. Given the increasing competition for land, implementing such measures involves a high level of resource use. Small-scale measures—such as hedges, erosion control strips, vegetated drainage channels, wooded strips, retention basins and ditch pockets, often grouped under the term NWRM [34]—require significantly less land and have therefore been the focus of various studies [30,35].

However, the use of models to evaluate such measures is subject to important limitations. First, model calibration and validation typically rely on discharge data, which are often unavailable in small or landlocked catchments, increasing uncertainty in model-based assessments. Second, spatially explicit modelling of small-scale measures remains challenging: models such as SWAT represent runoff response using Hydrological Response Units

(HRUs), defined based on land use, soil type and slope class [36], while approaches such as the Curve Number method estimate runoff-effective precipitation from hydrological soil groups and land use [37]. Since HRUs are not spatially delineated within the model itself, and since the choice of spatial units has been shown to influence results [38], these approaches offer only limited spatial resolution—a particular constraint when evaluating small-scale, site-specific measures.

For the reasons outlined above, an approach is being tested here that focuses more on site-specific criteria and high-resolution spatial data to identify suitable areas for small-scale measures appears to be appropriate. In Switzerland, an approach has been developed that examines the spatial heterogeneity of the runoff response in detail. This involves determining the dominant runoff process based on field data collection [39,40]. In addition to saturation runoff, the model also takes into account runoff generated by excess infiltration, as well as subsurface runoff in the form of intermediate runoff or deep percolation. In contrast to approaches such as HRUs, which group areas based on combinations of land use, soil type and slope class to parameterize a generic runoff calculation, this approach directly assigns dominant runoff process classes to individual areas, providing a more direct, process-based characterization of runoff generation. This provides a tool that, in principle, makes it possible to identify areas with favorable conditions for implementing water retention measures, based on information regarding the runoff response. Further developments have included the automation of process assessment using geodata for selected categories, namely prolonged rain and heavy rain [41,42]. However, this GIS-based assessment of runoff process types is carried out in isolation from the location within the catchment area. Furthermore, if the contiguous sub-areas for the same runoff process types become too large, there is no subdivision or prioritization within these areas to enable them to be used as a basis for planning small-scale measures.

Existing approaches have demonstrated the value of multi-criteria analyses and hydrological models in identifying suitable areas for climate change adaptation measures. Whilst multi-criteria analyses tend to focus on urban areas, model-based simulations require calibration and validation using runoff data, which is often unavailable in small or non-runoff rural catchments. Furthermore, the spatial resolution of previous methods is frequently too coarse to adequately represent small-scale hydrological processes. Consequently, there is a lack of high-resolution, process-based approaches for small-scale measures that can be applied in rural areas and are supported by field validation.

The aim of this study is to apply and further develop the existing GIS-based approach for identifying dominant runoff process types from [42] in rural areas. With regard to the application, detailed field studies are being carried out based on the classification key from [43] in order to evaluate the reliability of the underlying classification of runoff processes and to assess the robustness of the GIS-based results. A further development involves supplementing the information regarding location in order to allow for small-scale differentiation within the same types of runoff processes. Location is taken into account via the parameters of the accumulated catchment area and the distance to the watercourse. The resulting potential map can serve as a basis for the spatially differentiated assessment of small-scale action options and is therefore suitable regardless of the uncertainties inherent in model-based approaches. The analysis is to be carried out using a sub-catchment area characterized by agriculture in the Weserbergland low mountain range region in Germany as an example. In the present study area, discharge data are unavailable, which limits the applicability of calibration-based hydrological models. This constitutes a key motivation for adopting the DRP approach, which does not require discharge data for model calibration or validation.

2. Materials and Methods

2.1. Study Area—Amelunxen

The study area Amelunxen is located in Germany, in the federal state of North Rhine-Westphalia (52.0° N, 7.7° E, WGS84). This is a small hydrological catchment area covering just under 8.7 km^2. The catchment drains into the Nethe, which in turn flows into the Weser. The location of the study area within Germany is shown in Figure 1. The area can be classified as part of the Weser-Leine Bergland natural region. Characteristic of this predominantly rural region is the varied alternation of agricultural basins and often steeply rising mountain ranges [44]. A large proportion of the steeper areas within the catchment area are covered by forest (26%) and are, for the most part, also used for forestry. The flatter slopes are used for agriculture, partly as grassland (18%), but a significantly larger proportion is used for arable farming (51%). The built-up area, or sealed surfaces, accounts for only a very small proportion (5%) An additional land use map of the study area is provided in Appendix A (Figure A1). In the catchment area under investigation, elevations of 300 m above mean sea level (MSL) are reached, dropping to approximately 100 m MSL at the valley floor, on the boundary with the built-up area.

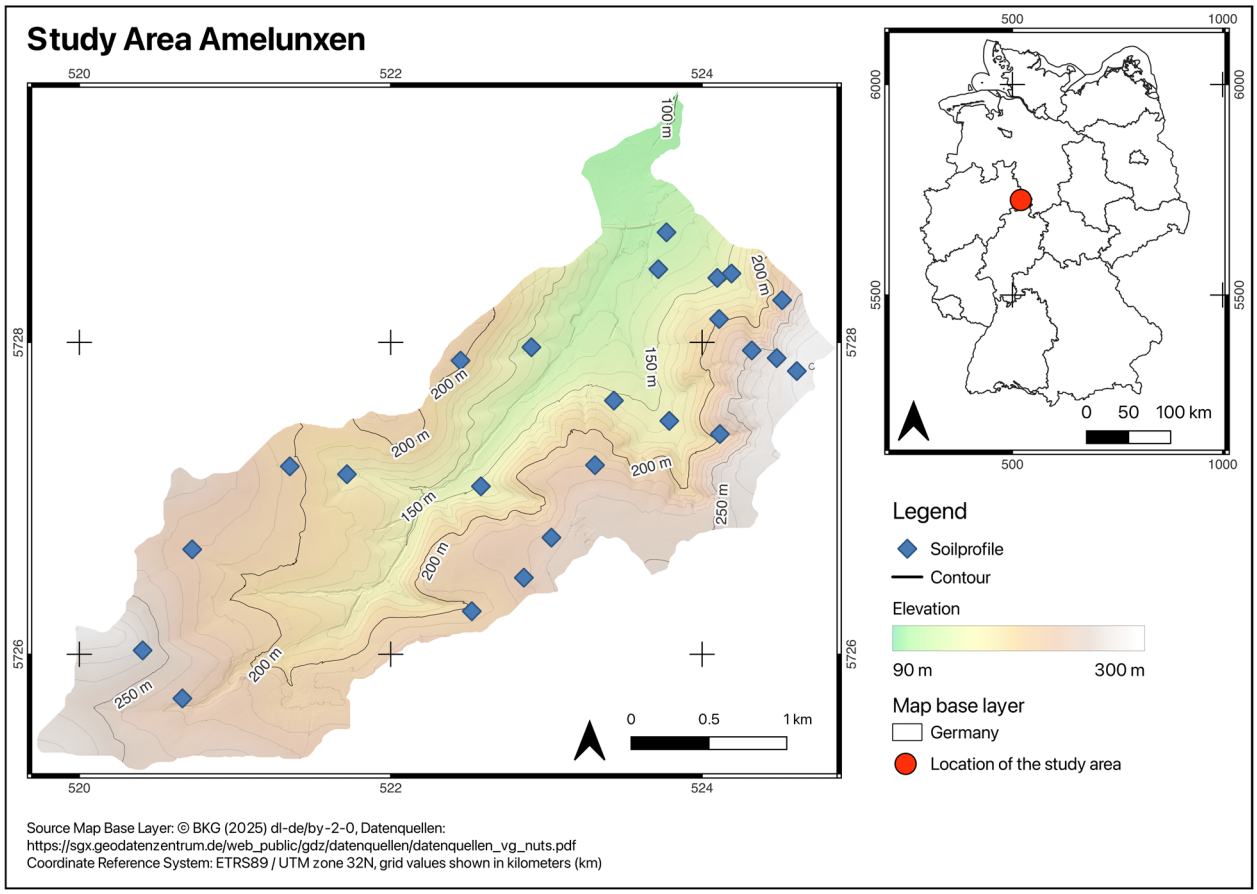


Figure 1. Study area: a small hydrological catchment area covering just under 8.7 km^2, located in Germany, in the federal state of North Rhine-Westphalia. The digital elevation model is shown with contour lines, supplemented by the sampling locations for the soilprofiles.

