Hydraulic Shortcuts Increase the Connectivity of Arable Land Areas to Surface Waters

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Abstract

Surface runoff represents a major pathway for pesticide transport from agricultural areas to surface waters. The influence of man-made structures (e.g. roads, hedges, ditches) on surface runoff connectivity has been shown in various studies. In Switzerland, so-called hydraulic shortcuts (e.g. inlets and maintenance manholes of road or field storm drainage systems) have been shown to influence surface runoff connectivity and related pesticide transport. Their occurrence, and their influence on surface runoff and pesticide connectivity have however not been studied systematically.

To address that deficit, we randomly selected 20 study areas (average size = 3.5 km^2) throughout the Swiss plateau, representing arable cropping systems. We assessed shortcut occurrence in these study areas using three mapping methods: field mapping, drainage plans, and high-resolution aerial images. Surface runoff connectivity in the study areas was analysed using a 2x2 m digital elevation model and a multiple-flow algorithm. Parameter uncertainty affecting this analysis was addressed by a Monte Carlo simulation. With our approach, agricultural areas were divided into areas that are either directly connected to surface waters, indirectly (i.e. via hydraulic shortcuts), or not connected at all. Finally, the results of this connectivity analysis were scaled up to the national level using a regression model based on topographic descriptors and were then compared to an existing national connectivity model.

Inlets of the road storm drainage system were identified as the main shortcuts. On average, we found 0.84 inlets and a total of 2.0 manholes per hectare of agricultural land. In the study catchments between 43 and 74 % of the agricultural area is connected to surface waters via hydraulic shortcuts. On the national level, this fraction is similar and lies between 47 and 60 %. Considering our empirical observations led to shifts in estimated fractions of connected areas compared to the previous connectivity model. The differences were most pronounced in flat areas of river valleys.

These numbers suggest that transport through hydraulic shortcuts is an important pesticide flow path in a landscape where many engineered structures exist to drain excess water from fields and roads. However, this transport process is currently not considered in Swiss pesticide legislation and authorisation. Therefore, current regulations may fall short to address the full extent of the pesticide problem. However, independent measurements of water flow and pesticide transport to quantify the contribution of shortcuts and validating the model results are lacking. Overall, the findings highlight the relevance of better understanding the connectivity between fields and receiving waters and the underlying factors and physical structures in the landscape.

1. Introduction

Agriculture has been shown to be a major source for pesticide contamination of surface waters (Stehle and Schulz, 2015;Loague et al., 1998). Pesticides are known to pose a risk to aquatic organisms and to cause biodiversity losses in aquatic ecosystems (Malaj et al., 2014;Beketov et al., 2013). For implementing effective measures to protect surface waters from pesticide contamination, the relevant transport processes have to be understood.

Pesticides are lost to surface waters through various pathways from either point sources or diffuse sources. In current research, surface runoff (Holvoet et al., 2007;Larsbo et al., 2016;Lefrancq et al., 2017), preferential flow through macropores into the tile drainage system (Accinelli et al., 2002;Leu et al., 2004a;Reichenberger et al., 2007;Sandin et al., 2018), and spray drift (Carlsen et al., 2006;Schulz, 2001;Vischetti et al., 2008) are considered of major importance. Other diffuse pathways like leaching into groundwater and exfiltration into surface waters, atmospheric deposition or aeolian deposition are usually less important.

Past research showed that different catchment parts can largely differ in their contribution to the overall pollution of surface waters (Pionke et al., 1995;Leu et al., 2004b;Gomides Freitas et al., 2008). This is the case for soil erosion or phosphorus, but also for pesticides. Areas largely contributing to the overall pollution load are called critical source areas (CSAs). Models delineating such CSAs assume that those areas fulfill three conditions (Doppler et al., 2012): i) They represent a substance source (e.g. pesticides, soil, phosphorus), ii) they are connected to surface waters, and iii) they are hydrologically active (e.g. formation of surface runoff).

Linear landscape structures, such as hedges, ditches, tile drains, or roads have been shown to be important features for the connectivity within a catchment (Fiener et al., 2011;Rübel, 1999). Undrained roads were reported to intercept flow paths, to concentrate and accelerate runoff, and therefore also to influence pesticide connectivity within a catchment (Carluer and De Marsily, 2004;Dehotin et al., 2015;Heathwaite et al., 2005;Payraudeau et al., 2009). Additionally, Lefrancq et al. (2013) showed that undrained roads act as interceptor of spray drift, possibly leading to significant pesticide transport during subsequent rainfall events when intercepted pesticides are washed off the roads.

However, such linear structures and the related connectivity effects exhibit substantial regional differences due to natural conditions or various aspects of the farming systems. In contrast to other countries, many roads in agricultural areas in Switzerland are drained by stormwater drainage systems (Alder et al., 2015). Inlets of stormwater drainage systems are also found directly in fields (Doppler et al., 2012;Prasuhn and Grünig, 2001). Since those stormwater drainage systems were reported to shortcut surface runoff to surface waters, those structures were called *hydraulic shortcuts* or short-circuits. Doppler et al. (2012) showed in a small Swiss agricultural catchment that hydraulic shortcuts were creating connectivity of remote areas to surface waters and had a strong influence on pesticide transport. Only 4.4 % of the catchment area was connected directly to surface waters, while 23 % was connected indirectly (i.e. via hydraulic shortcuts). For the same catchment, Ammann et al. (2020) showed that the uncertainty of a pesticide transport model could be reduced by 30 % by including catchment-specific knowledge about hydraulic shortcuts and tile drainages.

The occurrence of hydraulic shortcuts and their influence on catchment connectivity has only been studied for a few other catchments in Switzerland. Prasuhn and Grünig (2001) found that only 3.2 % of the arable land in five small catchments were connected directly to surface waters, while 62 % were connected indirectly. Consequently, 90 % of the sediment lost to surface waters was transported through shortcuts.

To our knowledge, these two studies are the only ones systematically assessing the occurrence of hydraulic shortcuts and their influence on (sediment) connectivity. However, since these studies only covered a small total area in specific regions, it remains unknown if these findings are generally valid for Swiss agricultural areas.

Two other studies in Switzerland addressed connectivity on a larger scale using a modelling approach. Both indicated that more areas were connected through shortcuts than directly. Bug and Mosimann (2011) estimated 12.5 % of the arable land in the canton of Basel-Landschaft to be connected directly to surface waters, and 35 % to be connected indirectly. Later, Alder et al. (2015) created a national connectivity map of erosion risk areas. They estimated that 21 % of the agricultural area is connected directly to surface waters and 34 % indirectly. Since only for small areas the occurrence of hydraulic shortcuts was effectively known, generalizing assumptions on the occurrence of hydraulic shortcuts were made in both studies (e.g. classification of roads as drained by shortcuts or as undrained, based on their size). As also stated by Alder et al. (2015), these assumptions are a major source of uncertainty. Their influence on the estimated connectivity fractions remains unclear.

In summary, previous studies on hydraulic shortcuts were either restricted to small study areas in a specific region, or were based on generalizing assumptions, lacking a spatially explicit consideration of hydraulic shortcuts. This study aims for a systematic, spatially distributed, and representative assessment of hydraulic shortcut occurrence on Swiss agricultural areas. Based on this assessment we aim on quantifying the influence of hydraulic shortcuts on surface runoff connectivity and pesticide transport. Additionally, we aim on estimating how additional data on the occurrence of shortcuts influence the connectivity fractions reported by the existing national connectivity map. We focused our study on arable land, since this is the largest type of agricultural land with common pesticide application in Switzerland.

Our research questions therefore are:

1) How widespread do hydraulic shortcuts occur in Swiss arable land areas?
2) ~~What is their relevance for surface runoff connectivity and for surface-runoff related pesticide transport?~~What is the contribution of hydraulic shortcuts to surface runoff connectivity and what are potential implications for surface-runoff related pesticide transport?
3) How are additional data on the occurrence of shortcuts influencing the connectivity predictions at the national scale?

2. Material and Methods

2.1. Selection of study areas

We selected 20 study areas (Table 1) representing arable land in the Swiss plateau and the Jura mountains (Fig. 1). This selection was performed randomly on a nationwide small-scale topographical catchment dataset (BAFU, 2012). The probability of selection was proportional to the total area of arable land in the catchment as defined by the Swiss land use statistics (BFS, 2014). Random selection was performed using the pseudo-random number generator Mersenne Twister (Matsumoto and Nishimura, 1998).

On average, the study areas have a size of 3.5 km^2 and are covered by 59 % agricultural land. The agricultural land mainly consists of arable land (74 %) and meadows/pastures (21 %). The mean slope on agricultural land is 4.9 degrees and the mean annual precipitation amounts to 1159 mm yr^{-1}. A comparison of important catchment properties of the study areas to the corresponding distribution of all Swiss catchments with arable land demonstrated that the study areas represent the national conditions well (see Figure S 1).

Table 1: Catchment properties of the 20 study areas. Fractions of agricultural area and of arable land were determined from BFS (2014). Mean slope of agricultural areas was determined from BFS (2014) and Swisstopo (2018). Mean annual precipitation was determined from Kirchhofer and Sevruk (1992).

ID	Location	Can-ton	Receiving water	Area (km^2)	Fraction of agricultural area	Fraction of arable land	Mean slope of agricultural areas in the catchment (deg)	Mean annual precipitation (mm/yr)
1	Böttstein	AG	Bruggbach	3.3	52 %	30 %	8.5	1187
2	Ueken	AG	Staffeleggbach	2.0	42 %	39 %	7.6	1164
3	Rüti b. R.	BE	Biberze	2.2	29 %	11 %	11.2	1403
4	Romont	FR	Glaney	3.4	78 %	48 %	4.0	1344
5	Meyrin	GE	Nant d'Avril	10.0	49 %	31 %	3.2	1133
6	Boncourt	JU	Saivu	5.9	44 %	23 %	5.5	1093
7	Courroux	JU	Canal de Bellevie	2.8	82 %	75 %	2.9	1082
8	Hochdorf	LU	Stägbach	2.4	84 %	59 %	4.1	1213
9	Müswangen	LU	Dorfbach	3.0	79 %	61 %	4.0	1482
10	Fleurier	NE	Buttes	1.0	24 %	11 %	9.6	1538
11	Lommiswil	SO	Bellacher Weiher	3.8	50 %	40 %	6.8	1388
12	Illighausen	TG	Tobelbach	1.9	54 %	30 %	1.8	1122
13	Oberneunforn	TG	Brüelbach	3.3	69 %	52 %	4.2	968
14	Clarmont	VD	Morges	2.4	75 %	70 %	5.3	1163
15	Molondin	VD	Flonzel	4.2	74 %	65 %	5.9	1064

16	Suchy	VD	Ruiss. des Combes	3.3	72 %	63 %	5.6	1026
17	Vufflens	VD	Venoge	2.8	39 %	30 %	5.7	1006
18	Buchs	ZH	Furtbach	3.9	57 %	48 %	4.9	1182
19	Nürensdorf	ZH	Altbach	2.3	59 %	44 %	3.6	1225
20	Truttikon	ZH	Niederwisenbach	5.1	66 %	49 %	4.6	960
			Mean	**3.5**	**59 %**	**44 %**	**4.9**	**1159**

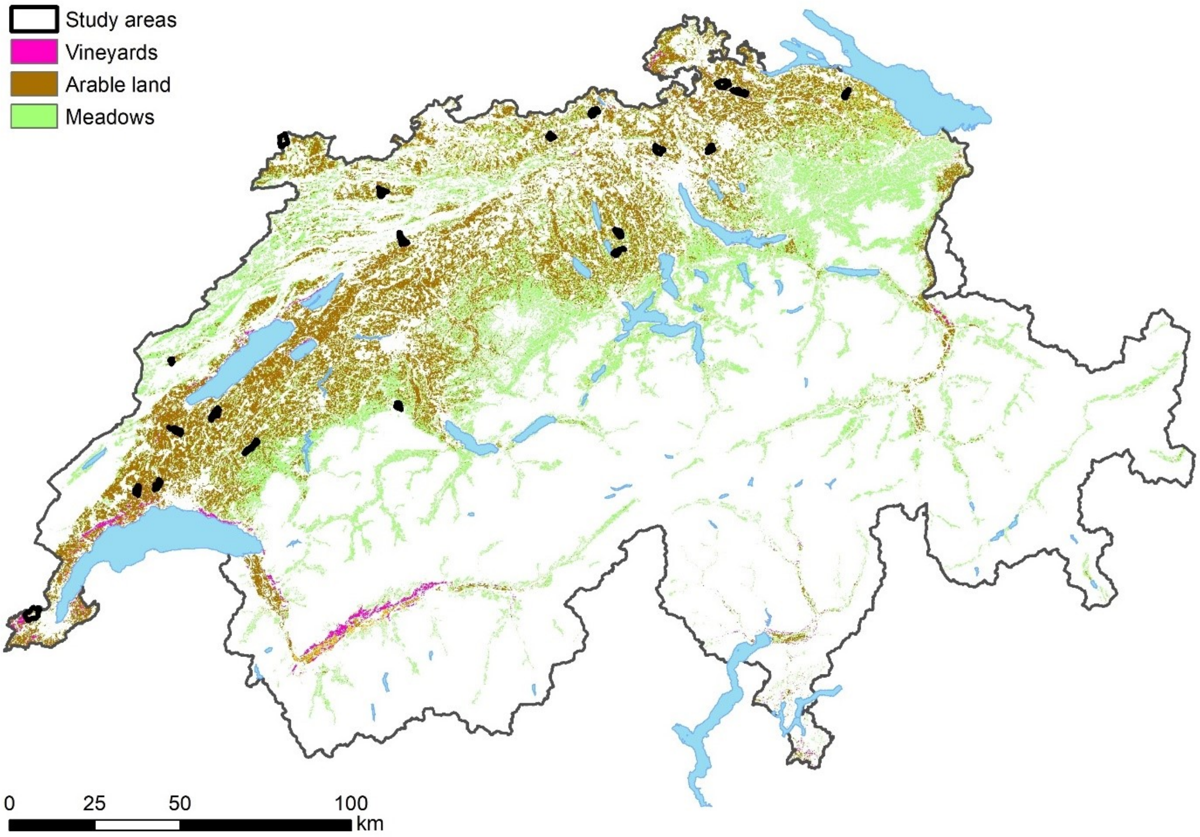


Figure 1: Study areas (black) and distribution of arable land (brown), vineyards (pink), and meadows/pastures (green) across Switzerland. Source: Swisstopo (2010);BFS (2014)

2.2. Assessment of hydraulic shortcuts

Shortcut definition

We define a hydraulic shortcut as *a man-made structure increasing and/or accelerating the process of surface runoff reaching surface waters (i.e. rivers, streams, lakes) or making this process possible in the first place*. In this study, we focused on the following structures (example photos can be found in Figure S 2 to Figure S 13):

A) Storm drainage inlets on roads, farm tracks and crop areas

B) Maintenance manholes of storm drainage systems or tile drainage system on roads, farm tracks and crop areas

C) Channel drains and ditches on roads, farm tracks and crop areas

If one of these structures is present, we defined this as a *potential shortcut*. If surface runoff can enter the structure and if the structure is drained to surface waters or to a wastewater treatment plant, this is defined as a *real shortcut*. Other processes that are sometimes referred to as hydraulic shortcuts (e.g. tile drains) are not considered in this study. Tile drains have already received considerable attention in pesticide research and the transport to tile drains includes flow through natural soil structures.

Shortcut location and type

We mapped the location and types of potential shortcuts in each study area by combining three different methods.

i) *Field survey*: Field surveys were performed between August 2017 and May 2018 (details see Table S 5). In a subpart of each study area, we walked along roads and paths and mapped all the potential shortcut structures. The starting point was selected randomly, and we mapped as much as we could within one day. Consequently, the field survey data only cover a part of the catchment. For each of the potential shortcuts we recorded its location, as well as a set of properties using a smartphone and the app “Google My Maps”. This included a specification of the type of the shortcut (e.g. inlet, inspection chamber, ditches, channel drains), its lid type (e.g. grid, sealed lid, lid with small openings), and its lid height relative to the ground surface. A list of all possible types can be found in the supporting information (Table S 2 to Table S 4).

ii) *Drainage plans*: For all municipalities covering more than 5 % of a study area we asked the responsible authorities to provide us with their plans of the road storm drainage systems and the agricultural drainage systems. For 38 and 26 of the 46 municipalities concerned we received road storm drainage system plans and tile drainage system plans, respectively. Reasons for missing data are either that the responsible authorities did not respond or that data on the drainage systems were not available. From the plans, we extracted the locations of shortcuts and, if available, the same properties were specified as in the field survey.

iii) A*erial images*: Between August 2017 and August 2018 (details see Table S 5) we acquired aerial images of the study areas with a ground resolution of 2.5 to 5 cm. We used a fixed-wing UAV (eBee, Sensefly, Cheseaux-sur-Lausanne) in combination with a visible light camera (Sony DSC-WX220, RGB). The study areas were fully covered by the UAV imagery, with the exception of larger settlement areas, forests, and lakes, and of no-fly zones for drones (e.g. airports). The UAV images were processed to one georeferenced aerial image per study area using the software Pix4Dmapper 4.2. In the no-fly zones of the study areas Meyrin (Geneva), Buchs (Zürich), and Nürensdorf (Zürich) we used aerial images provided by the cantons of Geneva (Etat de Genève, 2016) and Zürich (Kanton Zürich, 2015). Ground resolutions were 5 cm, and 10 cm respectively. Using ArcGIS 10.7, we gridded the aerial images, scanned by eye through each of the grid cells, and marked all potential shortcut structures manually. If observable from the aerial image, the same properties as for the field survey were specified for each potential shortcut structure.