In the Leine-Weser Uplands, the grey limestones of the Muschelkalk often lie over the red-colored, mostly sandy rocks of the Buntsandstein. Loess, which was deposited by wind during the Pleistocene, can be found on the valley slopes [45]. In the built-up area, along the course of the Nethe, there are lower terraces (gravel and sand, slightly silty to clayey) alternating with alluvial deposits. The rugged Muschelkalk hills are classified

as edaphically arid, in accordance with the notes on the geological map. It is only the underlying red clay layers that form an impermeable base, which can lead to the formation of springs [46].

According to the German soil classification and World Reference Base for Soil Resources [47], brown forest soils (WBR: Cambisol), as well as shallow, calcareous soils over limestone (clayey–loamy; WRB: Rendzic Leptosols), shallow, humus-rich soils on calcareous loose or soft bedrock (clayey–silty; WRB: Rendzic Leptosols/ Calcaric Regosols) and soils influenced by groundwater (clayey–silty; WRB: Gleysols), have formed over the rocks of the Lower Muschelkalk bedrock. Despite their high clay content, *Rendzic Leptosols* and Rendzic Leptosols/Calcaric Regosols are often well aerated [48]. Fertile brown soils characterized by a well-developed clay-enriched argic horizon formed through the process of clay illuviation (clayey–silty; WRB: Luvisols) have formed from loess deposits. They are prone to silting due to the accumulation of fine particles in the leached topsoil, making them especially vulnerable to erosion on slopes [48]. In addition, there are colluvial soils (clayey–silty; WRB: Colluvic Regosols) formed as a result of soil cultivation; these are humus-rich soils that have been reworked by water. In the settlement area towards the Nethe, the Vega soil type (clayey–loamy; WRB: Fluvisols) has formed, which belongs to the category of alluvial soils. An additional soil map of the study area is provided in Appendix A (Figure A2).

Long-term average climate data is available for a weather station near the study area (name of the station: Bevern, Kr. Holzminden; Station ID: 2323). The average annual rainfall for the period 1981–2020 was 764 mm [49]. The long-term average annual temperature is 9.8 °C [50]. Heavy rainfall events in the study area have repeatedly led to slope runoff, causing erosion and flooding in the built-up area. In the northwest of the study area, there is a raised railway embankment that surrounds the built-up area. In the event of flooding caused by heavy rainfall, the railway embankment acts as a barrier. Two underpasses connect this critical backwater area with the residential area behind it.

2.2. Data

The analyses presented in this study were based on the following freely available geospatial datasets and were conducted using QGIS (version 3.34.3-Prizren) and SAGA GIS (version 9.8.1). All spatial datasets used in this study were clipped to the catchment boundary and used in their original resolution and coordinate system, without further resampling or reprojection.

- Geological map [51];
- Hydrogeological map [52];
- Soil map [53,54];
- Landcover [55];
- Digital terrain model [56];
- Digital orthophoto [57].

2.3. Methodological Framework

The overall methodological framework of this study is shown in Figure 2 and comprises three main steps: (i) GIS-supported identification of runoff process types, based on [42] (described in Section 2.4.1), (ii) validation using data collected in the field based on [43] (described in Section 2.4.2), and (iii) spatial differentiation within a runoff process type as the basis for creating a potential map for small-scale climate adaptation measures, specifying three focal areas or a combination of these (described in Section 2.5).

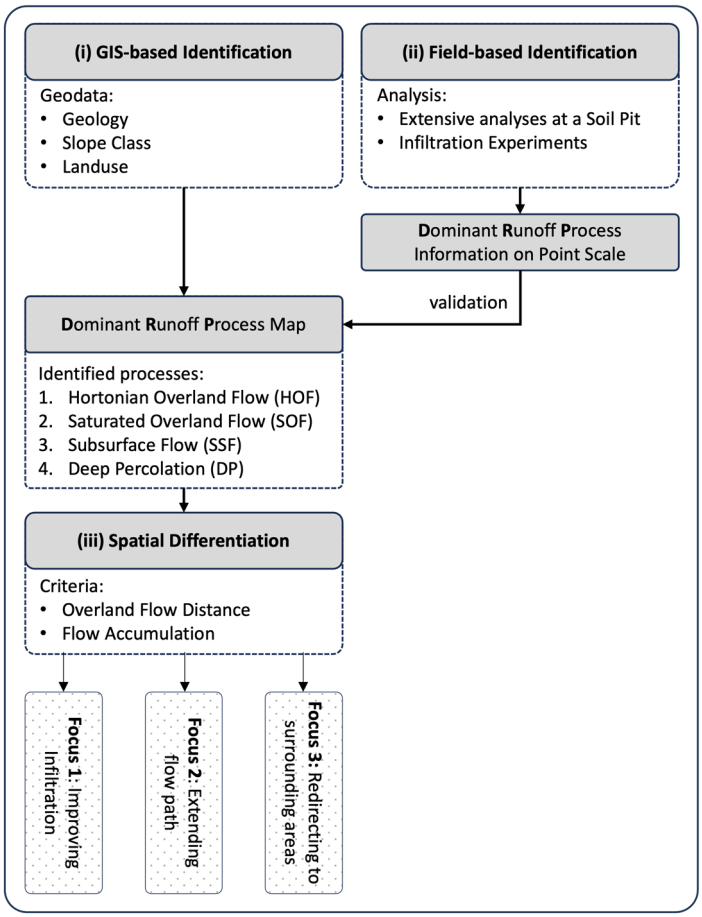


Figure 2. Methodological flow chart including the GIS-based and field-based identification of dominant process types and the spatial differentiation of these types, as a basis for creating a potential map for small-scale climate adaptation measures.

2.4. Identification of the Dominant Runoff Process

The classification of runoff process units and their respective intensity classes (Table 1) was developed by [40,43] on the basis of field trials. A distinction is made between four process types, each of which is further subdivided into intensity classes. This classification was originally developed in Switzerland and has since been applied in Switzerland [40,58] and in Rhineland-Palatinate (Germany) [41,59], suggesting a certain degree of transferability to Central European landscapes with comparable geomorphological and climatic conditions. Its applicability to regions with significantly different soil, relief or climatic characteristics has not yet been systematically tested and would require further validation based on field data from the respective region.

Table 1. Process units [43].

Process	Explanation	Runoff Intensity
HOF 1	Hortonian Overland Flow	immediately
HOF 2		slightly delayed
SOF 1	Saturated Overland Flow	immediately
SOF 2		delayed
SOF 3		significantly delayed
SSF 1	Subsurface Flow	fast
SSF 2		delayed
SSF 3		significantly delayed
DP	Deep Percolation	(directly into deeper soil layers)

2.4.1. GIS-Based Identification

The approach described in [42] was used to identify the DRP across the entire area. As a first step, the slope gradient was calculated as a percentage based on a digital elevation model [56], and classified into five slope gradient classes (0–3%, >3–5%, >5–20%, >20–40%, and >40%). In a second step, the geological subsurface was assessed for permeability. To this end, information on lithology was gathered based on the geological map [51], and permeability data was obtained from the hydrogeological map [52]. The following lithological units were classified as impermeable: calcareous marl and dolomite, silt, silt and clay, claystone to silty claystone, and sandstone. This assessment is consistent with the information from the hydrogeological map (classification for these areas: low to very low permeability). The following lithological units were classified as permeable: limestone, gravel and sand. In the hydrogeological map, these areas were rated as moderately to medium permeable. Land use was categorized into three classes: arable land, grassland, and forest. The slope gradient class, permeability class and land use category [55] were overlaid in the GIS and each unique combination of these three input layers was assigned a corresponding DRP value based on a purely combinatorial lookup table (Table 2), in which each unique combination of the three input layers corresponds to a specific DRP category. A DRP value could then be assigned to each site based on Table 2. The following additional assumptions were taken into account: built-up areas and sealed surfaces were assigned to category HOF 1. There is also a small stream within the catchment area. This stream and its banks were classified as SOF 1.

Table 2. GIS-DRP table extreme events [42].

Slope (%)	Impermeable Arable Land	Impermeable Grassland	Impermeable Forest	Permeable Arable Land	Permeable Grassland	Permeable Forest
0–3	HOF 2	SOF 2	SOF 2	HOF 2	SOF 2	DP
>3–5	HOF 2	SOF 2	SSF 2	HOF 2	SOF 2	DP
>5–20	HOF 2	SOF 2	SSF 1	HOF 2	SOF 2	DP
>20–40	HOF 1	SOF 1	SSF 1	HOF 1	SOF 1	DP
>40	HOF 1	SOF 1	SSF 1	HOF 1	SOF 1	DP

2.4.2. Field-Based Identification

The identification key from [43] was used to identify the DRP in the field. A key element of the assessment is the use of so-called process decision schemes (PDSs), for which various parameters must be recorded in the field. The general procedure for the assessment is shown in Figure 3 and described in detail below. To analyze the study area, the necessary baseline data was first compiled (see Figure 3). During an initial site inspection, potential representative areas were identified. These areas were first delineated using a GIS-based differentiation according to geology, soil type, land use, and slope class, resulting in zones of comparable characteristics. Within these zones, specific sites were then selected pragmatically in the field, taking into account practical constraints related to the infiltration experiments: sites were required to be at least 5 m from access paths—close enough to allow transport of the substantial amounts of water needed for the experiments, while avoiding disturbance from the path itself—and could not exceed a slope threshold beyond which the experiments could not be reliably conducted.

For the field study, relevant criteria for process assessment were recorded at each study site using a point scale, as shown in Figure 3. To this end, analyses were carried out on a soil pit and infiltration experiments were conducted. A key characteristic recorded via the soil pit was macroporosity (see Figure 4A). Field measurements focused exclusively on biogenic macropores. To this end, a horizontal soil section was exposed at three different

depths: Depth 1: 10 cm, Depth 2: 30 cm, and Depth 3: 50 cm. Care was taken to ensure the exposed areas were square with an edge length of 50 cm. The number of macropores was counted at each depth. Given that the influence on infiltration rate increases with macropore size, a distinction was made between macropores larger than 5 mm and those smaller than 5 mm. Other criteria relevant to the assessment included characteristics of the surface (hydrophobicity, surface roughness), the topsoil (soil matrix, susceptibility to silting, packing density), and the subsoil (plough pan, matrix permeability, thickness, lateral flow paths and drainage, impaction layers, compaction characteristics, compaction density). All criteria were determined in the field in accordance with the recommendations of [43]. The degree of hydrophobicity, for example, was determined using the water drop penetration time. The tendency to silt up was estimated via a wet sieving test. With regard to compaction density, a qualitative assessment of various texture characteristics was carried out at the soil pit. A detailed description of the various tests, as well as the classification relevant for further assessment, can be found in [43].

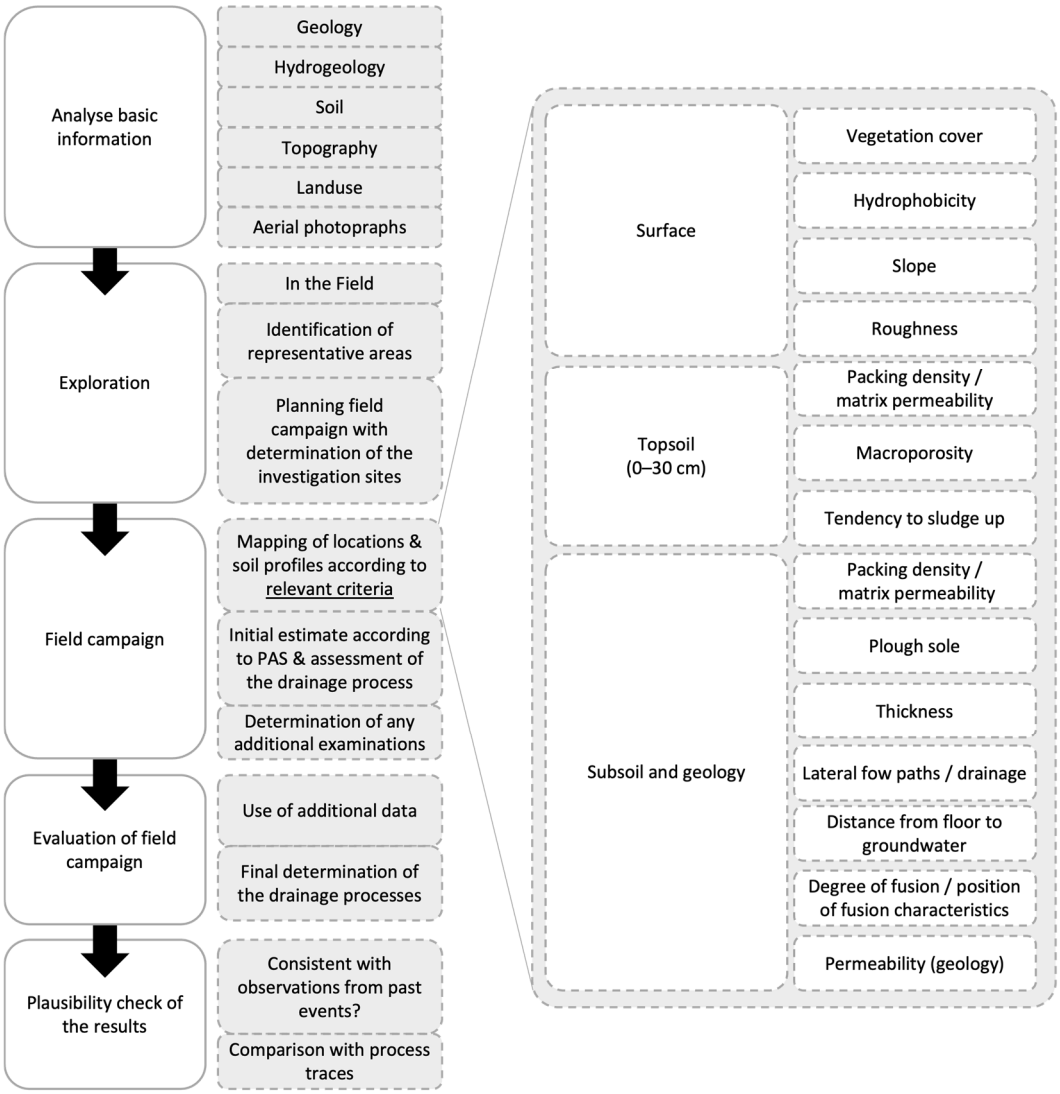


Figure 3. General procedure for applying the determination key for identifying areas relevant to flooding (own elaboration based on [43]).

The identification guide recommends carrying out additional infiltration experiments. For this purpose, double ring infiltrometers (Eijkelkamp Soil & Water B.V., Giesbeek, The Netherlands) were used (see Figure 4B). During the infiltration experiments, care was

taken to conduct three tests in parallel whenever possible. Measurement duration varied depending on how quickly a constant infiltration rate was reached, in some cases exceeding one hour. A measurement was deemed complete as soon as the infiltration rate had not changed by more than 10% compared to the previous value. This is to ensure that the value is constant and approaches the saturated permeability; soil saturation was thus implicitly assumed once this criterion was met, rather than ensured through a separate pre-wetting procedure. The resulting values were then compared with one another. Infiltration rates were classified according to DIN 18130-1, which assigns measured values to permeability categories ranging from weakly to highly permeable. A replicate was excluded when it fell into a distinctly different permeability category than the other replicates at the same site. An average value was calculated from the resulting value to represent the site. It should be noted that point-based field measurements, including both the soil profile data and the infiltration measurements, operate at a small spatial scale relative to the representative areas they are meant to characterize. Even within apparently homogeneous areas, soil and infiltration properties can vary substantially over short distances (e.g., due to macropores or local compaction).