We combined the three datasets originating from the three methods to a single dataset. If a potential shortcut structure was only found by one of the mapping methods, its location and type were used for the combined dataset. If it was found by more than one of the mapping methods, we used the location and type of the mapping method that we expected to be the most accurate. For the location information, this is UAV imagery, before field survey, and maps. For the type specification, this is field survey, before UAV imagery, and maps.

Assigning shortcuts to different landscape elements

In order to better understand where hydraulic shortcuts occur the most, we assigned them to different landscape elements. Using the topographic landscape model of Switzerland “swissTLM3D” (Swisstopo, 2010) we defined five landscape elements: Paved roads, unpaved roads, fields, settlements, and other areas (e.g. railways, other traffic areas, forests, water bodies, wetlands, single buildings). For all landscape elements except roads and railways, shortcuts were assigned to their landscape elements by a simple intersection. However, shortcuts belonging to road or railway drainage systems are in many cases not placed on the road or railway directly, but on the adjacent agricultural land or settlement. Therefore, shortcuts were assigned to the landscape elements road or railway if they were within a 5 m buffer.

In addition, we correlated the density of shortcuts per study area to different study area properties. We selected study area properties that we expected to have explanatory power: density (length per area) of paved roads, density of unpaved roads, density of surface rivers, density of subsurface rivers, mean annual precipitation, and mean slope on agricultural areas.

Drainage of shortcuts

A potential shortcut only turns into a real one if it is drained to surface waters by pipes or other connecting structures, such as ditches. Therefore, using the plans provided by the municipalities, we investigated where potential shortcuts drain to. They were allocated to one of the following categories of recipient areas: surface waters, wastewater treatment plants/combined sewer overflow, infiltration areas (e.g. forest, infiltration ponds, fields, grassland), or unknown.

2.3. Surface runoff connectivity model

To assess how hydraulic shortcuts contribute to surface runoff connectivity, ~~W~~we created a surface runoff connectivity model. ~~to estimate which fraction of potentially pesticide-loaded surface runoff originating on agricultural land is reaching surface waters via hydraulic shortcuts in comparison to direct transport.~~

The model is based on the concept of critical source areas (CSAs, see introduction). It mainly focuses on the first two elements of the CSA concept (pesticide application and connectivity to surface waters).~~,~~ ~~while~~ In contrast, the question whether an area is hydrologically active is only addressed partially because many relevant information such as soil properties are not available at the national scale.

The model (see Figure 2) distinguishes *source areas* on which surface runoff is produced, and *recipient areas* on which surface runoff ends up. A *connectivity model* connects those areas by routing surface runoff through the landscape. These model parts are conceptually described in more detail in the section “model structure”. In the section “model parametrization”, we describe how we parametrized the model and how we assessed the uncertainty of model output given the parameter uncertainty. In the last section "hydrological activity", we explain the testing for systematic differences in the hydrological activity between areas with direct or indirect connectivity.

Model structure

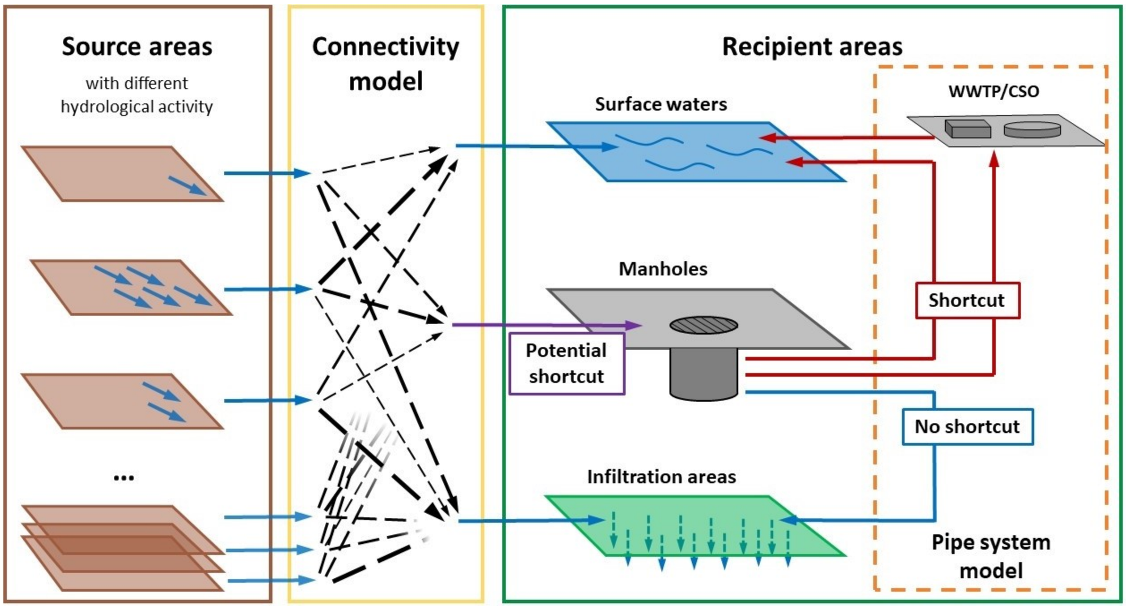


Figure 2: Structure of the surface runoff connectivity model. WWTP: Waste water treatment plants, CSO: Combined sewer overflow

Source areas. All crop areas on which pesticides are applied should in theory be considered as source areas. However, a highly resolved spatial dataset of land in a crop rotation for our study areas is lacking. Therefore, we considered the total extent of agricultural areas (i.e. arable land, meadows/pastures, vineyards, orchards, and gardening) as source areas, since those areas could be derived in high resolution. The extent of agricultural areas was defined by subtracting all non-agricultural areas from the extent of the study area. For this, we used non-agricultural areas (forests, water bodies, urban areas, traffic areas, and other non-agricultural areas) as defined by the national topographical landscape model SwissTLM3D (Swisstopo, 2010) ~~from the total area of each study area~~. According to the Swiss proof of ecological performance (PEP), pesticide usage within a distance of 6 m from a river, and within 3 m from hedges and forests is prohibited. The extent of agricultural areas was reduced accordingly except along forests (parameters *river spray buffer*, *hedge spray buffer*).

Recipient areas. Surface runoff generated on a source area and routed through the landscape can end up in three different types of landscape elements, referred to as recipient areas: Surface waters, infiltration areas (i.e. forests, hedges, internal sinks), and shortcuts. The extent of surface waters (rivers that have their course above the surface, lakes, and wetlands), was defined by the SwissTLM3D model as was the extent of forests and hedges. Since forests and hedges are known to infiltrate surface runoff (Sweeney and Newbold, 2014;Schultz et al., 2004;Bunzel et al., 2014;Dosskey et al., 2005) we assumed that forests with a certain width (parameter *infiltration width*) act as an infiltration area. Hedges were assumed either to act as infiltrations areas, or to have no effect on surface runoff. Accordingly, the parameter *hedge infiltration*, was varied between yes (hedges act as infiltration areas) and no (hedges don't act as an infiltration areas).

Internal sinks in the landscape were defined using the 2x2m digital elevation model (Swisstopo, 2018). All sinks larger than two raster cells and deeper than a certain depth (parameter *sink depth*) were defined as internal sinks. All other sinks were filled completely.

Shortcuts were defined in two different ways (parameter *shortcut definition*): In definition A, all inlets, ditches, and channel drains were considered as potential shortcuts. In definition B, manholes lying in internal sinks were additionally considered as potential shortcuts. Potential shortcuts were defined to act as real shortcuts if they are known to discharge to surface waters or wastewater treatment plants. From the drainage plans of the municipalities, we know that most of the inlets discharge into either a surface water body or a wastewater treatment plant. Therefore, also potential shortcuts with unknown drainage location were assumed to act as real shortcuts. Potential shortcuts discharging into forests or infiltration structures were assumed not to act as shortcuts and were not used in the model. Shortcut recipient areas were defined as the raster cells of the digital elevation model on which the shortcut is located and all the cells directly surrounding it (see Figure S 14 in the SI).

Connectivity model. For modelling connectivity we used the TauDEM model (Tarboton, 1997) which is based on a D-infinity flow direction approach. As an input we used a 2x2m digital elevation model (DEM) (Swisstopo, 2018). This DEM was modified as follows: We assumed that only those internal sinks that were defined as sink recipient areas (see above) effectively act as sinks. Therefore, firstly, all sinks were filled, and sink recipient areas were carved 10 m into the DEM. Secondly, all other recipient areas (shortcuts, forests, hedges, surface waters) were carved between 10 and 50 m into the DEM. Carving the recipient areas into the DEM ensured that surface runoff reaching a recipient area was not routed further on to another recipient area. Thirdly, to account for the effect of roads accumulating surface runoff (Heathwaite et al., 2005), roads were carved into the DEM by a given depth defined by the parameter *road carving depth*.

The modified DEM, the source areas, and the recipient areas were used as an input into the TauDEM tool “D-Infinity upslope dependence”. Like this, each raster cell belonging to a source area was assigned with a probability to be drained into one of the three types of recipient areas.

The connectivity of a source area may depend on the flow distance to surface waters. For longer flow distances, water has a higher probability to infiltrate before it reaches a surface water. Therefore, for each source area raster cell, we calculated the flow distance to its recipient area using the tool “D-infinity distance down”.

Model parametrization and sensitivity analyses

The model parameters mentioned in the section above vary in space and time. Since this variability could not be addressed with the selection of a single parameter value, we performed a Monte Carlo simulation with 100 realizations. The probability distributions of the parameters are provided in Table 2. The bounds or categories of these distributions were based on our prior knowledge about the hydrological processes involved, about structural aspects (e.g. depths of sinks), and on our experience from field mapping. The parameters *river spray buffer* and *hedge spray buffer* were assumed constant according to the guidelines of the Swiss proof of ecological performance (PEP).

To assess the influence of single parameters on our modelling results, we performed a local sensitivity analysis against a benchmark model (one realization of the model with a specific parameter set, see Table 2). When selecting the benchmark model parameter set, we kept the changes in the digital elevation model small (i.e. *road carving depth* = 0 cm, *sink depth* = 10 cm). For the other model parameters, we selected the values that we assumed to be the most probable in reality. For the local sensitivity analysis, each of the model parameters was varied individually within the same boundaries as for the Monte Carlo analysis.

Table 2: Summary of parameter distributions used for the Monte Carlo analysis and parameter values used as a benchmark for the sensitivity analysis. PEP: Swiss proof of ecological performance.

Parameter	Handling of parameter uncertainty	Distribution	Bounds / Categories	Benchmark model
Sink depth	Monte Carlo & sensitivity analysis	Uniform distribution	5 cm ≤ x ≤ 100 cm	10 cm
Infiltration width	Monte Carlo & sensitivity analysis	Uniform distribution	6 m ≤ x ≤ 100 m	20 m
Road carving depth	Monte Carlo & sensitivity analysis	Uniform distribution	0 cm ≤ x ≤ 100 cm	0 cm
Shortcut definition	Monte Carlo & sensitivity analysis	Bernoulli distribution	[Definition A; Definition B]	Definition A
Hedge infiltration	Monte Carlo & sensitivity analysis	Bernoulli distribution	[yes; no]	Yes
River spray buffer	Assumed as certain, based PEP guidelines	Constant	6 m	6 m
Hedge spray buffer	Assumed as certain, based PEP guidelines	Constant	3 m	3 m

Hydrological activity

As mentioned earlier, a critical source area has to be hydrologically active, i.e. surface runoff has to be generated on that area. Runoff generation depends on many variables (e.g. crop types, soil types, soil moisture, rain intensity) for which no data are available in most of our study areas and which are strongly variable over time. Since we are interested in the general relevance of shortcuts, we focused on the question whether there is a systematic difference in the hydrological activity between areas directly or indirectly connected to streams.

For soil moisture, we tested for such differences by calculating the distribution of the topographic wetness index (TWI) (Beven and Kirkby, 1979) for the source areas of the benchmark model. We calculated the TWI as follows, using the “Topographic Wetness Index” tool of the TauDEM model:

$$\mathrm{TWI} = \frac{\ln(a)}{\tan(\beta)}$$

The local upslope area a, and the local slope β were calculated using the D-infinity flow direction algorithm that was already used for the surface runoff connectivity model. As an input, we used the source areas and the modified DEM as specified for the surface runoff connectivity model.

The formation of surface runoff on agricultural areas is also influenced by their slope. Therefore, we calculated the distribution of slopes for source areas draining to different destinations. For this we used the slopes from the Swiss digital elevation model (Swisstopo, 2018).

For other variables (e.g. crop type, rain intensity), there is no indication for such systematic differences. Therefore, we assumed that they do not differ systematically between areas draining to different recipient areas.

2.4. Extrapolation to the national level

Extrapolation of the local connectivity model

~~In order to assess the relevance of shortcuts for the whole country and to evaluate how the empirical data affect the predictions on the national scale,~~ In a last step, we developed a model for extrapolating the results from our study areas (local surface runoff connectivity model, LSCM) to the national scale. This extrapolation was then used to evaluate how the results of this study compare to a pre-existing connectivity model (Alder et al., 2015).

Selection of explanatory variables: We calculated a list of catchment statistics based on nationally available geodatasets that could serve as explanatory variables. As catchment boundaries, the polygons from the national catchment dataset (BAFU, 2012) were used. Details on the datasets used for calculating those catchment statistics can be found in Table S 1.

We created a linear regression between each of those catchment statistics to the median fractions of agricultural areas directly, indirectly, and not connected to surface waters, as reported by the LSCM ($f_{LSCM,dir}$, $f_{LSCM,indir}$, $f_{LSCM,nc}$). The strongest correlations were found for the fractions of agricultural areas directly, indirectly, and not connected to surface waters, as reported by the NECM ($f_{NECM,dir}$, $f_{NECM,indir}$, $f_{NECM,nc}$, see Table S 8). Therefore, we used them as explanatory variables for building an extrapolation model of our local results to the national scale.

The model predictions for each catchment have to fulfil specific boundary conditions: Firstly, the sum of areal fractions of the three types of recipient areas k per catchment c has to equal one ($\sum_{k=1}^{K} f_{k,c} = 1$), and secondly, area fractions cannot be negative ($f_{k,c} \geq 0$). To ensure these conditions, we performed the model fit after a unit simplex data transformation. To address the uncertainty introduced by the selection of our study catchments, we additionally bootstrapped the model one hundred times. The resulting modelling approach is shown in Figure 3. Mathematical details are provided in the SI (chapter S1.5).

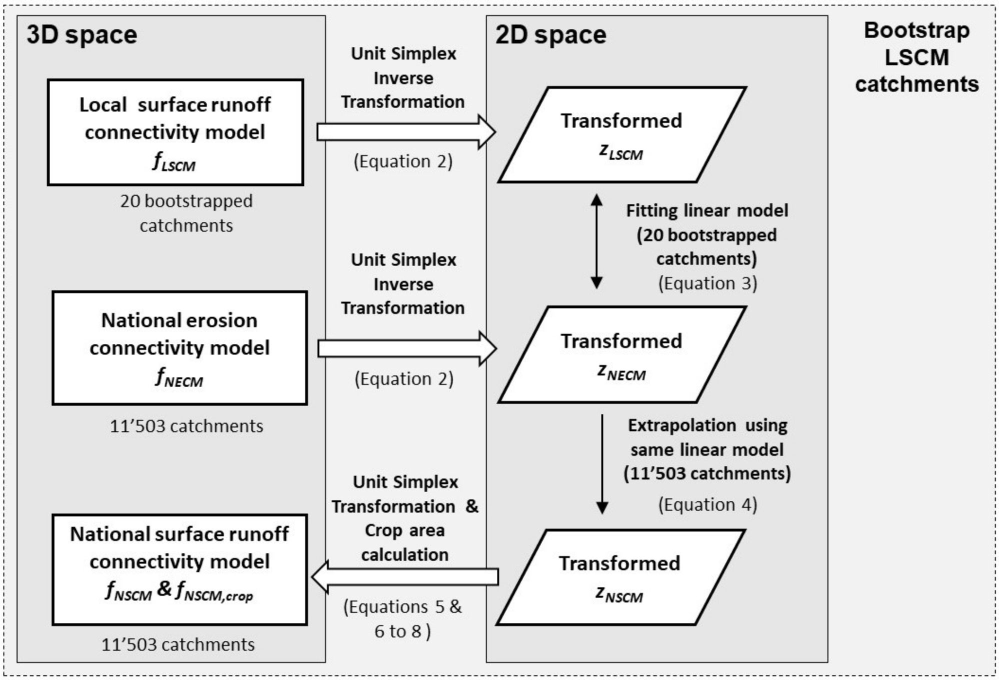


Figure 3: Extrapolation of the local surface runoff connectivity model (LSCM) to the national scale (NSCM) using a unit simplex transformation approach.

As a result, we obtained a national surface runoff connectivity model (NSCM). The NSCM provides an estimate for the fractions of agricultural areas directly, indirectly, and not connected to surface waters ($f_{NSCM,dir}$, $f_{NSCM,indir}$, $f_{NSCM,nc}$) for the catchments of the national catchment dataset. Since in the NECM mountainous regions of higher altitudes are excluded, those areas are also excluded in the NSCM.