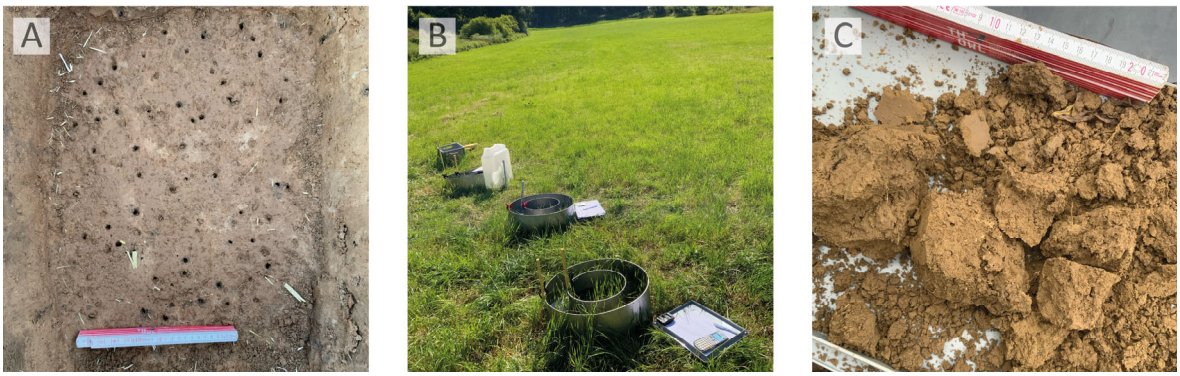


Figure 4. (**A**) Soil profile for analyzing macropores; (**B**) double-ring infiltrometer for determining the infiltration rate; (**C**) spade sample for analyzing soil aggregates.

This was followed by the evaluation of the field study. The process assessment schemes described in [43] were used for this purpose. The criteria collected in the field served as a structured decision-making aid along the respective decision trees. In a final step, the results were checked for plausibility. Essentially, this involved a comparison with the results of the infiltration experiments, supplemented by process observations made on-site following heavy rainfall.

The results from the field survey were used to validate the results of the GIS-based mapping. Spatial agreement was quantified using absolute concordance for all 24 study sites. To this end, the number of sites where the field and GIS classifications were identical was counted. The result is expressed as a percentage. In addition, the spatial distribution of the discrepancies was also taken into account: do the field and GIS classifications differ by one intensity level (e.g., SSF 2 vs. SSF 3) or by an entire process type class (e.g., SSF vs. SOF)?

2.5. Spatial Differentiation

2.5.1. Derivation of the Location Within the Catchment Area

Specific Catchment Area Size

In SAGA GIS, the first step was to fill the depressions in the digital elevation model. Flow accumulation was then determined for each cell using the D8 method [60]. The D8 method was chosen because it assigns flow to a single downslope direction, which is appropriate for representing the maximum-flow scenario relevant to heavy rainfall

events. In addition, the study area is characterized by high relief energy and few flat areas, conditions under which single-flow-direction algorithms such as D8 tend to yield more realistic results than multiple-flow-direction algorithms (e.g., D-Infinity or MFD), which offer greater advantages in flatter terrain. The range of values in the resulting raster was simplified using seven classes. As the frequency distribution is strongly right-skewed, a logarithmic classification was chosen. This approach ensures that each order of magnitude—corresponding to different hydrological process areas ranging from diffuse slope runoff (lowest classes) to concentrated channel runoff (highest classes)—is represented as a separate class. The value ranges can be found in Table 3.

Table 3. Classification of flow accumulation.

Class	Value Range (m^2)
1	1–10
2	>10–100
3	>100–1000
4	>1000–10,000
5	>10,000–100,000
6	>100,000–1,000,000
7	>1,000,000–10,000,000

Overland Flow Distance

The 'Overland Flow Distance to Channel' tool in SAGA GIS was used to determine the distance to the channel. Rather than selecting the lowest point in the catchment as the target outlet, a central channel was calculated (Method D8, threshold value 1,000,000). As the railway embankment in the northeast of the catchment area also constitutes a central barrier in the direction of flow, it was additionally defined as a target outlet. This decision reflects the hydrological consideration that the effectiveness of small-scale water retention measures depends primarily on their proximity to the receiving water body—in this case, the railway embankment—regardless of the size of the catchment area. Classes with a width of 500 m were applied, resulting in six classes covering the entire range of distances observed in the study area (0–2698 m) (see Table 4).

Table 4. Classification of overland flow distance to channel.

Class	Value Range (m)
1	0–500
2	>500–1000
3	>1000–1500
4	>1500–2000
5	>2000–2500
6	>2500–3000

2.5.2. Definition of Spatial Assessment Units

To enable spatial differentiation, a polygon vector layer with a regular grid of hexagons was generated in order to standardize the assessment units. The hexagons have an area of approximately 1000 m^2. This resolution was chosen as a compromise between the representation of small-scale runoff processes and the practical implementation scale of adaptation measures such as hedges, small retention basins, and vegetated drainage channels: at this size, hexagons typically encompass features such as field boundaries or access paths, making them a practicable spatial unit for planning such measures. This resolution was determined qualitatively, based on practical planning considerations rather

than a formal, literature-based derivation. The sensitivity of the results to the choice of hexagon size has not yet been systematically tested. The information on the dominant runoff process type, the specific catchment area and the distance to the channel was transferred to the hexagon grid using the Zone Statistics tool in QGIS. For the variables 'DRP' and 'distance to the channel', the resulting value within the hexagon was determined based on the largest overlapping area (Figure 5B). For flow accumulation, however, the maximum value was selected as the criterion (Figure 5C). The dominant runoff process type was also transferred to the hexagons. Here, too, the largest overlapping area led to the assignment (Figure 5D).

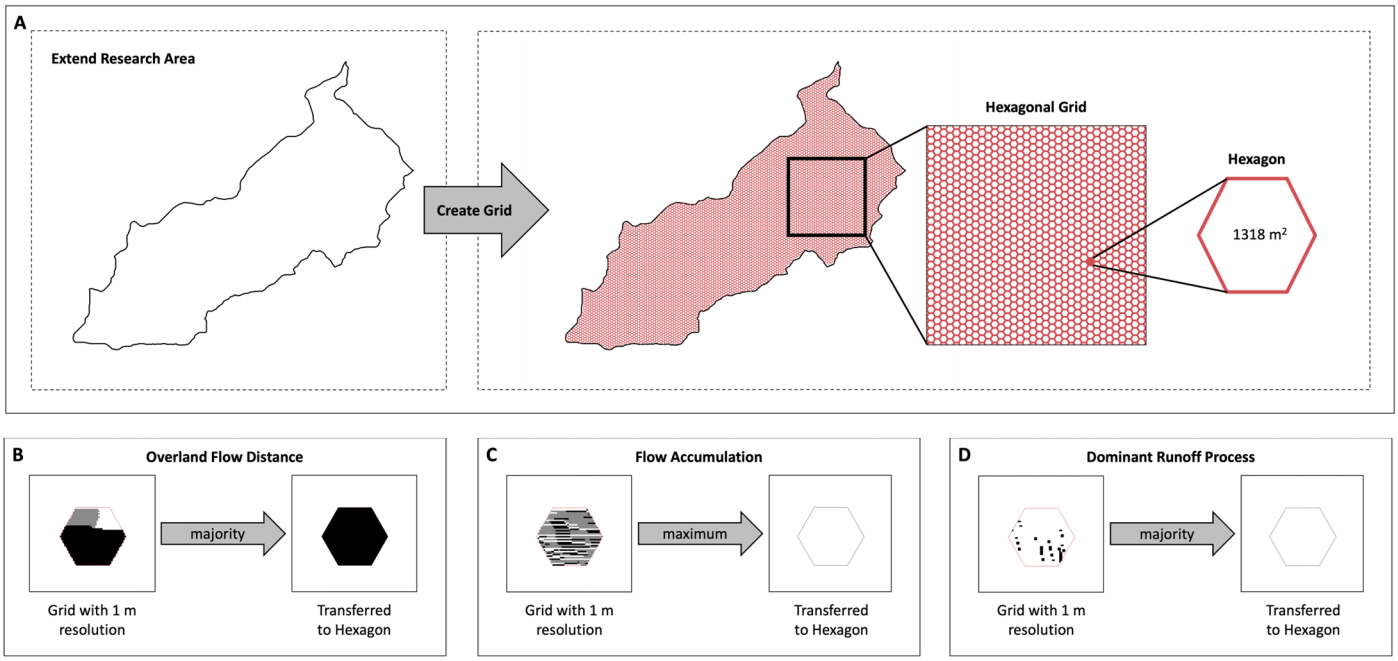


Figure 5. Schematic representation of the generation of reference areas using a hexagonal grid (**A**). (**B**–**D**) illustrate the procedure followed when transferring the target parameter data.

2.5.3. Combination of Criteria

As the focus is on water retention through small-scale measures, it is reasonable to consider only those types of runoff processes that also involve surface runoff (HOF and SOF at the respective intensity levels). Based on [61,62], three strategies for reducing flood peaks can be pursued, to which small-scale decentralized measures can contribute. Measures can be applied directly at the point of runoff generation and specifically aim to maximize the proportion of precipitation that is retained (1). Furthermore, the process of runoff concentration can be addressed (2). By extending the flow paths, a delay in surface runoff is achieved. Another option is the targeted diversion of runoff away from vulnerable areas. Based on concepts from [63,64], the strategy for identifying potential sites for small-scale water retention measures is to focus on topographically defined upper sub-catchments lacking upstream tributaries. These sub-catchments are independent runoff units within a catchment, where runoff is generated solely by local surface flow. Measures implemented within these units therefore have a direct effect on runoff generation before the runoff becomes concentrated through the confluence of several flow paths. A threshold value of 1000 m^2 has been chosen as an example to enable methodological operationalization. This is not a universal hydrological threshold. This results in specific combinations of distance from the channel and flow accumulation that are particularly relevant for small-scale measures and can be found in the Table 5.

Table 5. Focused strategies for identifying potential sites for small-scale water retention measures.

Focus	Goal	Flow Accumulation	Distance to Channel	Potential
Focus 1	Improving infiltration	≤1000 cells (class 1–3)	>1000 m (class 3–6)	measures to reduce surface runoff formation (e.g., activating or optimizing soil storage capacity)
Focus 2	Extending flow path	≤1000 cells (class 1–3)	≤1000 m (class 1 & 2)	measures to extend the flow path in order to delay the resulting surface runoff. This can be achieved both topographically (e.g., keyline design) and through the roughness of the terrain.
Focus 3	Redirecting to surrounding areas			Where hexagons dominated by surface runoff (HOF and SOF) border areas where interflow or deep percolation is more likely to occur, there is potential to divert the water accordingly.

The assignment of measure types to the two Focus categories follows a process-based rationale that combines two criteria: the size of the accumulated contributing area and the distance to the nearest watercourse. Both categories are defined for locations with a small accumulated contributing area (Class 1–3, ≤1000 accumulated cells), i.e., locations at which surface runoff is still locally generated and not yet substantially influenced by inflow from upstream areas. Within this group, the distance to the watercourse determines which stage of the runoff process is most effectively addressed by a given measure: for locations with a medium to large distance to the watercourse (Class 3–6, >1000 m; Focus 1), surface runoff has a comparatively long flow path before reaching the channel network. At these locations, measures aimed at improving infiltration and soil water storage capacity at or near the point of runoff generation (e.g., activating or optimizing soil storage capacity) are considered most effective, as they intervene before runoff can travel far enough to become relevant for downstream flooding. For locations with a short distance to the watercourse (Class 1–2, ≤1000 m; Focus 2), the short flow path limits the opportunity for infiltration-based measures to take effect before runoff reaches the channel. At these locations, measures that extend the effective flow path and thereby increase the time available for infiltration and attenuation—either through topographic design (e.g., keyline design) or through increased surface roughness—are therefore recommended instead.

3. Results

3.1. Spatial Distribution of Runoff Process Types (GIS-Based)

The GIS-based classification revealed that the majority of the area within the catchment under investigation are characterized by HOF 1 and HOF 2. HOF 2 predominates, accounting for 49% of the total area. Consequently, almost half of the entire catchment is characterized by slightly delayed surface runoff due to infiltration barriers, which occurs on unsealed surfaces. HOF 1 was found to account for 10% of the area, while the combined shares of SOF 1 and SOF 2 amount to 16% of the total area. This means that 75% of the catchment area is characterized by surface runoff. Deep percolation also accounts for a significant proportion of the area, at just over 20%. Only a very small proportion of the area was classified as intermediate runoff. For process class SSF 2, this amounts to just 0.1%. Overall, the proportion of areas leading to subsurface runoff is thus significantly lower than those where surface runoff is the predominant process. A breakdown of the area proportions is shown in Table 6.

Table 6. Area proportions of the calculated runoff processes.

Process	Area (m^2)	Area (%)
HOF 1	849,448	9.8
HOF 2	4,202,107	48.6
SOF 1	352,086	4.1
SOF 2	1,078,580	12.5
SSF 1	386,861	4.5
SSF 2	8479	0.1
DP	1,777,624	21.5
Sum	8,655,185	100.0

The spatial distribution of runoff processes (Figure 6) shows that the HOF 2 process type forms large contiguous areas. These are primarily fragmented by the road network. However, the road network itself is also classified as surface runoff due to barriers to infiltration (at intensity level HOF 1). In some cases, these are adjoined by areas with delayed saturation runoff (SOF 2). Surface runoff therefore not only dominates in terms of area coverage but also forms large contiguous areas within the catchment. The classification of the road network as HOF 1 is of particular relevance beyond its role in fragmenting the contiguous HOF 2 areas. As a largely sealed or compacted linear structure, the road network not only generates fast surface runoff itself but also acts as a preferential flow path that can collect and channel runoff from adjacent areas. This distinction may be relevant for stakeholder discussions, as measures addressing runoff from the road network may differ from those applied to the surrounding agricultural areas. Underground runoff processes, on the other hand, occur predominantly in the peripheral areas of the catchment. In particular, deep infiltration has been identified mainly on slopes and in the upper parts of the catchment area. The transition zones between surface and underground runoff processes are partly characterized by intermediate runoff, which also occurs along a stream course.

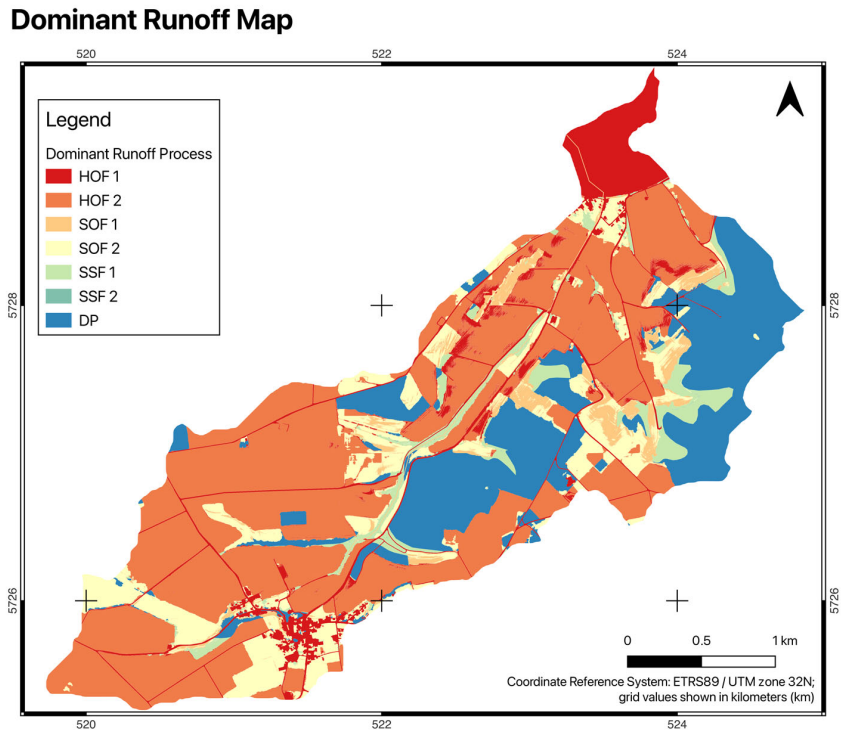


Figure 6. Dominant runoff map based on GIS analysis.