Connectivity of crop areas

~~Since there are no~~During the time of this study, high-resolution datasets of Swiss crop areas ~~yet~~ were not available in Switzerland.~~,~~ Therefore, we considered the total extent of agricultural areas for building the local surface runoff connectivity model and extrapolation to the national scale. ~~These areas include~~ This includes areas with rare pesticide application, such as meadows and pastures.

The Swiss land use statistics dataset (BFS, 2014) is a raster dataset with a resolution of 100 m, dividing agricultural areas into different categories (e.g. arable land, vineyards, meadows/pastures). On the national scale, the usage of such a lower-resolution dataset is more reasonable. Hence, we used this dataset for calculating fractions of connected crop areas.

The fractions of directly, indirectly, and not connected crop areas per total agricultural area per catchment c ($f_{NSCM,crop,c}$) were calculated as follows:

$$f_{NSCM,crop,c} = f_{NSCM,c} \cdot r_{crop,c} \tag{6}$$

With r_{crop} being the ratio of crop area to total agricultural area in a catchment:

$$r_{crop,c} = \frac{A_{crop,c}}{A_{crop,c} + A_{mead,c}} \tag{7}$$

$$A_{crop,c} = A_{arab,c} + A_{vin,c} + A_{orch,c} + A_{gard,c} \tag{8}$$

with: $A_{crop,c}$ = Crop area in catchment c (ha)

$A_{mead,c}$ = Meadow and pasture areas in catchment c (ha)

$A_{arab,c}$ = Arable land area in catchment c (ha)

$A_{vin,c}$ = Vineyard area in catchment c (ha)

$A_{orch,c}$ = Orchard area in catchment c (ha)

$A_{gard,c}$ = Gardening area in catchment c (ha)

3. Results

3.1. Occurrence of hydraulic shortcuts

In the following section, we first show the results of the field mapping campaign for manholes (inlets, maintenance manholes) followed by the results for channel drains and ditches. Afterwards we present results on the accuracy of our mapping methods.

Manholes

In total, we found 8213 manholes, corresponding to an average manhole density of 2.0 ha^{-1} (min.: 0.51 ha^{-1}, max.: 4.4 ha^{-1}; Table 3). Forty-two percent of the manholes mapped were inlets. A plot showing the density of manholes mapped per catchment and manhole type can be found in Figure S 15 in the supporting information.

For roughly half of the inlets and maintenance manholes we were able to identify a drainage location. Both manholes types discharge in almost all cases into surface waters, either directly (87 % of inlets, 63 % of maintenance manholes) or via wastewater treatment plants or combined sewer overflow (12 % of inlets, 37 % of maintenance manholes). Only 1.4 % of the inlets and no maintenance manhole at all, were found to drain to an infiltration area, such as forests or fields.

Table 3: Number of manholes found on agricultural areas of the study areas per shortcut category and drainage location.

	Inlets		**Maintenance manholes**		**Other manholes**		**Unknown type**	
Drainage location	**Count**	**Fraction**	**Count**	**Fraction**	**Count**	**Fraction**	**Count**	**Fraction**
Surface waters	1568	46 %	1205	29 %	0	0 %	0	0 %
WWTP/CSO	218	6 %	705	17 %	0	0 %	0	0 %
Infiltration areas	26	1 %	0	0 %	0	0 %	0	0 %
Unknown	1615	47 %	2227	54 %	31	100 %	618	100 %
Total	**3427**	**100 %**	**4137**	**100 %**	**31**	**100 %**	**618**	**100 %**

Most of the inlets mapped (90 %) are located on paved or unpaved roads (see Table 4). Only very few inlets (2.8 %) are found directly on fields. In contrast, maintenance manholes are found much more often on fields and therefore less often on paved or unpaved roads. The fractions of inlets and maintenance manholes belonging to a certain landscape element for each study area can be found in Figure S 18 in the supporting information.

Table 4: Percentage of manholes found on a certain type of landscape element. The category "other areas" integrates several types of landscape elements: railways, other traffic areas, forests, water bodies, wetlands, and single buildings.

	Paved roads	Unpaved roads	Settle-ments	Fields	Other areas
Inlets	79 %	10 %	5.5 %	2.8 %	2.2 %
Maintenance manholes	52 %	7.2 %	16 %	21 %	4.5 %

We correlated the densities of inlets and maintenance manholes per study area with possible explanatory variables. Only the density of paved roads was significantly correlated to the density of inlets ($R^2 = 0.33$, $p = 0.008$) and maintenance manholes ($R^2 = 0.37$, $p = 0.005$) (see Table S 6 and Table S 7).

Channel drains and ditches

In addition to manholes, we also mapped channel drains and ditches. With the exception of the study areas Meyrin (4.2 m ha^{-1}) and Buchs (4.0 m ha^{-1}) these structures were rarely found (< 1.2 m ha^{-1}; see Figure S 16). In Meyrin and Buchs, most channel drains and ditches (98 % of the total length) drain to surface waters, and only few of them to infiltration areas (2 %).

Mapping accuracy

The results above were generated using three different mapping methods (*field survey*, *UAV images*, and *drainage plans*). These methods differ in their ability to identify and classify a potential shortcut structure correctly and in the study area they cover. We determined the accuracy of the mapping methods aerial images and drainage plans using the field survey method as a ground truth (see Table 5) for those parts of the study areas where all three methods were applied. Since channel drains and ditches were rare, this assessment was only performed for manholes.

The recall (i.e. the probability that a potential shortcut is found by a mapping method) was limited for the aerial images method (53 % for inlets, and 62 % for maintenance manholes), and even lower for the drainage plans method (32 % for inlets, and 21 % for maintenance manholes). However, identified shortcuts were in most of the cases classified correctly (accuracy: 93 % to 94 % for aerial images, 88 % to 89 % for drainage plans).

For the entire study areas, Figure 4 shows the number of potential shortcuts identified by the three mapping methods. Despite a low recall, aerial images identified the largest number of potential shortcuts. This is due to the large spatial coverage by the aerial images method. Since the overlap between the three methods is small (only 32 % of the inlets and 15 % of the maintenance manholes were found by more than one method), each of the methods was important to determine the total number of potential shortcuts in the study areas. Because the aerial images and drainage plans have a low recall, but cover large parts of the study areas that were not assessed by the field survey, the numbers reported above are a lower boundary estimate.

Table 5: Recall and classification accuracies of the mapping methods aerial images and drainage plans. The recall corresponds to the probability that a potential shortcut is found by the mapping method. Percentages indicate the recall of each individual mapping method. In brackets, the recall of the combination of both methods is given. The accuracy corresponds to the sum of true positive fraction and true negative fraction.

Mapping method	Manhole type	Identification	Classification				
		Recall	True positives	False positives	True negatives	False negatives	Accuracy
Aerial images	**Inlets**	53 % (60 %)	61 %	1.3 %	33 %	4.9 %	94 %
	Maintenance manholes	62 % (69 %)	32 %	5.3 %	61 %	1.3 %	93 %
Drainage plans	**Inlets**	32 % (60 %)	67 %	4.5 %	22 %	6.6 %	89 %
	Maintenance manholes	21 % (69 %)	20 %	7.1 %	68 %	5.3 %	88 %

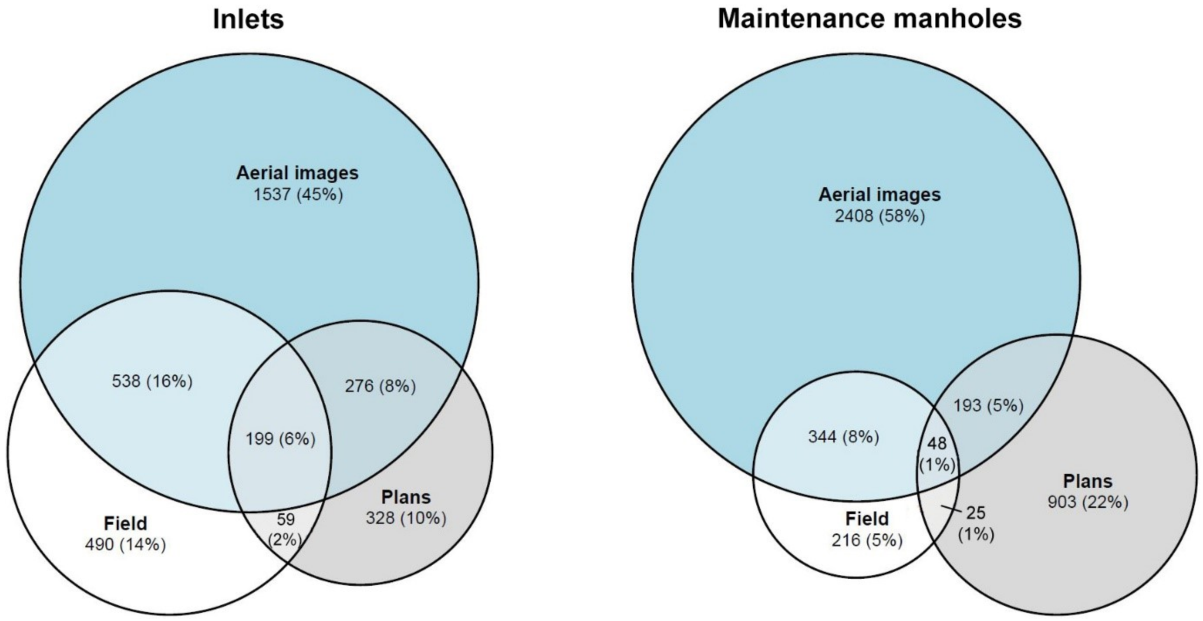
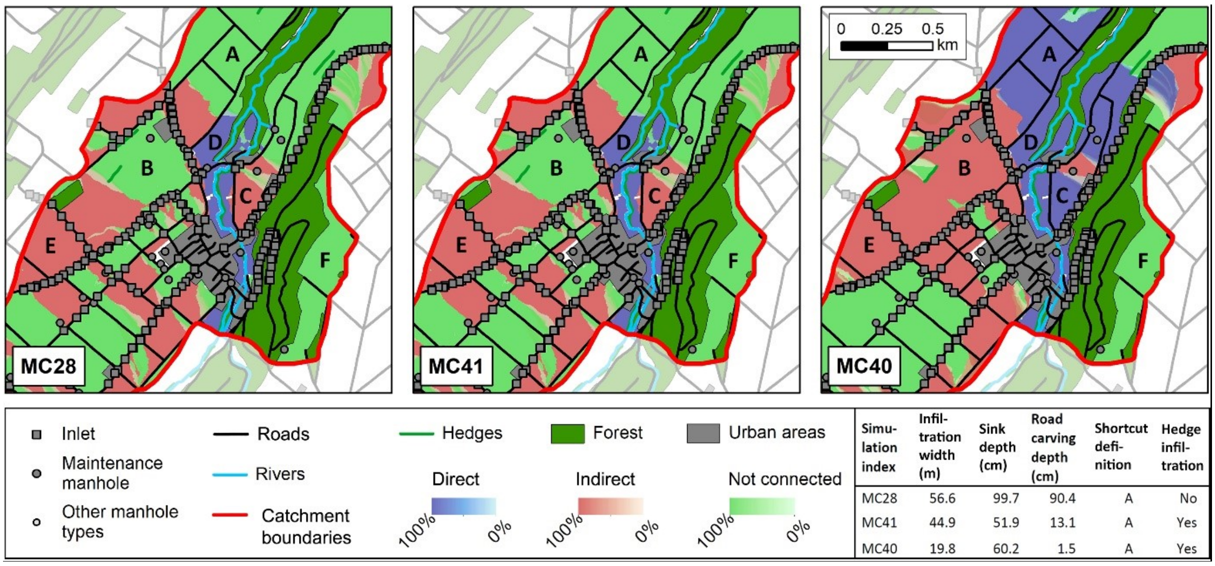


Figure 4: Number of inlets (left) and maintenance manholes (right) identified by the different mapping methods.

3.2. Surface runoff connectivity

3.2.1. Study areas

From the Monte Carlo analysis of the surface runoff connectivity model, we obtained an estimate for the fractions of agricultural areas that are connected directly, indirectly, or not at all to surface waters. To illustrate the variability resulting from these Monte Carlo (MC) runs, Figure 5 shows the output of three MC simulations (MC28, MC41, and MC40) for Molondin. These simulations correspond to the 5 %, 50 %, and 95 % quantile of the median fraction of indirectly connected per total connected agricultural area over all study catchments. The classification of certain catchment parts is changing depending on the model parametrisation (e.g. letters A to C). However, for other parts, the results are consistent across the different MC simulations (e.g. letters D to F). Overall, the results show that not only agricultural areas close to surface waters (e.g. letter D) are connected to surface waters. Hydraulic shortcuts also create surface runoff connectivity for areas far away from surface waters (e.g. letter E).



Simu-lation index	Infil-tration width (m)	Sink depth (cm)	Road carving depth (cm)	Shortcut defi-nition	Hedge infil-tration
MC28	56.6	99.7	90.4	A	No
MC41	44.9	51.9	13.1	A	Yes
MC40	19.8	60.2	1.5	A	Yes

Figure 5: Results of three example Monte Carlo (MC) simulations for a part of the study area Molondin. The color ramps show the probability of agricultural areas to be directly connected (blue), indirectly connected (red) and not connected (green). The simulations represent approximately the 5 % (MC28), 50 % (MC41), and 95 % (MC40) quantiles with respect to the resulting median fractions of indirectly connected per total connected area over all study catchments. The parameters of the example MC simulations are shown on the bottom right. Source of background map: Swisstopo (2010)

In order to assess the importance of hydraulic shortcuts, we calculated the fraction of indirectly connected area to the total connected area. Across all Monte Carlo simulations, the median of this fraction over all study catchments ranges between 43 % and 74 % (mean: 57 %, median: 58 %; Figure 5). Despite considerable uncertainty, the results demonstrate that a large fraction of the surface runoff connectivity to surface waters is established by hydraulic shortcuts.

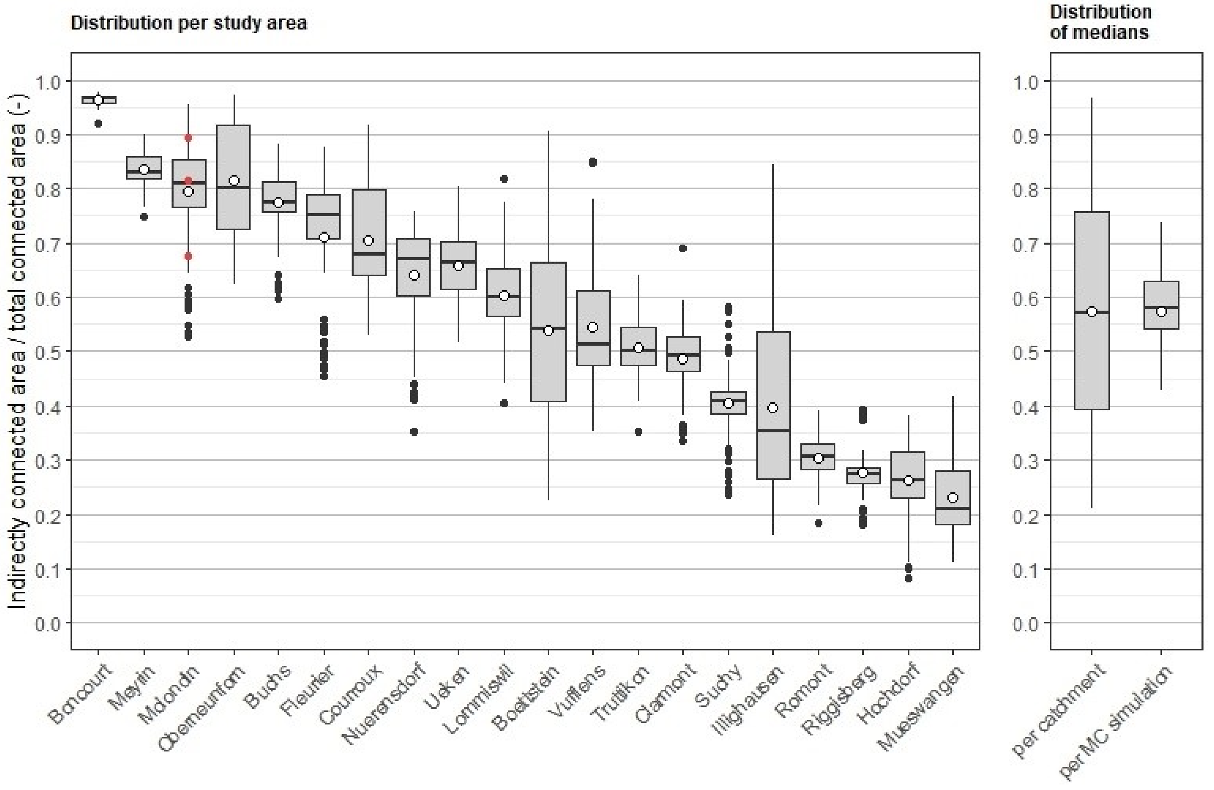


Figure 6: Left: Fractions of indirectly connected areas per total connected areas as calculated by the Monte Carlo analysis for each study area. White dots indicate the means of the distributions. The red dots indicate the results of the example Monte Carlo simulations (MC28, MC41, and MC 40) shown in Figure 5. Right: Distribution of medians of fractions of indirectly connected areas per total connected areas per study catchment and per Monte Carlo simulation.

For different flow distances, the fraction of indirectly connected area to the total connected area underlies only minor variations (see Figure S 24). However, this fraction varies strongly between the study areas, with median fractions ranging from 21 % in Müswangen to 97 % in Boncourt. Although the occurrence of hydraulic shortcuts is a prerequisite of indirect connectivity, high manholes densities are not necessarily leading to high fractions of indirect connectivity in a catchment. The densities of inlets and maintenance manholes show only a weak positive correlation to the catchment medians of the fraction of indirectly connected areas (inlets: $R^2 = 0.11$, $p = 0.15$; maintenance manholes: $R^2 = 0.08$, $p = 0.23$; see Table S 8). By contrast, the two study areas with high channel drain and ditch densities (Meyrin and Buchs) show high fractions of indirect connectivity. Similarly, the density of surface waters is strongly negatively correlated to the fraction of indirect connectivity ($R^2 = 0.51$, $p < 0.001$). This suggests that line elements like channel drains, ditches and surface waters usually have an influence on connectivity if they occur in a catchment. By contrast, the influence of point elements seems to depend a lot on the surrounding landscape structure.

As a further consequence of the structural differences between the study areas, not all of them reacted the same way to changes in model parameters of the Monte Carlo analysis. For example, the fraction of indirectly to total connected areas in the study area Boncourt was quite insensitive to changes in model parameters. Since Boncourt has a very low water body density, only small areas are connected directly, independent of the model parametrization. The study area Illighausen, on the other hand, reacted very sensitively (range of results = 68 %). Since Illighausen is a very flat catchment, changes in the sink depth parameter had a large influence on the estimated fractions of direct and indirect connectivity.

So far, we only reported on the fraction of indirectly connected per total connected area. In Table 6, we additionally report the fractions of total agricultural area connected directly, indirectly, and not at all to surface waters. On average, we estimate between 5.5 % and 38 % (mean: 28 %) of the agricultural area to be connected directly, 13 % to 51 % (mean: 35 %) to be connected indirectly, and 12 % to 77 % (mean: 37 %) not to be connected to surface waters. However, the variation between the catchments is much larger than the variation of the Monte Carlo analysis.

Table 6: Fractions of directly, indirectly, and not connected agricultural areas in our study catchments. The first row represent the mean fraction over all catchments and Monte Carlo simulations. The second row represents the median of the median over all catchments per MC simulation. The third row represents the median of the median over all MC analyses per catchment. In brackets, the minimum and the maximum median are given.

Statistic	**Fraction of directly connected agricultural area f_{dir}**	**Fraction of indirectly connected agricultural area f_{indir}**	**Fraction of not connected agricultural area f_{nc}**	**Fraction of indirectly per total connected area $f_{fracindir}$**
Mean	28 %	35 %	37 %	57 %
Median per MC simulation	25 % (5.5 %; 38 %)	38 % (13 %; 51 %)	32 % (12 %; 77 %)	58 % (43 %; 74 %)
Median per catchment	26 % (1.8 %; 70 %)	37 % (12 %; 60 %)	35 % (3.9 %; 53 %)	57 % (21 %; 97 %)

Sensitivity analysis

To analyse which model parameters have the largest influence on our model results, we tested the local model parameter sensitivity on our benchmark model. The fraction of indirectly to total connected area reacts most sensitive to changes in the road carving depth parameter. The difference between the minimal and maximal fraction reported was 17 %. Results were also sensitive to the parameters shortcut definition (14 %) and sink depth (13 %). Infiltration width (4.3 %) and hedge infiltration (2.5 %) had only a minor influence on the fraction reported (see Figure S 22 and Figure S 23)..

Hydrological activity

Systematic differences in hydrological activity between directly and indirectly connected areas would have a major influence on the interpretation of our connectivity analysis. We therefore tested for such differences by calculating the distributions of slope and topographic wetness index on these areas.

The distributions of both, slope and topographic wetness index were very similar for directly, indirectly, and not connected areas (see Figure S 25 and Figure S 26). Only the slope of not connected areas was found to be slightly smaller than the slope of connected areas. Hence, we could not identify any systematic differences in the factors affecting hydrological activity between directly and indirectly connected areas.

Consequently, given the current knowledge, the proportions of direct and indirect surface runoff entering surface waters are expected to be equal to the proportions of directly and indirectly connected agricultural areas. ~~Analogously, the proportion of directly and indirectly transported pesticide loads are expected to be equal to the proportions of directly and indirectly connected crop areas.~~Analogously, if other boundary conditions of pesticide transport remain unchanged, directly and indirectly transported pesticide loads are expected to be proportional to directly and indirectly connected crop areas.

3.2.2. Extrapolation to the national level

We created a model for extrapolating the results of our study areas to the national level, using area fractions of the national erosion connectivity model (NECM) (Alder et al., 2015) aggregated to the catchment scale as explanatory variables. The area fractions of the NECM were transformed such that they fit the area fractions of the local surface runoff connectivity model (LSCM) resulting from the Monte Carlo analysis in our study areas. The resulting dataset is called the national surface runoff connectivity model (NSCM). The NSCM provides a separate model for each of the 100 Monte Carlo runs of the LSCM. It is aggregated to the catchment scale and covers all catchments of the valley zones, hill zones and lower elevation mountain zones. The differences between the fitted NSCM and the LSCM were strongly reduced compared to the original NECM (see Figure 7). The root-mean-square error (RSME) on average reduced from 17 % to 9.5 % for directly connected fractions, from 12 % to 7.6 % for indirectly connected fractions, and from 18 % to 7.6 % for not connected fractions.

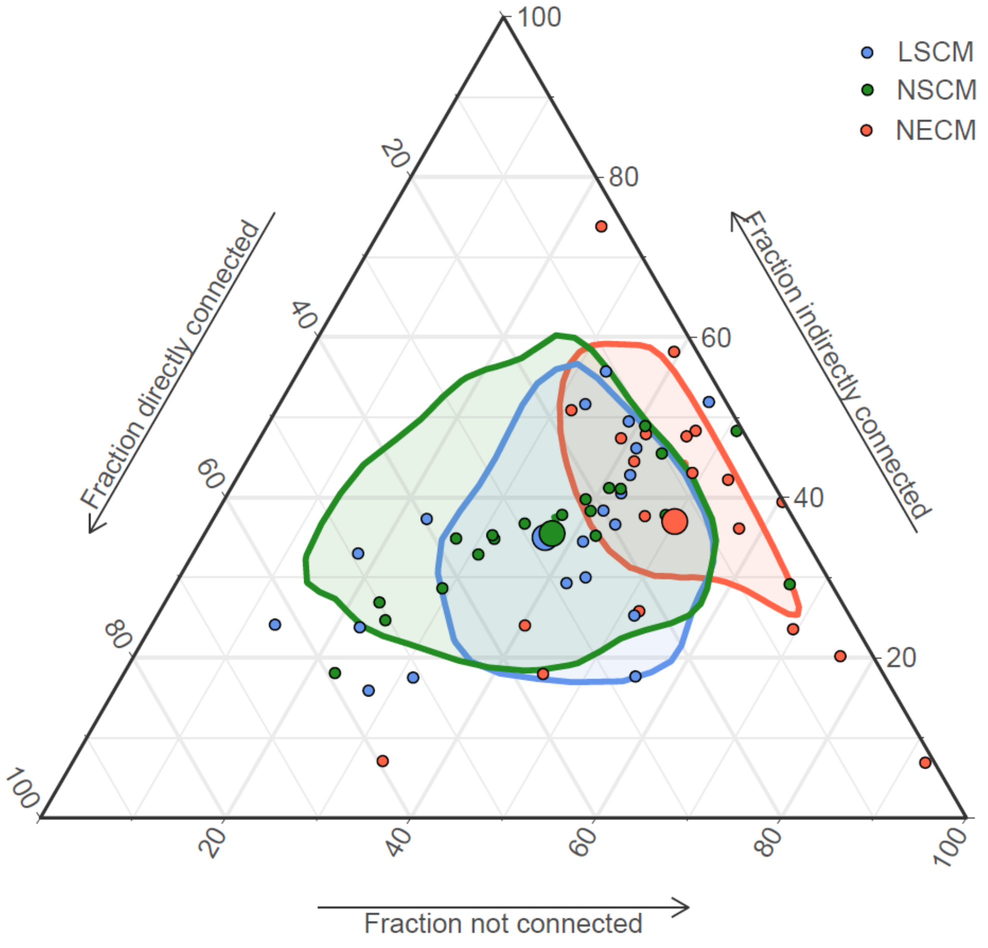


Figure 7: Fractions of directly connected (f_{dir}), indirectly connected (f_{indir}), and not connected areas (f_{nc}) per total agricultural area for the local surface runoff connectivity model (LSCM, blue), national erosion connectivity model (NECM, red), and national surface runoff connectivity model (NSCM, green) in the 20 study areas. Small blue circles represent the catchment medians of all Monte Carlo simulations of the LSCM, small red circles represent the data reported by the NECM, and small green circles represent the catchment medians of the NSCM. Large circles

represent the means of the LSCM (blue), NECM (red), and NSCM data (green). Shaded areas represent normal Kernel density estimates of the LSCM, NECM, and NSCM data.

By combining the NSCM with land use data, we came up with an estimate of connected crop areas on the national scale. Half of the Swiss agricultural areas in the model region are crop areas (i.e. arable land, vineyards, orchards, horticulture) and therefore potential pesticide source areas. On average, twenty six percent of crop areas (13 % of total agricultural area) are connected directly, 34 % (17 % of total agricultural area) indirectly, and 40 % (20 % of total agricultural area) not at all (details: Figure S 27; MC simulation quantiles: Table S 9; spatial distribution: Figure S 30 to Figure S 36). From the total connected crop area, 54 % (between 47 and 60 %) are connected indirectly.

These results are similar to those obtained for the 20 study areas. Mean fractions of directly and indirectly connected agricultural areas are a bit smaller in the national scale estimation than for the 20 study areas (-2.0 %, and -1.9 %), while the fraction of not connected agricultural area is a bit larger (+3 %). The fraction of indirectly connected crop area per total connected crop area is slightly smaller (-2.6 %).

To assess if the national erosion connectivity model (NECM) is different from the national surface runoff connectivity model (NSCM), we determined the 5% and 95% quantiles of the NSCM predictions (see Table S 9). If a fraction of the NECM is outside of this range, we considered this as a significantly different model prediction that is not expected, given our field data.

Compared to the NSCM, the NECM on average predicts lower fractions of directly connected crop areas $f_{crop,dir}$ (-6.4 %), which is below the 5 % quantile of the NSCM results. For indirectly connected areas $f_{crop,indir}$ (-0.9 %), and not connected crop areas $f_{crop,nc}$ (+7.2 %), the data reported by the NECM are within the 5 % and 95% quantile of the NSCM results. However, the fraction of indirectly connected crop area per total connected crop area $f_{fracindir}$ reported by the NECM lies beyond the 95 % quantile of the NSCM (+11 %). In summary, $f_{crop,dir}$ and $f_{fracindir}$ reported by the NECM are significantly different from what would be expected from the NSCM. For $f_{crop,indir}$ and $f_{crop,nc}$, the reported fractions are in a similar range for both models. The results of the bootstrap (Figure S 28) show that the differences between the two models are significantly larger than the uncertainty introduced by the selection of the study catchments.

The average difference in predicted connectivity fractions of *agricultural* areas between the two models ($\Delta f = ((f_{NSCM,dir} - f_{NECM,dir}) + (f_{NSCM,indir} - f_{NECM,indir}) + (f_{NSCM,nc} - f_{NECM,nc}))/3$) is strongly variable in space. Large differences are mainly found in large valleys (e.g. the Aare, Alpenrhein, and Rhone valleys, and the valleys of Ticino) and in the region of Lake Constance (see Figure S 40). However, when looking at the difference in average predicted connectivity fractions of *crop* areas ($\Delta f_{crop} = ((f_{NSCM,crop,dir} - f_{NECM,crop,dir}) + (f_{NSCM,crop,indir} - f_{NECM,crop,indir}) + (f_{NSCM,crop,nc} - f_{NECM,crop,nc}))/3$), large differences almost exclusively are found in a band of catchments with high crop densities spreading through the Swiss midland (see Figure 8).

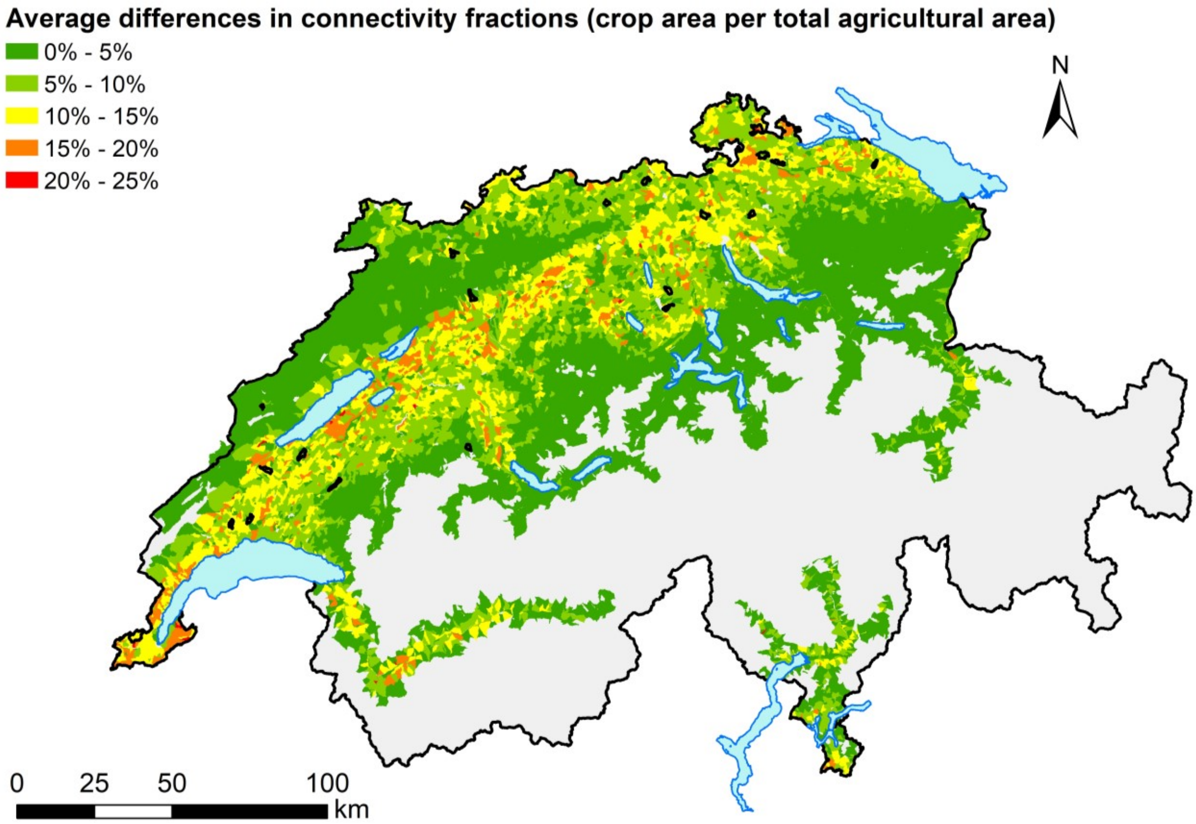


Figure 8: Average differences in connectivity fractions of crop areas between the NSCM and the NECM: $\Delta f_{crop} = ((f_{NSCM,crop,dir} - f_{NECM,crop,dir}) + (f_{NSCM,crop,indir} - f_{NECM,crop,indir}) + (f_{NSCM,crop,nc} - f_{NECM,crop,nc}))/3$. The map shows data for all Swiss catchments in the valley zones, hill zones and lower elevation mountain zones. Grey areas represent higher elevation mountain zones that were excluded from the analysis. Study areas are marked with black lines. Details on directly, indirectly, and not connected agricultural areas and crop areas are given in Figure S 37 to Figure S 43. For comparison, a map of crop densities is given in Figure S 29. Source of background map: Swisstopo (2010)

4. Discussion

Occurrence of hydraulic shortcuts

Our study shows that storm drainage inlets and maintenance manholes are common structures found in Swiss agricultural areas. While in neighbouring countries roads are often drained by ditches, Swiss roads are usually drained by storm drainage inlets (Alder et al., 2015). It is therefore not surprising that most of the inlets found in the study areas are located on roads. These findings are in accordance with the only other study in Switzerland reporting numbers on storm drainage inlets (Prasuhn and Grünig, 2001).

The vast majority of mapped storm drainage inlets were found to discharge to surface waters directly or via wastewater treatment plants (WWTPs). Thus, the occurrence of an inlet is in most cases directly related to a risk for pesticide transport to surface waters. The following three processes generate this risk: Firstly, pesticide loaded surface runoff produced on crop areas can enter the inlet. Secondly, spray drift deposited on roads can be washed off and enter the inlet. Thirdly, inlets can be oversprayed during pesticide application, which is mainly considered probable for inlets located in the fields.