3.2. Identification and Validation of Discharge Process Types Based on Field Studies

Overall, the GIS-based identification matched the manual field method in approximately 67% of cases. A comparison of the GIS-based identification with the manual field method shows that the high permeability of certain areas was not correctly represented by the GIS-based approach in all cases. Instead, these areas were predominantly assigned a surface runoff type. On the upland areas of the catchment, for example, three arable sites were investigated (ID 12, 19, and 24) that consisted of particularly shallow soils over heavily weathered bedrock. The evaluation using the manual method yielded the process type DP for all three sites. The infiltration experiments also confirmed the very high permeability. However, the GIS-based assessment assigned all sites to category HOF 2. It was also found that the study sites in the forest were all located on very shallow soils. The permeability values were assessed as very high in the field experiments. However, the GIS-based categorization did not result in any misclassification in this regard. The corresponding comparison for all sites is shown in Table 7. In addition to the land use class, the table also includes the infiltration rate measured in the field and the corresponding infiltration category. The overall calculated degree of agreement is 67%. Incorrect classifications always spanned an entire process class and affected all three land use classes, with the lowest error rate observed in the forest class.

Table 7. Comparison of manually collected DRP data with GIS-based data.

Plot-ID	Landuse	Infiltration Rate (m/s)	Infiltration Category (DIN 18130-1)	Manual-DRP	GIS-DRP
1	arable land	2.86×10^{-5}	permeable	HOF 2	HOF 2
2	arable land	3.00×10^{-5}	permeable	HOF 2	HOF 2
3	arable land	1.03×10^{-5}	permeable	HOF 2	HOF 2
4	grassland	3.11×10^{-4}	highly permeable/permeable	DP	SOF 1
5	forest	1.67×10^{-3}	highly permeable	DP	DP
6	forest	8.33×10^{-4}	highly permeable/permeable	DP	DP
7	forest	1.50×10^{-3}	highly permeable	DP	DP
8	forest	5.00×10^{-4}	highly permeable/permeable	DP	DP
9	arable land	9.83×10^{-6}	permeable/slightly permeable	HOF 2	HOF 2
10	arable land	8.33×10^{-7}	slightly permeable	HOF 2	HOF 2
11	forest	1.50×10^{-3}	highly permeable	DP	SSF 1
12	arable land	2.83×10^{-4}	highly permeable/permeable	DP	HOF 2
13	arable land	2.56×10^{-5}	permeable	HOF 2	HOF 2
14	forest	2.00×10^{-4}	highly permeable/permeable	DP	DP
15	arable land	7.67×10^{-6}	permeable/slightly permeable	SSF 2	HOF 2
16	forest	1.05×10^{-3}	highly permeable	DP	DP
17	grassland	5.28×10^{-6}	permeable/slightly permeable	HOF 2	SOF 2
19	arable land	1.46×10^{-4}	highly permeable/permeable	DP	HOF 2
20	grassland	5.33×10^{-5}	permeable	DP	SOF 2
21	grassland	1.67×10^{-5}	permeable	SOF 2	SOF 2
22	arable land	3.33×10^{-6}	permeable/slightly permeable	HOF 2	HOF 2
23	grassland	2.50×10^{-5}	permeable	SOF 2	SOF 2
24	arable land	1.67×10^{-4}	highly permeable/permeable	DP	HOF 2
26	arable land	7.50×10^{-5}	permeable	HOF 2	HOF 2

3.3. Differentiation by Area Within the Same Runoff Process Types

In line with the previous findings, the HOF 2 runoff process type dominates the catchment area. Therefore, a spatially differentiated analysis within this same runoff process type was carried out as an example. The evaluation of combinations of distance from the channel and flow accumulation revealed that 34% of the hexagons were identified as potential areas. This corresponds to an area of just under 150,000 m^2, which is potentially suitable for small-scale measures. Most of these areas can be assigned to Focus 2 (extending flow path). Slightly fewer hexagons fall under Focus 1 (improving infiltration) and Focus 3 (redirecting to surrounding areas). Combinations of Focus 1 and Focus 3, as well as Focus 2 and Focus 3, were also identified. Some of these areas are located at a considerable distance from water bodies. In certain sections, they also occur in a linear pattern along water bodies. Overall, however, these areas are significantly less common in comparison.

Figure 7 shows that hexagons with Focus 1 occur predominantly in the southwestern and southeastern parts of the catchment area. Areas with the potential to extend the flow path are widely scattered along the defined channel. Notable are larger contiguous areas towards the northwest. These consist of relatively steep and short slopes used for arable farming. Hexagons assigned to Focus 3 are predominantly found along the stream course in the center of the catchment area. Further hexagons with Focus 3 can also be located at the edges of the catchment area towards the watershed, although there are significantly fewer than along the stream course. The adjacent hexagons in the 'underground discharge' category are not always located in the direction of flow, but rather upstream. All identified hexagons form both contiguous areas and occur in isolation. Where individual hexagons are located on agricultural land, no pattern regarding their position within field boundaries can be discerned. Contiguous areas usually form within field boundaries, though in a few exceptions they extend beyond them.

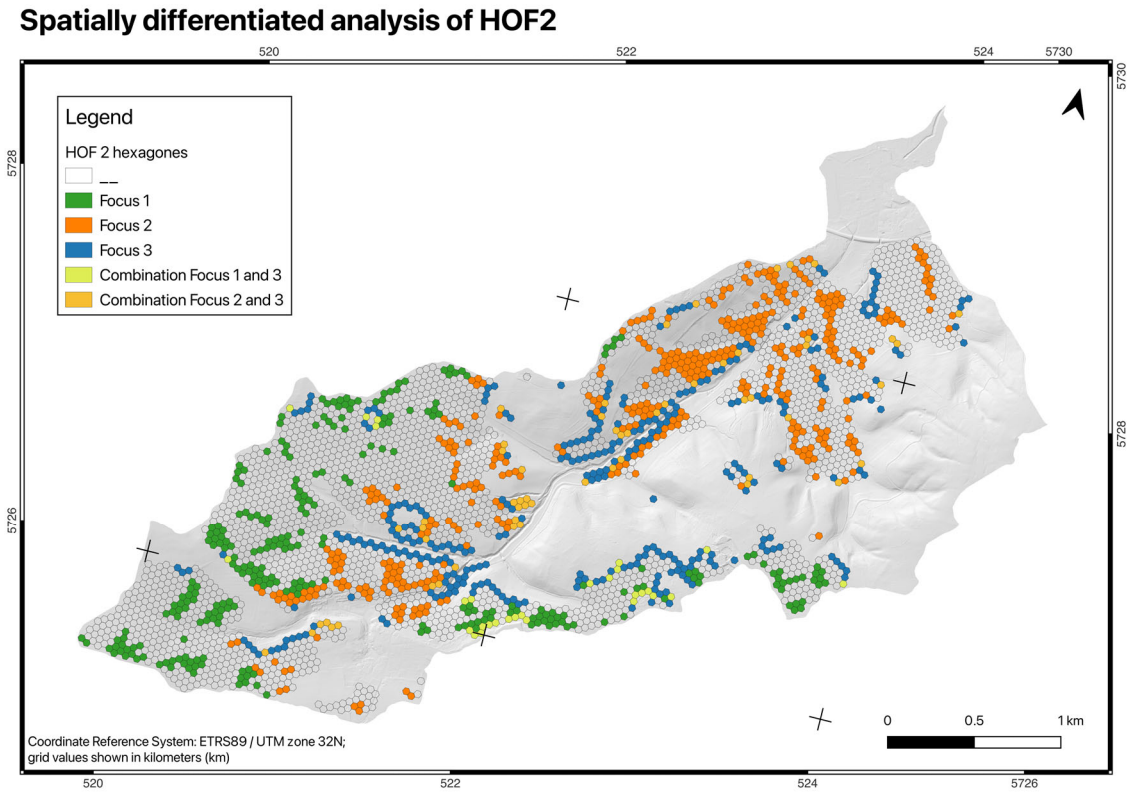


Figure 7. A spatially differentiated analysis of the dominant runoff process type HOF2 based on the parameters 'Flow Accumulation' and 'Overland Flow Distance to Channel'.