Although maintenance manholes were also found to discharge to surface waters directly or via WWTPs, their occurrence does not directly translate into a risk for pesticide transport to surface waters. In contrast to storm drainage inlets, maintenance manholes are not designed to collect surface runoff. Their lids are usually closed or only have a small opening, significantly decreasing the risk of surface runoff entering the manhole or of overspraying. In addition, lids of maintenance manholes in fields are often elevated compared to the soil surface. Maintenance manholes on roads are (in contrast to inlets) usually positioned such that concentrated surface runoff is bypassing them. However, as also shown by Doppler et al. (2012), maintenance manholes can collect surface runoff from fields if they are located in a sink or a thalweg and water is ponding above them during rain events. During our field mapping campaign, we additionally found several damaged maintenance manholes that could easily act as a shortcut.

Channel drains and ditches discharging into surface waters were rare in most study areas with two exceptions. In Meyrin, the large length of these structures can be explained by the existence of a large vineyard. Additionally, the density of manholes in this vineyard was higher than on the surrounding arable land. This indicates that vineyards could generally have higher shortcut densities than arable land. In Buchs, around 60 % of the channel drain and ditch length consists of ditches that cannot be clearly distinguished from small streams. They are not appearing in the national topographic landscape model (Swisstopo, 2010) that was used for the definition of rivers and streams and did not appear to be streams during field mapping or when analysing aerial images.

The number of mapped shortcuts represents a lower boundary estimate of the shortcuts present (see results) and therefore leads to an underestimation of indirect connectivity. Probabilities for missing shortcuts during our mapping campaign depend on their location. While aerial images were at almost full coverage of the study areas, field mapping was performed mainly along roads. Drainage plans were available more often along roads than on fields. Therefore, we expect that detection probability of shortcuts is generally higher along roads than on fields. Besides coverage, various other factors influence the detection probabilities of the mapping methods. Field mapping and aerial image detection performance is reduced if shortcuts are covered. Along roads, this is mainly caused by leaves, soil, and for aerial images also by trees and vehicles. On the fields, this is mainly caused by soil or by crops. Detection performance of the aerial images method is additionally influenced by image quality and ground resolution. Image quality is mainly influenced by wind and light conditions during the UAV flights. In order to ensure high image quality, we planned UAV flights such that weather conditions were favourable (low wind, slightly overcast). However, differences in image quality between the study areas could not be completely avoided. Higher ground resolution could further improve the data produced. Although detection performance is not expected to be limited by the ground resolution used, higher resolution could improve the correct classification of shortcut types.

Surface runoff connectivity

Our study ~~shows~~ suggests that around half of the surface runoff connectivity in our study areas, but also on the national scale, is generated by hydraulic shortcuts. Surface runoff is considered one of the most important processes for pesticide transport to surface waters. Consequently, a large amount of the pesticide loads found in surface waters during rain events is expected to be transported by hydraulic shortcuts. These findings are in accordance to the results of other studies investigating the influence of hydraulic shortcuts on surface runoff connectivity (Alder et al., 2015;Prasuhn and Grünig, 2001;Bug and Mosimann, 2011) and on pesticide transport (Doppler et al., 2012).

The fraction of indirect connectivity was found to be very different between study areas. The variability introduced by the different properties of the study areas was larger than the variability introduced by the different model parameters of the Monte Carlo analysis, indicating that our results are robust against changes of our model parameters. Our model was most sensitive to changes of the parameters *road carving depth*, *shortcut definition*, and *sink depth*. These parameters are discussed in the following.

The parameter *road carving depth* accounts for the property of roads of collecting and concentrating surface runoff. This effect is strongly dependent on microtopography, extremely variable in space, and can therefore not be properly accounted for by a space-independent parameter. Usage of a higher resoluted digital elevation model could however reduce the uncertainty on the effect of roads on connectivity. Higher resolved digital elevation models could also help in capturing the influence of other microtopographical features better. For example, small ditches or small elevations on the ground can easily channel surface runoff. This can either direct surface runoff into a shortcut from areas not modelled to drain to a shortcut, or vice versa. In Switzerland, a new digital elevation model with a raster resolution of 0.5 m (Swisstopo, 2019) recently became available and could be used for this purpose. This elevation model was not used within this study, since the study already had progressed further by the time the dataset was published.

The model parameters *shortcut definition* (i.e. are maintenance manholes in a sink considered as a shortcut) and *sink depth* are both related to the fate of surface runoff ponding in a sink. This indicates that maintenance manholes in sinks could have an important influence on surface runoff connectivity of agricultural areas. During our field mapping campaign, only few maintenance manholes in sinks were investigated. It is therefore unclear if most maintenance manholes in sinks are capturing ponding surface runoff, if surface runoff is usually infiltrating into the soil, or if it continues to flow on the surface. Sensitivity of our model to the parameter *sink depth* additionally indicates that sinks might play an important role for connectivity. Therefore, they should not be filled completely during GIS analyses, as this is done by default by some flow routing algorithms.

Surface runoff is usually assumed to drain to the receiving water of its topographical catchment. However, in various cases, the pipes draining hydraulic shortcuts were found to cross topographical catchment boundaries. Consequently, surface runoff and related pesticide loads are transported to a different receiving water than expected by the topographical catchment. This may be important to consider when interpreting pesticide monitoring data from small catchments. Similar effects were already reported for karstic aquifers or the storm drainage systems of urban areas (Jankowfsky et al., 2013;Luo et al., 2016).

Hydrological activity

We did not find any indication on systematic differences between the factors controlling hydrological activities of directly and indirectly connected agricultural areas by analysing slope and topographic wetness index. Those variables are a proxy for surface runoff formation, soil moisture, groundwater level, but also physical properties of the soil (Sorensen et al., 2006;Ayele et al., 2020). However, the hydrological activity of an agricultural area also depends on other factors that were not quantitatively analysed, such as *rainfall intensities, crop types, soil management practices*, or the presence of *tile drainage systems*.

Rainfall intensities: Because of the small size of the study areas and the close proximity between directly and indirectly connected areas, systematic differences in rainfall intensities within a catchment can be excluded.

Crop types and soil management can have a strong impact on runoff formation. These practices are chosen by the farmers and there could be systematic differences of these variables. For example, farmers aware of the effect of surface runoff and erosion on the pollution of surface waters might use different cultivation methods or crops (e.g. conservation tillage) on fields close to surface waters than on fields far away. This would lead to a higher probability of surface runoff formation on indirectly connected areas compared to directly connected areas. However, different cultivation methods require different farm machinery. Therefore, cultivation methods are often constrained by the machinery available and farmers use the same cultivation method per crop for all of their fields. Consequently, systematic differences in crop types or soil management between directly and indirectly connected areas of a catchment are unlikely.

Tile drainage systems: Maintenance manholes and inlets found in the field often belong to a tile drainage system. Therefore, fields on which maintenance manholes or inlets are located, have a higher probability to be drained by tile drainage systems than other fields. This could lead to higher infiltration capacities and consequently to reduced surface runoff on indirectly connected areas compared to directly connected areas. However, since most of the inlets and manholes are located along roads (see results) such differences would only have a minor effect on the overall surface runoff connectivity.

Although rainfall intensities, crop types, or soil management practices, are not expected to differ systematically within a catchment, they do differ across catchments. As mentioned in the results, we therefore expect the proportion of directly connected areas to indirectly connected areas in a catchment to be a good indicator for the proportion of surface runoff formed on directly and indirectly connected areas in this catchment. However, due to differences in hydrological activity, two catchments with similar total connected areas may differ strongly in the total amount of surface runoff formed.

Extrapolation to the national level

A major source of uncertainty in the national erosion connectivity model (NECM) is the usage of generalising assumptions due to lack of empirical data. Our results show that some of the estimated connectivity fractions of crop areas change significantly, when the NECM is transformed based on additional empirical data from our field study. However, the results of both models still are in the same order of magnitude and lead to the same general conclusion: ~~Also at~~At the national level, more than half of the connected crop area is connected to surface waters via hydraulic shortcuts, as we observed for the 20 study catchments. As shown in the results, large differences between the NECM and the NSCM in the predictions of crop area connectivity are almost exclusively found in one band of catchments with high cropping densities in the Swiss midland. Potential further empirical investigations or improvements of the NECM should therefore focus on a better representation of these catchments.

However, it is important to note, that within this study none of the models (NECM, LSCM, and NSCM) has been tested and validated empirically with independent data regarding their actual capacity to quantify the connectivity effects on surface runoff and related pesticide transport. These models provide predictions given the current availability of empirical observations. Suggestions for validating these models are given in the "further research" section.

From all tested variables, the NECM connectivity fractions showed the strongest correlations to the connectivity fractions reported by the local connectivity model (LSCM) in our study areas. This ~~indicates~~ suggests that the NECM is a useful ~~valid~~ tool for assessing ~~the~~ potential pesticide connectivity ~~to surface water across catchments~~ in relative terms (e.g. which catchments have high indirect connectivity compared to other catchments). Therefore, we recommend continuing to use the NECM in practice, e.g. as a starting point for identifying "hotspot" catchments of direct or indirect connectivity. Since the model results are not validated with independent data, they should always be combined with a verification in the field. ~~Therefore, we recommend continuing to use the NECM for decision-making in practice, but suggest that effort is put into improving the models in regions where the NECM and NSCM substantially differ.~~

~~It is, however, important to note, that within this study none of the models (NECM, LSCM, and NSCM) has been tested and validated empirically regarding their actual capacity to quantify the connectivity effects on surface runoff and related pesticide transport. This aspect is addressed in detail in the "further research" section.~~

For creating the NSCM, all crop areas on which pesticides are commonly applied (arable land, vineyards, orchards, horticulture) were assumed to contribute by the same amount to the pesticide transport via surface runoff. However, these crop types are known to differ in the amounts of pesticide applied (De Baan et al., 2015), in the amounts of surface runoff produced, and also with respect to their connectivity to surface waters. This assumption could therefore be refined by considering pesticide application data and by investigating surface runoff connectivity in vineyards, orchards and horticulture in more detail.

Relevance in a broader geographical context

This study focussed on the relevance of hydraulic shortcuts in Switzerland. To our knowledge, no studies have systematically analysed the occurrence of hydraulic shortcuts in other countries. Nevertheless, the available literature suggests that in some regions such man-made structures like roads, pipes, or ditches are important for connecting fields with the stream network. For example, this was reported in the regions Alsace (FR) (Lefrancq et al., 2013), Lower Saxony (DE) (Bug and Mosimann, 2011), Baden-Wuerttemberg (DE) (Gassmann et al., 2012), or Rhineland-Palatinate (DE) (Rübel, 1999). Based on our findings, we hypothesise that shortcuts are mainly important in areas with small field sizes. This increases the density of linear structures such as roads for access.

Implications for practice

In Swiss plant protection[1] legislation and authorisation, the effect of hydraulic shortcuts on pesticide transport is currently not considered. Pesticide application is prohibited within a buffer of 3 m along open water bodies and according to the Swiss proof of ecological performance (PEP) vegetated buffer strip have to at least 6 m wide. In contrast, along roads, a buffer of only 0.5 m is required. Hence, the current Swiss legislation is protecting surface waters against direct, but not against indirect transport. This contrasts with the results of this study, ~~showing~~ suggesting that approximately half of the surface runoff related pesticide transport is occurring indirectly. This implies that there is evidence of a systematic gap in understanding and regulating pesticide risk at the national scale. ~~This~~ The same gap ~~between legislation on direct and indirect transport~~ was already pointed out by Alder et al. (2015) for soil erosion. However, beyond anecdotal evidence (e.g. Doppler et al. (2012)), this gap has not yet been validated with independent measurements of surface runoff and pesticide transport in the field.

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[1] In this study, we have been using the general term “pesticides” instead of “plant protection products” to make the text more readable. Since we only looked at substances used for plant protection in an agricultural context, the term “plant protection products” would have been more precise. The term “pesticides”, however, also includes “biocides” which are substances for control of plants or animals used in a non-agricultural context and were not subject of this study. The substances addressed in this study are regulated in the Swiss plant protection legislation and authorisation.

While there remain important scientific questions about the validation of the suggested gap, authorities may wish to decide on mitigation measures despite such uncertainties. We therefore elaborate on potential mitigation measures in the following.

The most evident measure based on the current legislation are vegetated buffer strips along drained roads and around hydraulic shortcuts, infiltrating surface runoff before it reaches a shortcut. Generally, measures increasing infiltration capacity on the field would reduce pesticide transport. Other measures could aim on the shortcut structures themselves (e.g. construction of shortcuts as small infiltration basins, removal of shortcuts, or treatment of water in shortcuts) or on the pipe outlets (e.g. drainage of shortcuts to infiltration basins, treatment of water at the pipe outlet).

Finally, pesticide transport via hydraulic shortcuts ~~should~~ could be incorporated into the registration procedure and be considered for the mandatory mitigation measures that go with a registration. Models used in this context are currently only considering transport via direct surface runoff, erosion, tile drainages, and spray drift (De Baan, 2020).

Further research

Model validation. The model estimations presented here can give insight on pesticide transport via hydraulic shortcuts on ~~a large scale~~the catchment and the national scale. However, as pointed out above, ~~they have not been tested and~~these models lack a field validation~~validated in the field~~ with independent measurements on flow and pesticide transport. In the following, we suggest validation approaches to overcome this limitation.

~~Targeted measurements are needed to provide evidence on the quantitative relevance of this flow path. A field study in one catchment in the Swiss plateau (Schönenberger et al., in preparation) demonstrates that pesticide concentrations in shortcuts can be very high. However, more systematic research is needed to quantify the relevance of shortcuts. Ideally, catchment-scale experiments – e.g., with controlled pesticide applications (see Leu et al. (2004b);Doppler et al. (2012)) – would be carried out to quantify loss rates from directly and indirectly connected fields. Apart from the practical problems of implementing such experiments in the context of farmers managing their land, this~~

~~approach will often face the problem that many fields are also tile drained. Consequently, any signal in the stream is a superposition of different potential flow pathways.~~

In our opinion, a validation of the local surface runoff connectivity model is ideally performed by measuring runoff and pesticide transport in a set of different small catchments. This should be done along a gradient of ratios between indirectly to directly connected areas (see Figure 6). Ideally, the catchments should be similar with respect to their structure (e.g. size, stream length, slope, land use, climate, or soil properties). Signals measured at the catchment outlet are always a superposition of different flow pathways. Therefore, runoff and pesticide transport through hydraulic shortcuts cannot be directly measured at the catchment outlet. To disentangle transport through hydraulic shortcuts from other pathways we foresee two different approaches.

~~Given that the transport through shortcuts has no unique characteristic in the receiving stream, it is difficult to disentangle and quantify these pathways. This implies that one has to observe simultaneously flow and transport within a catchment at locations where one can differentiate between the flow paths.~~

The first approach aims on observing flow and transport within a catchment at locations where an unambiguous differentiation between the flow paths is possible. For example, hydraulic shortcuts in a catchment could be equipped with a discharge measurement and a water sampler. Such a setup would allow to determine the proportion of total catchment runoff and pesticide load that is transported via hydraulic shortcuts. In addition, isotopic tracers and runoff separation techniques could be used to determine the total amount of surface runoff contributing to catchment runoff. If the model is valid, the ratio of measured direct to measured indirect surface runoff should be proportional to the ratio of directly to indirectly connected areas. Additionally, these measurements could be used to improve the parametrisation of the local connectivity model.

However, due to the large numbers of measurement locations needed, the above-mentioned validation approach would be very laborious. The second validation approach therefore aims on disentangling transport through hydraulic shortcuts while only measuring at the catchment outlet of a set of catchments. For the interpretation of the local connectivity model, we assumed that direct and indirect surface runoff are proportional to the directly and indirectly connected area. If this assumption is valid, more surface runoff should reach the stream in catchments with larger fractions of connected areas. Consequently, in such catchments, runoff coefficients should be higher during discharge events that are predominenantly triggered by Hortonian overland flow such as intensive thunderstorms. For these events, uncertainties introduced by different subsurface properties of the catchments play a minor role compared to other events. Furthermore, if a set of catchments has similar fractions of directly connected area, but different fractions of indirectly connected area, larger runoff coefficients should be measured in catchments with larger fractions of indirectly connected area.

If the local connectivity model proves valid on the catchment scale, the question would be how to improve on the spatial extrapolation to the national scale. Except for the occurrence of hydraulic shortcuts, all input data for the local connectivity model are available on this larger scale as well. Therefore, the local connectivity model can easily be extended to much larger scales if the occurrence of hydraulic shortcuts is known. However, the shortcut mapping procedure used in this study is time-consuming. Thus, to efficiently map shortcuts on larger scales, automated algorithms for inlet localization using remote sensing data could be used (e.g. Mattheuwsen and Vergauwen (2020), Moy de Vitry et al. (2018)). An application of the local connectivity model to larger scales could then replace the extrapolation approach used in this study, eliminating the associated uncertainty.

Shortcuts in vineyards. Our results (i.e. Meyrin and additional field observations) suggest that the presence of hydraulic shortcuts as well as the fraction of indirectly connected areas are higher in vineyards than on arable land. Since this study focused mainly on the latter, the sample size was too small for a quantitative analysis of vineyards. The fact that Swiss vineyards usually have high road densities points into the same direction. In Swiss vineyards, pesticides are applied more often and in larger amounts than on arable land (De Baan et al., 2015). Therefore, an assessment of hydraulic shortcut relevance in vineyards is needed.

Spray drift on roads. Hydraulic shortcuts are not only collecting surface runoff from target areas, but also from non-target areas such as roads. As shown by Lefrancq et al. (2013), large amounts of spray drift can be deposited on roads. These deposits are expected to be washed off during rain events and to be transported to surface waters via hydraulic shortcuts. Further research is needed to quantify the relevance of this process for pesticide pollution in streams.~~should aim on quantifying the amounts of spray drift deposited on roads and transported to surface waters via hydraulic shortcuts.~~

Hydrological activity. In our discussion on the hydrological activity (see above), we explained that systematic differences in hydrological activity are unlikely within a catchment, but are expected across catchments. Further research should aim on quantifying the differences in hydrological activity across catchments and their influence on runoff formation. Some of the datasets that could serve such a comparison are available on the national scale (e.g. map of tile drainage potential (Koch and Prasuhn, 2020), or rainfall statistics (e.g. Frei et al. (2018)). Other datasets are currently being developed (e.g. a national plot-specific crop type dataset) or have to be developed (e.g. national soil maps).

5. Conclusions

Our study shows that hydraulic shortcuts are common structures found in Swiss arable land areas of the Swiss plateau. Shortcuts are found mainly along roads, but also directly in the field. The analyses suggests that on average, around half of the surface runoff connectivity on Swiss arable land is caused by hydraulic shortcuts. Further analyses on hydrological activity and crop density suggest that the same proportion of surface runoff and related pesticide load is transported to surface waters through hydraulic shortcuts. This statement holds for both, the selected study catchments, and the whole country. However, in Swiss pesticide legislation and pesticide authorisation, hydraulic shortcuts are currently not considered. Therefore, current regulations may fall short to address the full extent of the problem.

The field data acquired in this study ~~show~~ suggest that the national erosion connectivity model (NECM) is a useful ~~valid~~ tool for relatively comparing potential pesticide connectivity between catchments. However, the results also show that additional ~~empirical~~ field data ~~from the field~~ significantly changed the reported connectivity fractions and ~~that~~ improved the model reliability. ~~can be improved by additional empirical data.~~

Overall, the findings highlight the relevance of better understanding the connectivity between fields and the receiving water, ~~and~~as well as the underlying factors and physical structures in the landscape. The model results of this study lack a validation with field measurements on actual water flow and pesticide transport in hydraulic shortcuts. This should be addressed in further research. Propositions for such validations are presented in the discussion section.

This study focused on the contribution of hydraulic shortcuts to surface runoff connectivity and related pesticide transport on arable land. However, ~~hydraulic shortcuts on surface runoff on~~ for other crop types, ~~other types of agricultural crops~~, ~~such as orchards or vineyards~~the contribution of shortcuts is expected to be different. Especially in vineyards, we expect a higher contribution due to their spatial structure (e.g. high road densities, or steep slopes) and due to higher pesticide use.

6. Code availability

If the manuscript is accepted, the following code will be made available via https://opendata.eawag.ch/ (FAIR repository):

- Code for random selection of study areas
- Code for definition of agricultural areas

7. Data availability

If the manuscript is accepted, the following datasets will be made available via https://opendata.eawag.ch/ (FAIR repository):

- Study areas (GIS dataset)
- Aerial images
- Shortcut locations (GIS dataset)
- Estimated fractions of directly and indirectly connected areas for all catchments in valley zones, hill zones and lower elevation mountain zones (results of the NSCM model)

8. Team list

Urs Schönenberger, Christian Stamm

9. CRedit author contribution statement

Urs Schönenberger: Conceptualization, Methodology, Investigation, Formal analysis, Software, Data curation, Writing - original draft, Visualization

Christian Stamm: Conceptualization, Methodology, Writing - review & editing, Funding acquisition

10. Competing interests

Author Christian Stamm is a member of the editorial board of the HESS journal.

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S. Supporting Information

S1. Methods

S1.1. Catchment statistics

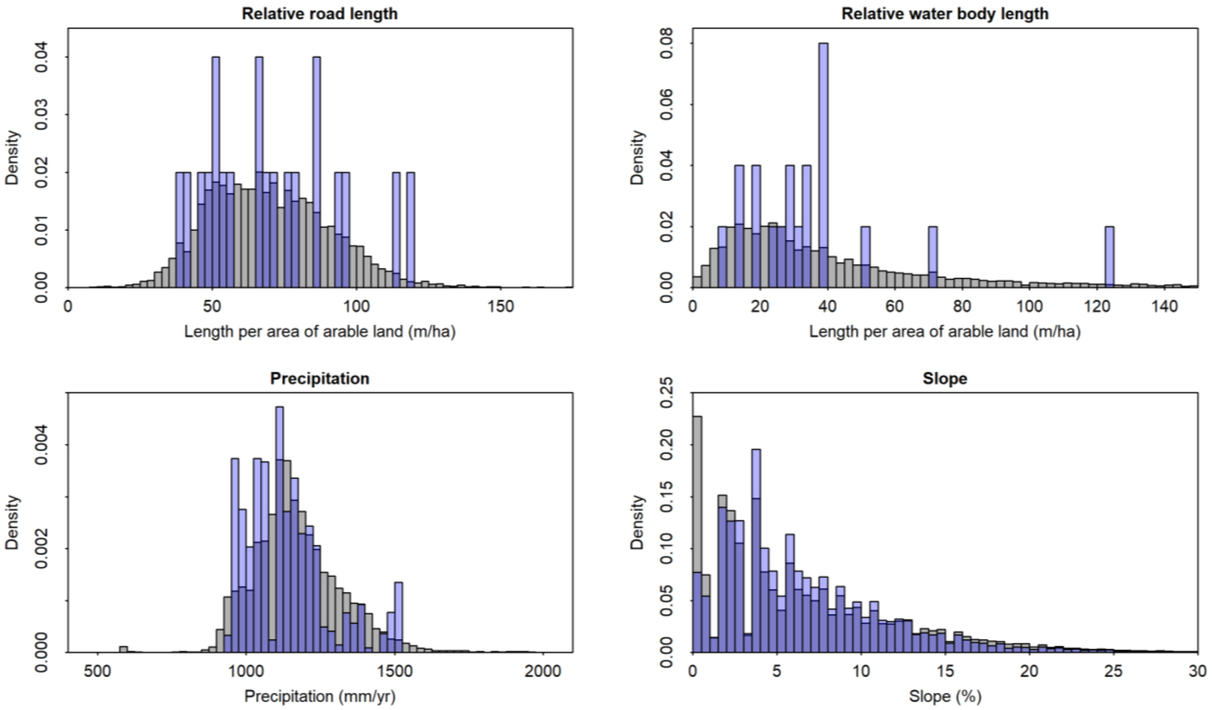


Figure S 1: Histogram of catchment statistics for study areas (blue) and all catchments in Switzerland containing arable land (grey). Catchment statistics were calculated only for catchment parts defined as arable land areas by the dataset BFS (2014). Relative road length (road length per arable land area) and relative water body length (water body length per arable land area) were derived from the dataset swissTLM3D (Swisstopo, 2010). Precipitation was derived from Kirchhofer and Sevruk (1992), and slope from Swisstopo (2018).

Table S 1: List of catchment statistics calculated for finding explanatory variables for extrapolation to the national scale. Additionally, the datasets used for calculating those statistics are shown.

Catchment statistic	Data source	Dataset used
Fraction of forests	swissTLM3D (Swisstopo, 2010): TLM_BODENBEDECKUNG	OBJEKTART in [12,13]
Fraction of agricultural area	swissTLM3D (Swisstopo, 2010): ○ TLM_BODENBEDECKUNG, ○ TLM_STRASSEN, ○ TLM_SIEDLUNGSNAME, ○ TLM_NUTZUNGSAREAL	(Total area) - (forests, water bodies, urban areas, traffic areas, and other non-agricultural areas)
Road density (total; paved; unpaved)	swissTLM3D (Swisstopo, 2010): TLM_STRASSEN	BELAGSART in [100,200]; BELAGSART = 100; BELAGSART = 200
Water body density (total; rivers; lakeshores)	swissTLM3D (Swisstopo, 2010): ○ TLM_FLIESSGEWAESSER ○ TLM_STEHENDES_GEWAESSER	Both datasets; TLM_FLIESSGEWAESSER only; TLM_STEHENDES_GEWAESSER only
Mean annual precipitation	Kirchhofer and Sevruk (1992)	Mean annual precipitation depths 1951-1980
Mean slope of agricultural areas	swissALTI3D (Swisstopo, 2018)	Slopes as calculated by swisstopo, agricultural areas as defined above
Area fractions (direct; indirect; not connected)	Alder et al. (2015)	Fraction of total directly connected area; fraction of total indirectly connected area; fraction of total not connected area

S1.2. Examples of mapped structures

A1 - Storm drainage inlets on or next to roads or farm tracks

Storm drainage inlets on or next to roads or farm tracks were always considered as a potential shortcut in the connectivity model.

Figure S 2: Storm drainage inlet with a gridded metal lid on a road in the study area Nürensdorf

Figure S 3: Lateral concrete storm drainage inlet next to a road in the study area Molondin

Figure S 4: Storm drainage inlet with a gridded metal lid on a road in the study area Oberneunforn

A2 - Strom drainage inlets on fields

Storm drainage inlets on fields are always considered as a potential shortcut in the connectivity model.

Figure S 5: Storm drainage inlet with a metal grid lid in a field of the study area Meyrin

Figure S 6: Storm drainage inlet with a concrete grid lid in a field of the study area Nürensdorf

B1 – Maintenance manholes on or next to roads

Maintenance manholes on or next to roads are considered a potential shortcut if they are located in an internal sink (only for shortcut definition B).

Figure S 7: Maintenance manhole with a metal lid with a pick hole next to a road in the study area Buchs

Figure S 8: Maintenance manhole with a concrete lid with a pick hole on a road in the study area Courroux

B2 – Maintenance manholes on fields

Maintenance manholes on fields are considered a potential shortcut if they are located in an internal sink (only for shortcut definition B).

Figure S 9: Damaged tile drainage maintenance manhole in a field in the study area Vufflens-la-Ville

Figure S 10: Tile drainage maintenance manhole in a field in the study area Molondin

C1 – Channel drains

Figure S 11: Channel drain on a road in the study area Clarmont

Figure S 12: Channel drain and inlet with a metal grid lid on a road in the study area Lommiswil

C2 – Ditches

Figure S 13: Ditch between a field and a road in the study area Meyrin

S1.3. List of mapped structures

Table S 2: Types of mapped point features

ID	Description	Potential shortcut
1	Inlet	Yes
2	Maintenance manhole	If lying in an internal sink (shortcut definition B)
3	Other manhole	If lying in an internal sink (shortcut definition B)
4	Stormwater tank	If lying in an internal sink (shortcut definition B)
5	Spillway	If lying in an internal sink (shortcut definition B)
6	Pumping station	No
7	House connection	No
8	Other point object	No
9	Unknown manhole	If lying in an internal sink (shortcut definition B)
10	Outfall	No
11	Infiltration structure	If lying in an internal sink (shortcut definition B)
12	Unknown object	No

Table S 3: Types of lids

ID	Description
1	Metal grid
2	Concrete lid with pick hole
3	Concrete lid without pick hole
4	Metal lid with pick hole
5	Metal lid without pick hole
6	Other lid type
7	Concrete grid
8	Concrete lid with lateral inlet
9	Metal lid with lateral inlet
0	Unknown lid type

Table S 4: Types of line features mapped

ID	Description	Potential shortcut
1	Drainage pipe	No
2	Tile drainage pipe	No
3	Other pipe	No
4	Channel drain	Yes
5	Ditch	Yes
6	Sequence of channel drains & ditches	Yes
7	Stone wall	No
8	Earth wall	No
9	Hedge	No
10	River	No
11	Other line objects	No
12	Unknown line objects	No

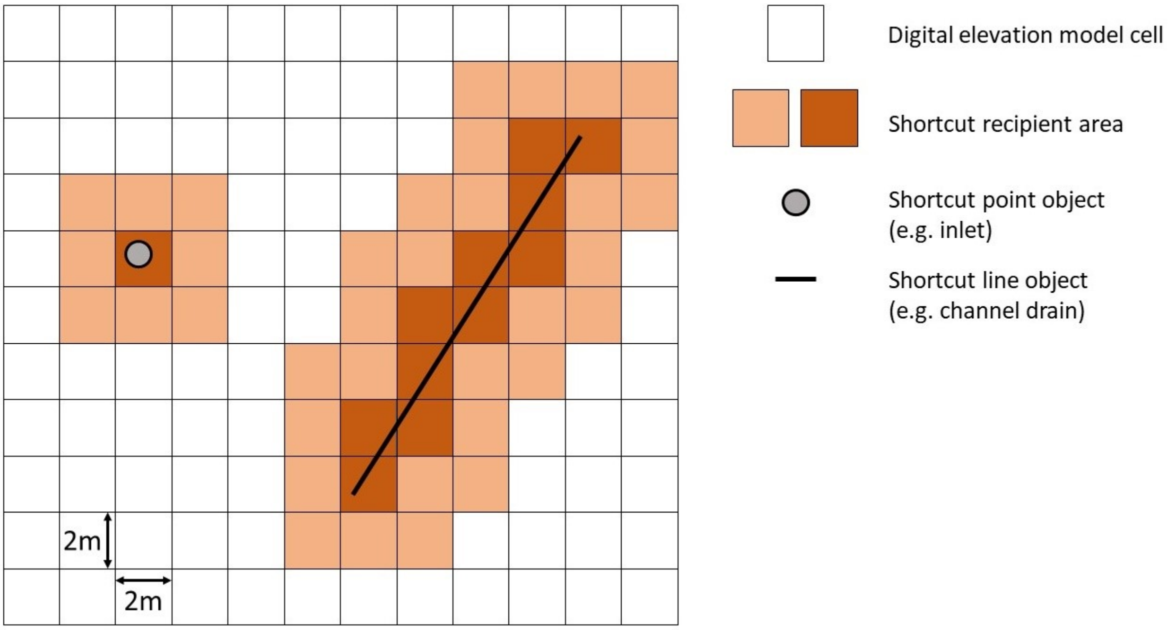


Figure S 14: Definition of shortcut recipient areas

S1.4. Dates of field mapping and drone flights

Table S 5: Dates of field mapping and drone flights for each study area. In some areas a second drone flight had to be performed to ensure sufficient image quality.

ID	Location	Date field mapping	Date drone flights
1	Böttstein	26.10.2017	26.10.2017
2	Ueken	25.10.2017	25.10.2017
3	Rüti b. R.	23.11.2017	23.11.2017
4	Romont	02.11.2017	03.11.2017
5	Meyrin	27.11.2017	Usage of cantonal aerial images only
6	Boncourt	24.11.2017	24.11.2017; 07.06.2018
7	Courroux	17.11.2017	17.11.2017
8	Hochdorf	29.09.2017	27.04.2018
9	Müswangen	21.09.2017	16.08.2018
10	Fleurier	24.05.2018	24.05.2018
11	Lommiswil	16.11.2017	16.11.2017
12	Illighausen	30.08.2017	07.12.2017
13	Oberneunforn	06.09.2017	01.11.2017; 19.04.2018
14	Clarmont	09.11.2017	10.11.2017; 04.12.2017
15	Molondin	02.11.2017	03.11.2017
16	Suchy	10.11.2017	08.11.2017
17	Vufflens	09.11.2017	08.11.2017; 24.08.2018
18	Buchs	23.08.2017	09.08.2017; 17.08.2017
19	Nürensdorf	18.09.2017	24.10.2017
20	Truttikon	20.09.2017	01.11.2017

S1.5. Extrapolation to the national scale

In the following, mathematical details on the extrapolation of the local surface runoff connectivity model (LSCM) to the national scale are given. A schematic overview is given in the main part of this publication. Our model is using the area fractions of the national erosion connectivity model (NECM) to extrapolate the LSCM to the national scale, resulting in area fractions of a national surface runoff connectivity model (NSCM).

We defined the area fractions of model *m* and catchment *c* as follows:

$$\boldsymbol{f_m} = \begin{pmatrix} \overrightarrow{f_{m,dir}}^T \\ \overrightarrow{f_{m,indir}}^T \\ \overrightarrow{f_{m,nc}}^T \end{pmatrix} = \begin{pmatrix} f_{m,dir,1} & \cdots & f_{m,dir,c} & \cdots & f_{m,dir,n} \\ f_{m,indir,1} & \cdots & f_{m,indir,c} & \cdots & f_{m,indir,n} \\ f_{m,nc,1} & \cdots & f_{m,nc,c} & \cdots & f_{m,nc,n} \end{pmatrix} = \begin{pmatrix} \frac{A_{m,dir,1}}{A_{tot,1}} & \cdots & \frac{A_{m,dir,c}}{A_{tot,c}} & \cdots & \frac{A_{m,dir,n}}{A_{tot,n}} \\ \frac{A_{m,indir,1}}{A_{tot,1}} & \cdots & \frac{A_{m,indir,c}}{A_{tot,c}} & \cdots & \frac{A_{m,indir,n}}{A_{tot,n}} \\ \frac{A_{m,nc,1}}{A_{tot,1}} & \cdots & \frac{A_{m,nc,c}}{A_{tot,c}} & \cdots & \frac{A_{m,nc,n}}{A_{tot,n}} \end{pmatrix} \tag{1}$$

with: m: Model (either LSCM, NECM, or NSCM)

$A_{m,dir,c}$: Directly connected agricultural area of model m in catchment c (ha)

$A_{m,indir,c}$: Indirectly connected agricultural area of model m in catchment c (ha)

$A_{m,nc,c}$: Not connected agricultural area of model m in catchment c (ha)

$A_{tot,c}$: Total agricultural area in catchment c (ha)

$f_{m,dir,c}$: Fraction of directly connected agricultural areas of model m in catchment *c* (-)

$f_{m,indir,c}$: Fraction of indirectly connected agricultural areas of model m in catchment *c* (-)

$f_{m,nc,c}$: Fraction of not connected agricultural areas of model m in catchment *c* (-)

The area fraction matrices $\boldsymbol{f_m}$ underlie two boundary conditions (see main part). To ensure that extrapolation model meets these boundary conditions, we used a unit simplex transformation approach.