4. Discussion

The aim of this study was to apply and extend the GIS-based approach described in [42] for identifying dominant runoff process types in rural catchments. The results show that the methodology can be successfully applied to an agricultural sub-catchment in the Weserbergland region, while field validation in accordance with [43] largely confirmed the reliability of the underlying runoff process classification. Furthermore, the inclusion of site parameters—in particular the accumulated catchment area and the distance to the water network—proved effective in enabling small-scale differentiation within identical runoff process types. The resulting potential map provides a spatially differentiated planning basis, representing a practical step forward, particularly for identifying small-scale nature-based solution options. However, the interpretation of the map requires the integration of additional data sources as well as the involvement of local and relevant stakeholders.

To identify the DRP, the matrix developed in [42] was applied, which is essentially based on three parameters: land use, geological permeability, and a classification of slope gradients. It has become apparent that, due to this limited selection of parameters, the differentiation of process types is restricted. Accordingly, in line with the matrix, only HOF 1 or HOF 2 is assigned to agricultural land, which, given that the catchment area is predominantly used for arable farming, inevitably leads to a dominance of these process types. A similar pattern is evident for grassland areas, where a distinction is made only between SOF 1 and SOF 2. Overall, only a rough classification into a few process classes is carried out, particularly as the differentiation is based primarily on land use. This limited flexibility of the matrix means that the actual heterogeneity of the landscape is inadequately represented. This is supported by field studies, which have demonstrated high permeability at several arable sites, contradicting the assigned process classes. The study by [65] reaches a similar conclusion. The authors attributed this primarily to inaccurate or low-resolution input data, as well as simplifying assumptions. For arable land sites, this study also found that the GIS-based approach described in [42] is insufficient to capture heterogeneity. A large-scale meta-analysis of field data on the effects of land use on annual runoff and soil loss in Europe and the Mediterranean region has shown that arable land generally produces more runoff than, for example, grassland [66]. Similar findings have also been reported by [67], who conducted large-scale irrigation experiments to quantify runoff responses to extreme rainfall events on natural slopes.

The resulting DRP map allows for a preliminary assessment of the catchment's sensitivity to extreme rainfall events. Although almost half of the catchment is classified as exhibiting only slightly delayed surface runoff, this runoff response still constitutes surface runoff rather than infiltration or percolation. Taken together with the remaining catchment area, this indicates that the catchment reacts predominantly with surface runoff under extreme rainfall conditions, while only a comparatively small proportion of the area is characterized by deep percolation. Moreover, the areas dominated by deep percolation are primarily located near the catchment's watersheds, rather than, for example, upstream of the settlement area, where they could act in a protective capacity by attenuating runoff before it reaches areas at risk.

For the assessment of areas with potential, only the area classified as process class HOF 2 was analyzed. As this class consists exclusively of land used for agricultural purposes, both production-related measures (e.g., adapted sowing methods, the use of catch crops or modified tillage methods) and landscape-shaping measures are suitable options. A comparison with aerial photographs shows that, particularly in Focus 1, there are several contiguous hexagons that encompass larger sub-areas within individual field boundaries. Production-related measures appear particularly suitable for these areas. In a study in Iowa, catch crops were rated particularly positively in terms of water retention compared

to other best management practices [68]. According to a study from the Czech Republic, the majority of farmers recognize the importance of water retention and are willing to implement nature-based measures [69].

In some cases, hexagons containing designated areas of potential are located in the center of fields. Where fields are smaller, it may still be possible to develop sensible management strategies for these areas. However, as field size increases, the feasibility of targeted measures decreases, meaning that no practical approaches can be devised in such cases. Hexagons or clusters of hexagons along field boundaries are also of particular interest. These areas offer a wide range of development potential. Ditch systems often run along field boundaries, and it is possible to assess whether these could be converted into retention areas. In some cases, relevant data sets are available for certain areas; alternatively, the presence of a ditch system can be easily verified through field surveys. Regulated drainage can have a positive impact on reducing the risk of flooding and may even further improve the economic viability of agricultural holdings [62]. A study in Germany has found that the restoration of wetlands and the removal of artificial drainage systems in the headwaters of the catchment area leads to reduced peak flows during wet periods and higher base flows during dry periods [70]. Furthermore, these edge areas provide opportunities for creating field margins or increasing structural diversity, for example, by planting hedges. Such measures help to improve infiltration and extend flow paths by increasing surface roughness. The findings of the study in [71] show that planting hedges has the potential to help reduce the risk of flooding, with this effect being more pronounced and occurring more rapidly on well-drained soils than on poorly drained soils.

Areas where several focus categories overlap are considered particularly relevant for water retention. Of particular note is the combination of Focus 1 and Focus 3. These areas are located at a greater distance from water bodies and therefore offer favorable conditions for diverting rainwater through targeted measures and retaining it within the area. However, such combinations occur only sporadically. In contrast, there are areas from Focus 3 where suitable infiltration zones are located topographically above them, meaning that a targeted diversion of stormwater runoff cannot be practically implemented. Furthermore, in certain sections, linear arrangements of Focus 3 areas occur along watercourses. In these cases, diversion would be counterproductive, as it would further increase the flow towards the watercourse.

This rule-based site suitability analysis can be classified methodologically as falling between a Boolean overlay and a Multi-Criteria Decision Analysis (MCDA), as it combines elements of both approaches. In contrast to the Weighted Linear Combination (WLC), however, there is no continuous trade-off between criteria, but rather a discrete, rule-based classification. The approach is thus closer to the Boolean method, but offers a higher degree of differentiation than a purely binary assessment through the use of multi-level classes. At the same time, the method is subject to several limitations: it is highly static in nature and permits only qualitative statements, whilst event-related dynamics are not taken into account. Only in the GIS-based identification of the DRP is the focus on precipitation load indirectly set through the choice of classification table for heavy rainfall events. Furthermore, aggregation to hexagonal grid cells leads to several restrictions. Firstly, there is a loss of information regarding resolution. This is further compounded by the fact that the hexagon size (approximately 1000 m^2) was determined qualitatively, based on practical planning considerations, rather than derived from a systematic, literature-based analysis. While point-based field measurements (soil profiles and infiltration tests) served to validate the GIS-based process assessment rather than being directly aggregated to the hexagon scale, small-scale spatial heterogeneity may nonetheless be present within a single hexagon, and the sensitivity of the results to this choice of resolution has not yet been

systematically tested. Moreover, where hexagons overlap with actual field boundaries, meaningful intersections are sometimes not obtained. If, for example, a hexagon with high potential for improving infiltration is situated in the middle of a field, no targeted recommendations for measures can be made for it. Overall, this partially reduces the scope for action. Furthermore, relevant factors such as land ownership, actual land use and economic costs are not integrated into the analysis. A further limitation is the lack of formal method validation.