We performed a unit simplex inverse transformation to the area fraction matrices of the LSCM $\boldsymbol{f_{LSCM}}$ and the NECM $\boldsymbol{f_{NECM}}$ (3x20 matrices), resulting in the matrices $\boldsymbol{z_{LSCM}}$ and $\boldsymbol{z_{NECM}}$ (2x20 matrices).

$$\boldsymbol{z} = \begin{pmatrix} \overrightarrow{z_1}^T \\ \overrightarrow{z_2}^T \end{pmatrix} = \begin{cases} logit^{-1}\left(\overrightarrow{f_k}^T + log\left(\frac{1}{K-k}\right)\right) & \mid k = 1 \\ \left(1 - \sum_{k=1}^{k-1} \overrightarrow{z_k}^T\right) \cdot logit^{-1}\left(\overrightarrow{f_k}^T + log\left(\frac{1}{K-k}\right)\right) = \left(1 - \overrightarrow{z_1}^T\right) \cdot logit^{-1}\left(\overrightarrow{f_k}^T\right) & \mid k = 2 \end{cases} \tag{2}$$

$$with: K = 3$$

In order to model the difference $\Delta\boldsymbol{z}$ (2x20 matrix) between the transformed LSCM and the transformed NECM ($\Delta\boldsymbol{z} = \boldsymbol{z}_{LSCM} - \boldsymbol{z}_{NECM}$), we tested the same list of nationally available catchment statistics that was already used before. For each of the two dimensions, we selected the variable that correlated best with $\Delta\boldsymbol{z}$. Those were the fraction of directly connected areas $f_{NECM,dir}$, and the fraction of indirectly connected areas $f_{NECM,indir}$. Using these variables, we performed the following linear regression to describe $\Delta\boldsymbol{z}$:

$$\Delta\boldsymbol{z} = \vec{a} + \vec{b} \cdot \begin{pmatrix} \overrightarrow{f_{NECM,dir}}^{T} \\ \overrightarrow{f_{NECM,indir}}^{T} \end{pmatrix} + \vec{\varepsilon} \qquad (3)$$

For each of the catchments of the transformed national erosion connectivity model ($\boldsymbol{z}_{NECM}$, 2xn matrix, n = 11’503), this linear regression was used to calculate the transformed national surface runoff connectivity model ($\boldsymbol{z}_{NSCM}$, 2xn matrix):

$$\mathbf{z}_{NSCM} = \mathbf{z}_{NECM} + \Delta\boldsymbol{z} \qquad (4)$$

Finally, using a unit simplex transformation, we transformed $\boldsymbol{z}_{NSCM}$ back, resulting in the area fraction matrix of the national surface runoff connectivity model $\boldsymbol{f}_{NSCM}$ (3xn matrix).

$$\boldsymbol{f}_{NSCM} = \begin{cases} \boldsymbol{f}_{NSCM,k} = logit\left(\boldsymbol{z}_{NSCM,k}\right) - log\left(\frac{1}{K-k}\right) & \mid \mathrm{k} = 1 \\ \boldsymbol{f}_{NSCM,k} = logit\left(\frac{z_{NSCM,k}}{1-\sum_{k=1}^{k-1} z_{NSCM,k}}\right) - log\left(\frac{1}{K-k}\right) & \mid \mathrm{k} > 1 \end{cases} \\ with\ K = 3 \qquad (5)$$

This extrapolation model was run for each of the 100 area fractions matrices resulting from the Monte Carlo analysis that was performed on the local scale.

To address the uncertainty introduced by the selection of our study catchments, we bootstrapped the model 100 times. For each of the bootstrapping iterations 20 of our study catchments were resampled randomly.

S2. Results

S2.1. Occurrence of hydraulic shortcuts

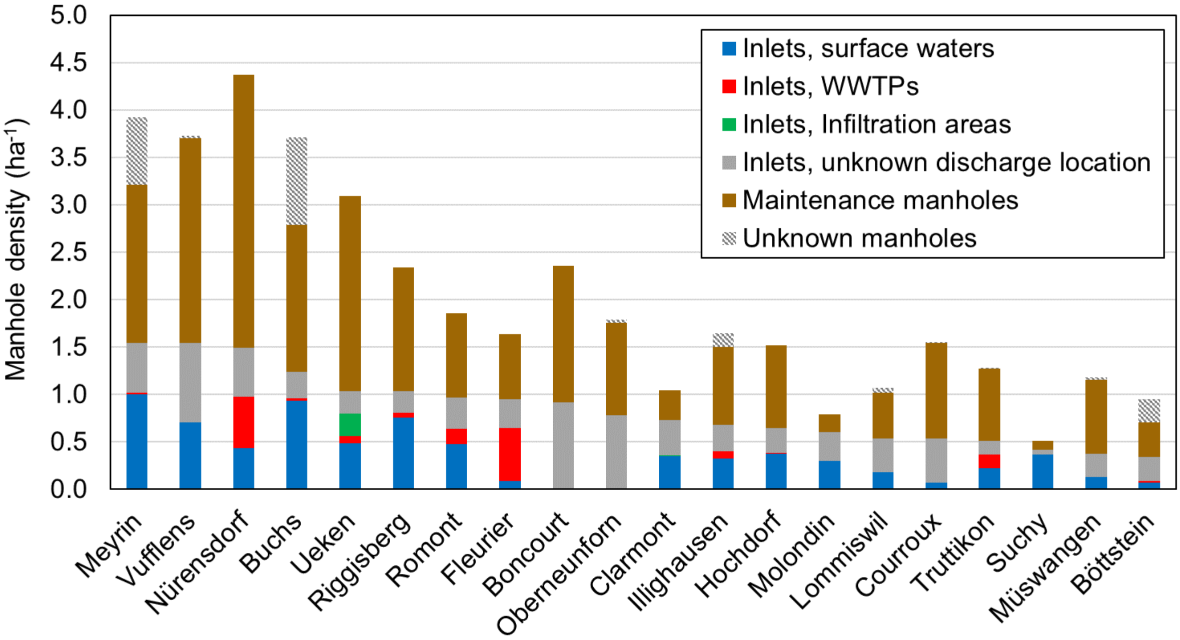


Figure S 15: Density of manholes (ha^{-1}) on agricultural areas of the study catchments

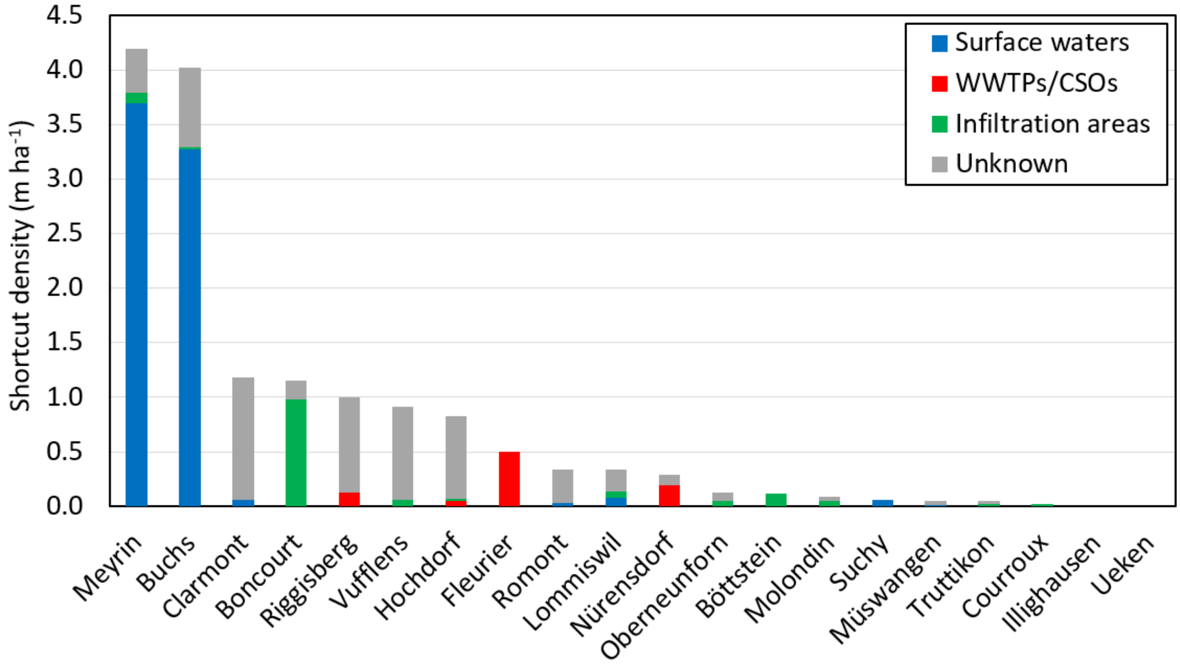


Figure S 16: Density of channel drains and ditches (m ha^{-1}) on agricultural areas of the study catchments

Table S 6: Linear regression of different catchment statistics with inlet densities (ha^{-1}) per study area. R^2 equals the coefficient of determination, m is the slope of the linear regression, and p is the p-value.

Catchment statistic	R^2	m	p
Paved road density (m^{-1})	3.3E-01	5.7E+01	8.4E-03**
Unpaved road density (m^{-1})	6.3E-02	-1.5E+01	2.8E-01
Mean annual precipitation (mm yr^{-1})	4.9E-04	-5.1E-05	9.3E-01
Mean slope on agricultural areas (deg)	8.3E-04	-4.7E-03	9.0E-01
Surface water body density (m^{-1})	4.4E-02	-4.3E-05	3.7E-01
Subsurface water body density (m^{-1})	6.2E-02	5.1E+02	2.9E-01

Table S 7: Linear regression of different catchment statistics with maintenance manhole densities (ha^{-1}) per study area. R^2 equals the coefficient of determination, m is the slope of the linear regression, and p is the p-value.

Catchment statistic	R^2	m	p
Paved road density (m^{-1})	3.7E-01	1.8E+02	4.6E-03**
Unpaved road density (m^{-1})	3.1E-02	-3.2E+01	4.6E-01
Mean annual precipitation (mm yr^{-1})	4.2E-03	-4.5E-04	7.9E-01
Mean slope on agricultural areas (deg)	1.6E-02	-6.2E-02	6.0E-01
Surface water body density (m^{-1})	3.5E-02	-1.2E-04	4.3E-01
Subsurface water body density (m^{-1})	1.2E-01	2.2E+03	1.3E-01

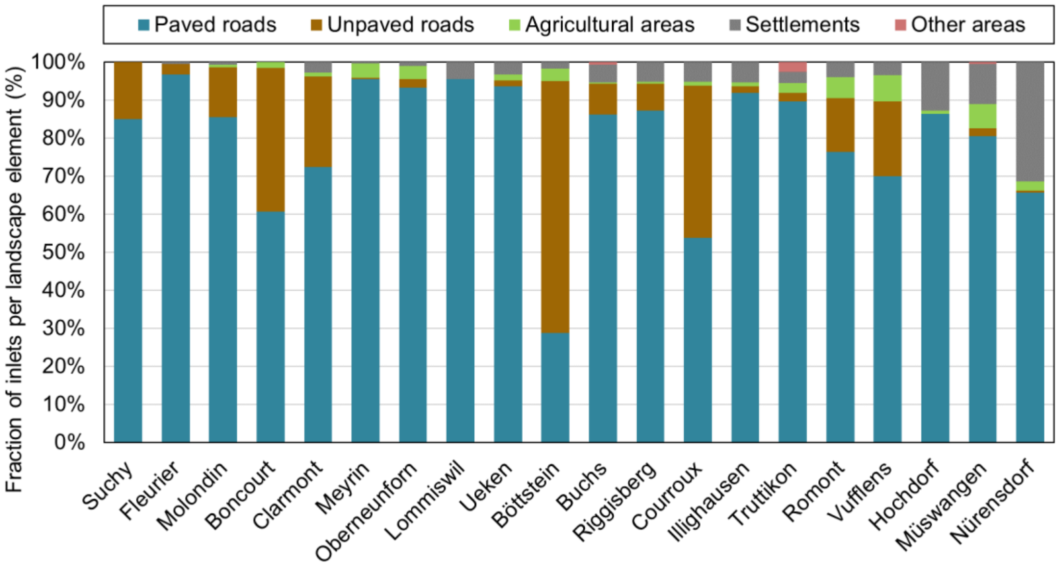


Figure S 17: Fraction of inlets per study area belonging to a certain landscape element

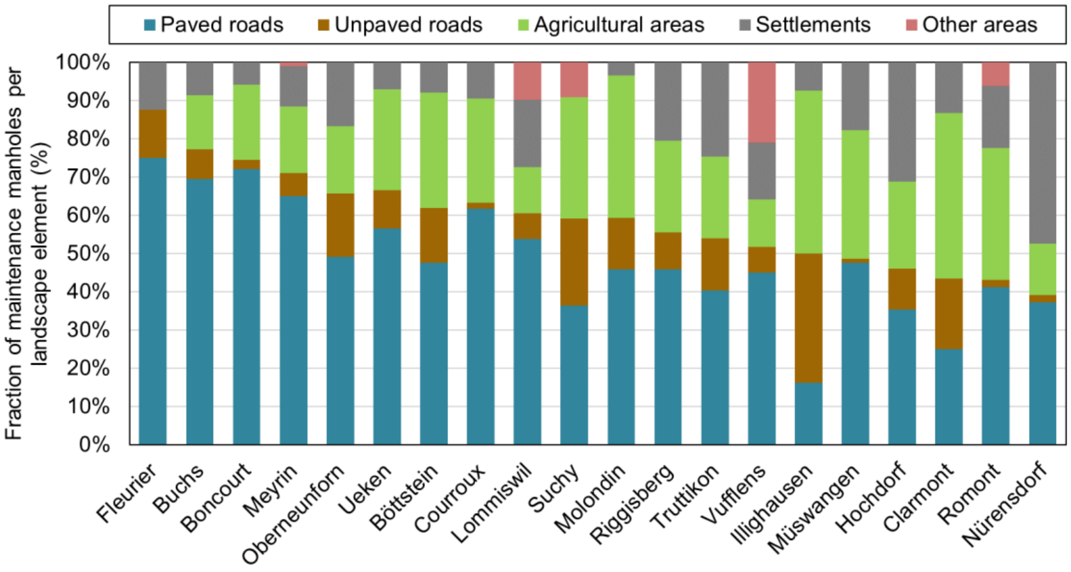
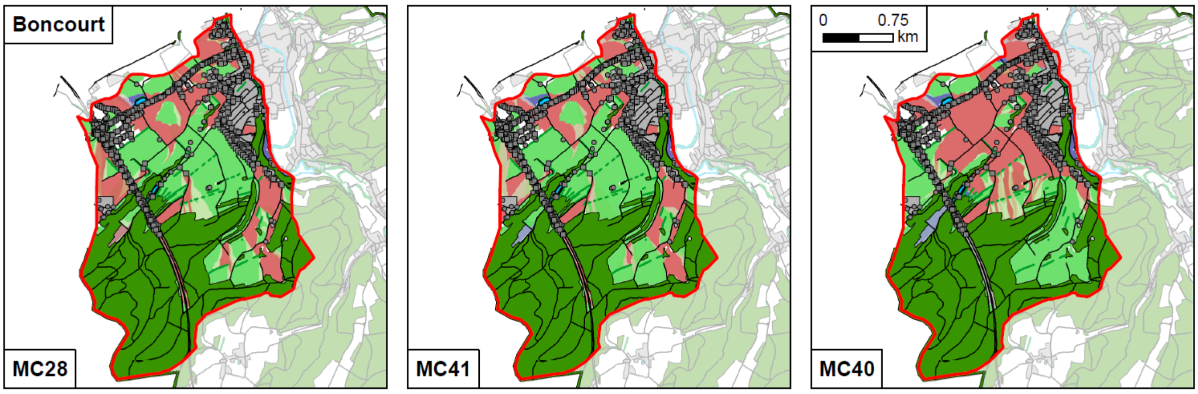


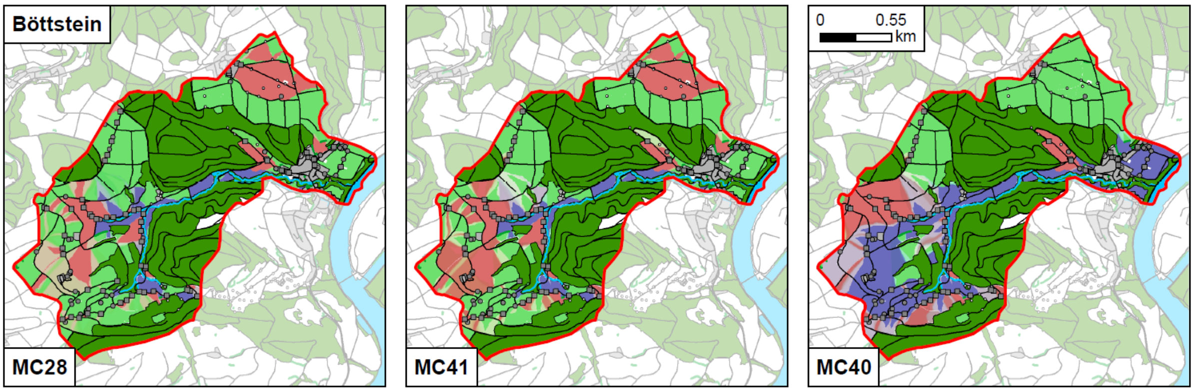
Figure S 18: Fraction of maintenance manholes per study area belonging to a certain landscape element