Key challenges in implementing climate change adaptation measures stem from inadequate legal and institutional frameworks. These include a lack of, or inconsistencies in, legal foundations; unclear responsibilities and division of roles; inadequate coordination mechanisms between the sectors involved; and differences in planning cultures [72]. A survey carried out in Austria shows that, at the local government level, the lack of financial and human resources, as well as a lack of specialist knowledge, is seen as a key challenge [73]. A similar assessment is also reached by [74]. In practice, therefore, decision making is often not based on a comprehensive analysis of the problem but is guided by existing approaches. These often stem from available funding schemes, experiences that can be applied in neighboring local authorities, or proposals from external planning and engineering firms. The approach presented in this study makes a direct contribution to supporting small local authorities in rural areas by providing a planning framework for small-scale measures—provided that the watersheds are of a similar nature. Potential sites are systematically identified and spatially delineated. This pre-selection makes the planning process more efficient, as subsequent steps, such as site visits or in-depth analyses, can be specifically limited to selected sub-areas of the catchment. In this way, the approach helps to conserve scarce resources and support decision making at the local level.

5. Conclusions

This study shows that the GIS-based approach to identifying dominant runoff processes can be successfully applied to an agricultural catchment in the Weserbergland region. Field validation largely confirms the classification, although deviations occur particularly on arable land; these are attributable to the limited selection of parameters in the underlying matrix. The best results were obtained for the forest landcover class. However, this classification was based on only five samples in total. If simplified assumptions are used to identify the DRP, the assessment will generally remain correct. Nevertheless, this remains a rough classification, that may require further refinement depending on the specific application. Further field studies should be conducted to better interpret these findings.

Overall, it becomes clear that concrete courses of action can only be identified once data are cross-referenced with supplementary sources, particularly aerial photographs. In addition, runoff path analyses provide important insights into potential runoff paths. However, in addition to topographic conditions and a potential analysis based on them, other factors—such as social interaction, financial resources, and institutional frameworks—also play a decisive role in the implementation of NWRMs [71]. On-site visits involving relevant stakeholders are therefore essential for developing site-specific solutions. It is clear that suitable water retention measures cannot be identified for all identified hexagons. Nevertheless, the potential map generally provides a valuable basis for further planning, dialogue with practitioners, and focusing on particularly relevant sub-areas for small-scale water retention measures. However, hydrological modeling is necessary to quantify the effectiveness of potential measures. Beyond its application within a single catchment, the presented framework may also serve as a basis for comparing spatial patterns of dominant runoff processes across different catchments, provided that the underlying classification is consistently applied and, where necessary, re-calibrated to local catchment characteristics.

Such comparisons could support catchment-scale assessments of vulnerability or resilience to extreme rainfall events.

For future GIS-based projects, it is recommended to include at least one soil map with the highest possible resolution in the analysis—one that shows, for example, the infiltration rate or the proportion of inorganic material in the soil. Furthermore, future work should conduct a sensitivity analysis regarding hexagon resolution, and examine its transferability to catchment areas with existing reference data. In addition, the proposed methodology should expand to include additional evaluation criteria in order to create a more holistic basis for decision making, for example, a linked analysis of the hexagons in relation to existing structures, since small-scale measures in the middle of large fields do not create meaningful synergies. Building on this, the development of a decision tree appears sensible, as it would systematically support and structure the selection of suitable measures. Furthermore, the underlying resolution of the hexagons was determined purely qualitatively in this study; therefore, a sensitivity analysis is required to investigate the influence of different resolutions and to identify an optimum. This could improve the robustness of the results. Future work should also examine the transferability of the approach to catchment areas with existing water retention structures or documented discharge measurements, in order to enable a systematic comparison of the GIS-based classification with independent reference data.

Author Contributions: Conceptualization, K.P.v.P.; methodology, K.P.v.P.; validation, K.P.v.P.; formal analysis, K.P.v.P.; investigation, K.P.v.P.; resources, K.P.v.P., C.M., K.M.; data curation, K.P.v.P.; writing—original draft preparation, K.P.v.P.; writing—review and editing, K.P.v.P., C.M., U.N., K.M.; visualization, K.P.v.P.; supervision, K.M., U.N. and C.M.; project administration, K.P.v.P. funding acquisition, K.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: TH OWL supports this tandem position in cooperation with Kreis Höxter to promote future professorial careers at Universities of Applied Sciences and Arts by resources of the PROFuture@TH-OWL project. This project is part of the 'FH Personal' funding line and supported by funds from the Federal Ministry of Research, Technology and Space (Bundesministerium für Forschung, Technologie und Raumfahrt—BMFTR) and the Joint Science Conference (Gemeinsame Wissenschaftskonferenz—GWK). During the preparation of this manuscript, the author(s) used ChatGPT (OpenAI, GPT-5.5) and Claude (Anthropic, claude.ai) to support literature exploration and the structural organization of the manuscript. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

NWRM	Natural Water Retention Measures
NBS	Nature-Based Solutions
DRP	Dominant Runoff Process
HRU	Hydrological Response Units
GIS	Geographic Information System
MSL	mean sea level

WRB	World Reference Base for Soil Resources
HOF 1	Hortonian Overland Flow, Intensity level 1
HOF 2	Hortonian Overland Flow, Intensity level 2
SOF 1	Saturated Overland Flow, Intensity level 1
SOF 2	Saturated Overland Flow, Intensity level 2
SOF 3	Saturated Overland Flow, Intensity level 3
SSF 1	Subsurface Flow, Intensity level 1
SSF 2	Subsurface Flow, Intensity level 2
SSF 3	Subsurface Flow, Intensity level 3
DP	Deep Percolation
PDS	process decision schemes

Appendix A

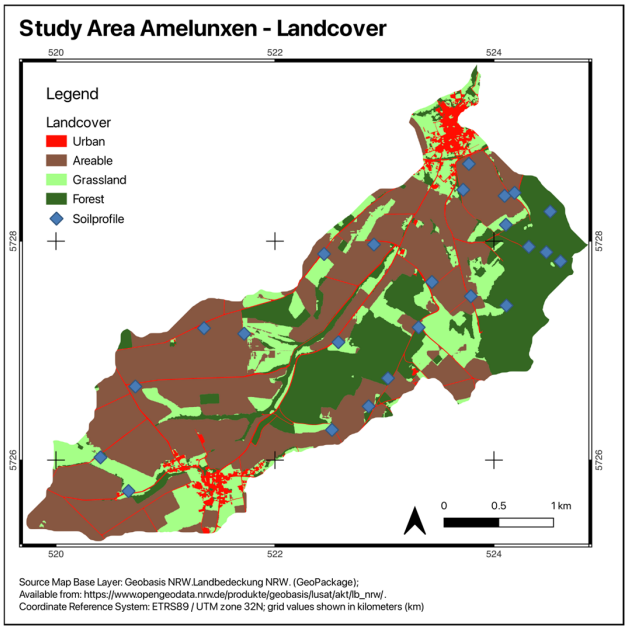


Figure A1. Landcover of the study area.

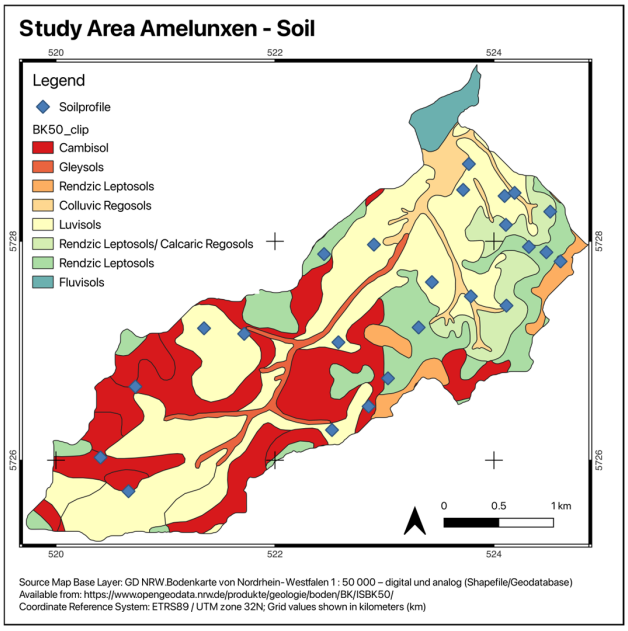


Figure A2. Soil map of the study area.

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