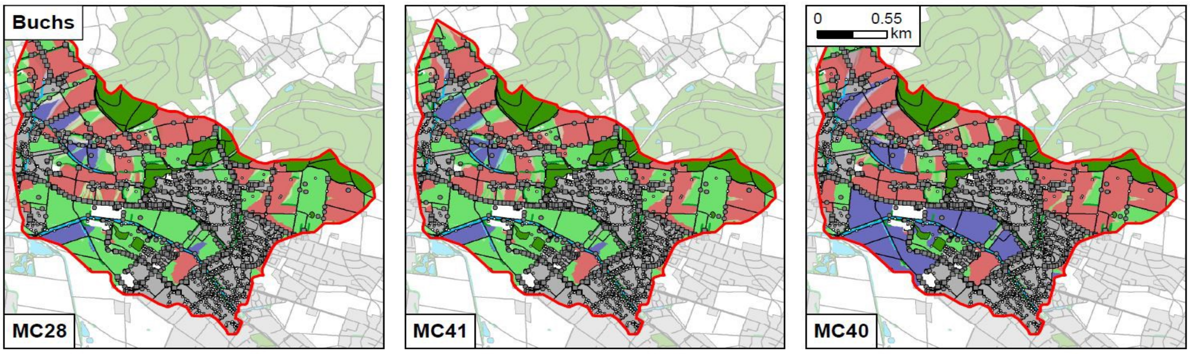
S2.2. Surface runoff connectivity: Study areas

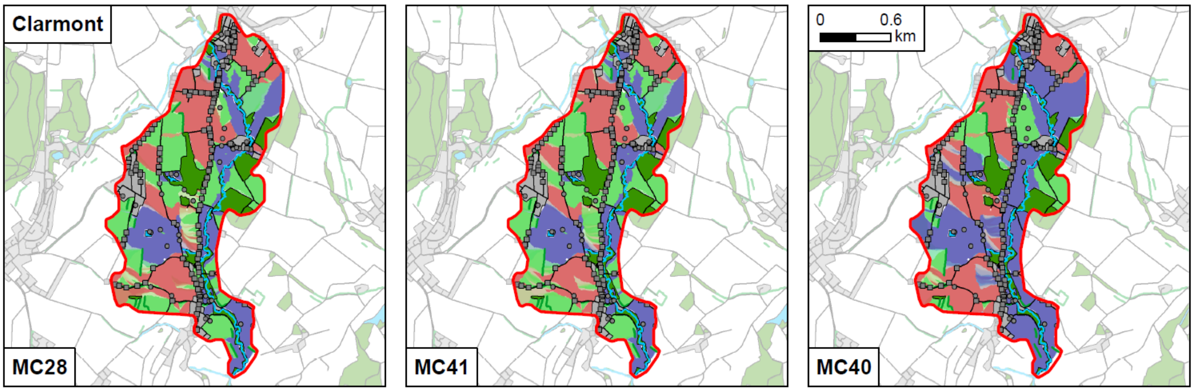
S2.2.1. Example results for each study area

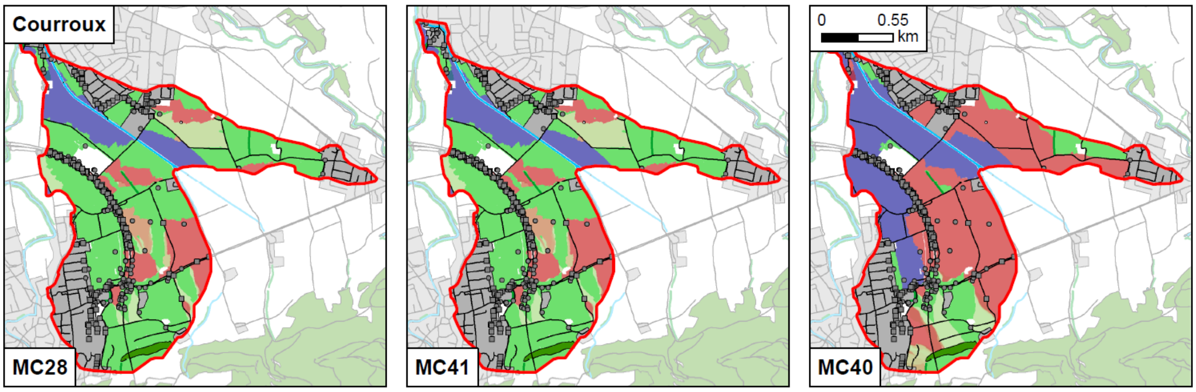
In the following, three example Monte Carlo analysis results (MC28, MC41, and MC40) are given for each of the study areas. The figures below correspond to Figure 5 in the main part.

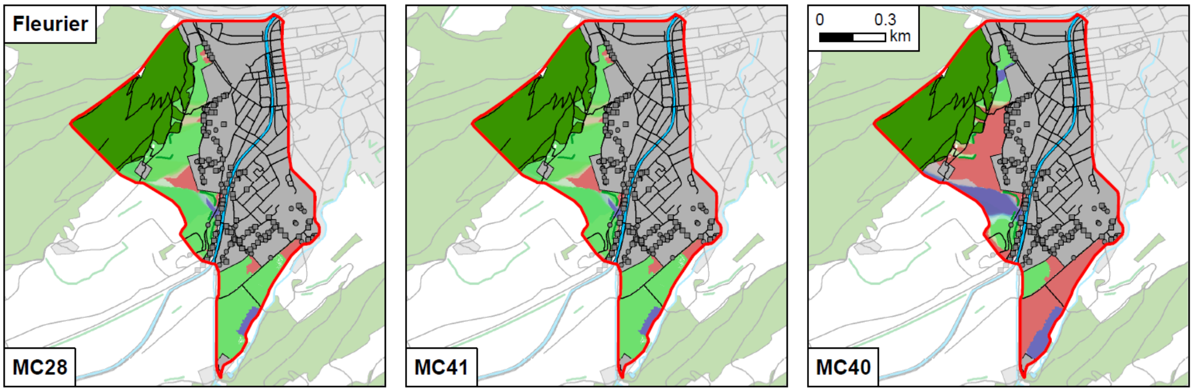


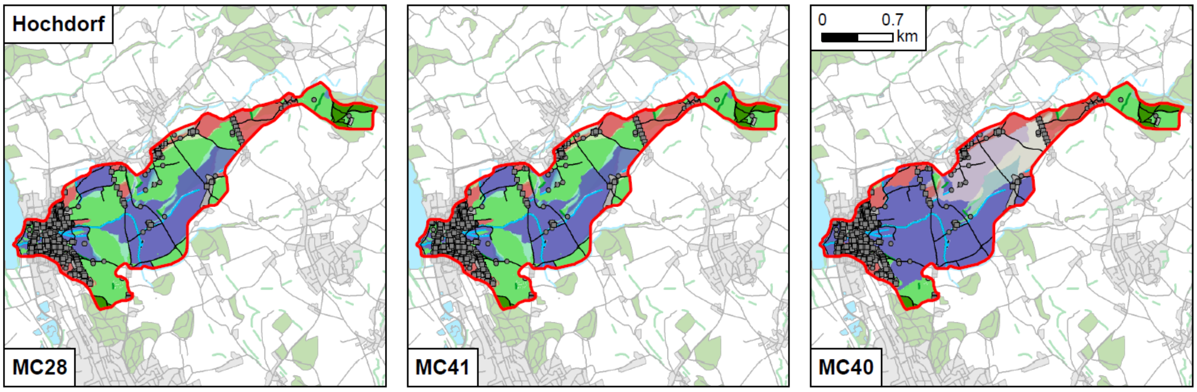

Böttstein
MC28
MC41
0
0.55
km
MC40

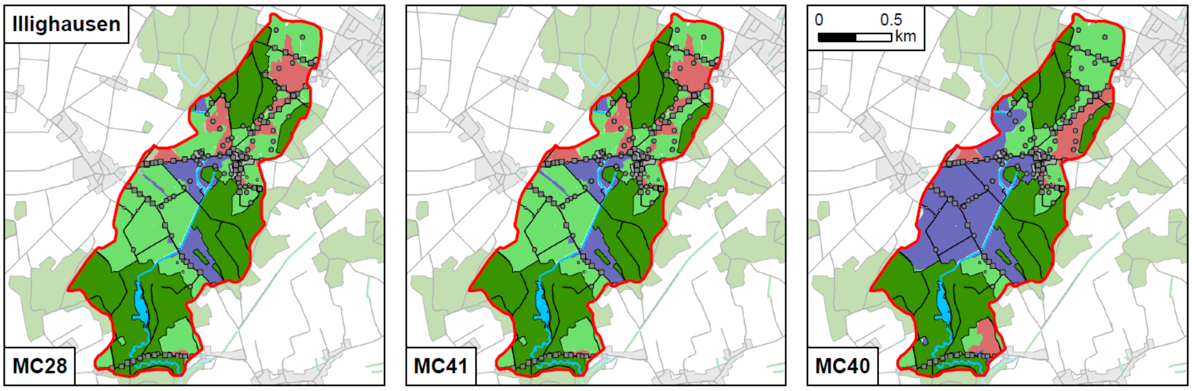

Buchs
MC28
MC41
0
0.55
km
MC40

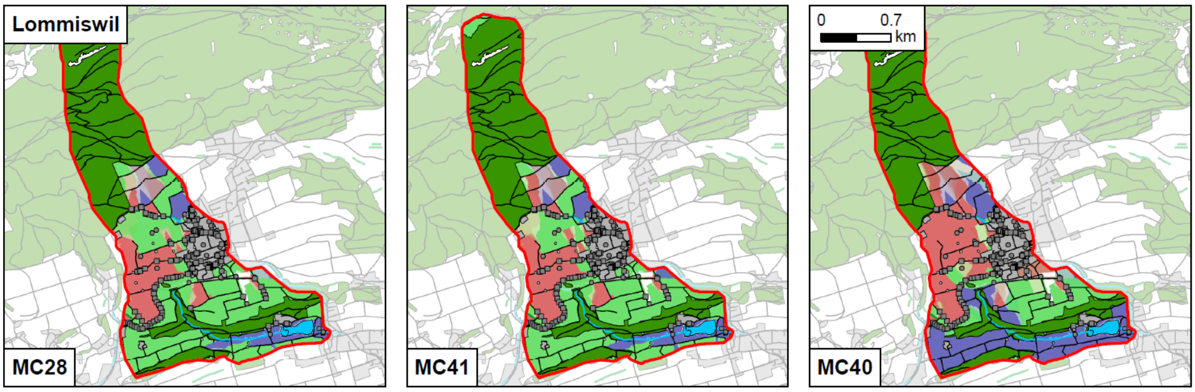

Clarmont
MC28
MC41
0
0.6
km
MC40

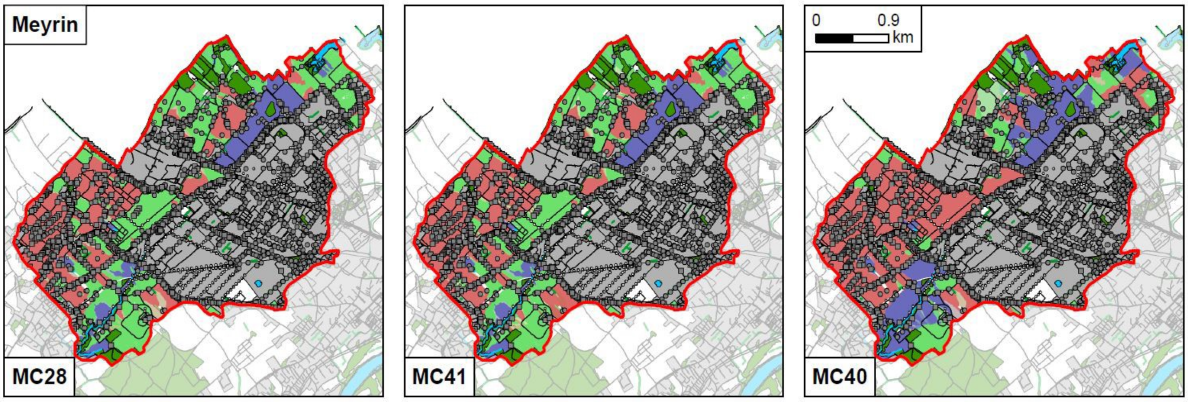

Courroux
MC28
MC41
0
0.55
km
MC40

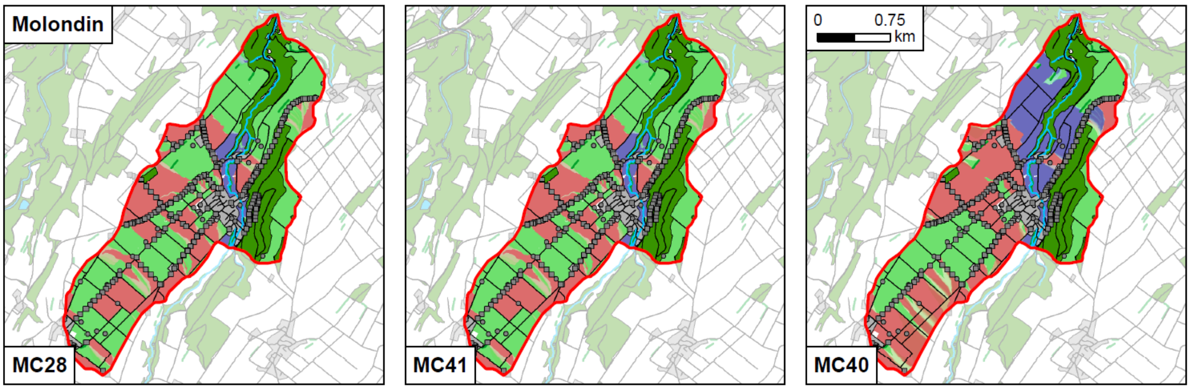

Fleurier
MC28
MC41
0
0.3
km
MC40

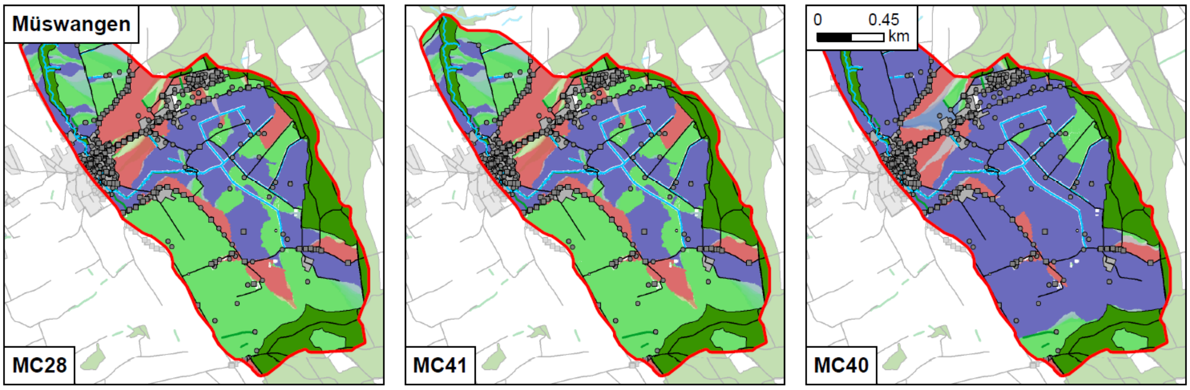

Hochdorf
MC28
MC41
0
0.7
km
MC40

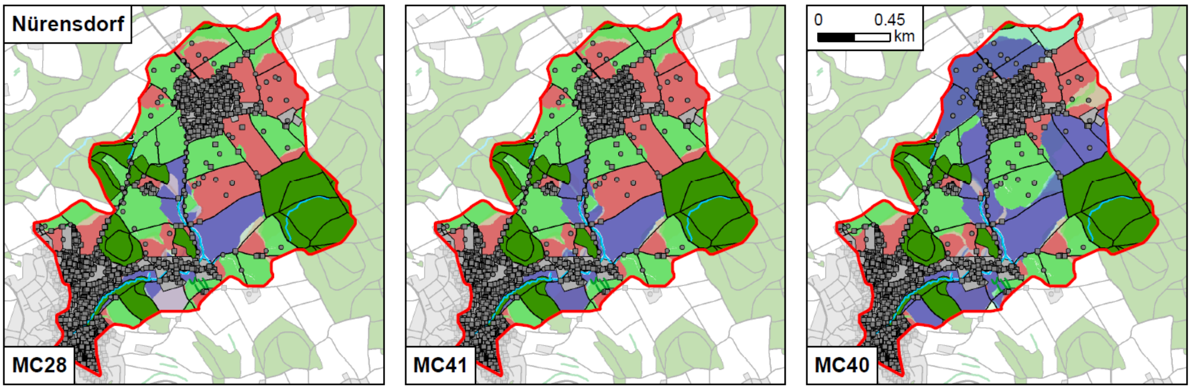

Illighausen
MC28
MC41
0
0.5
km
MC40

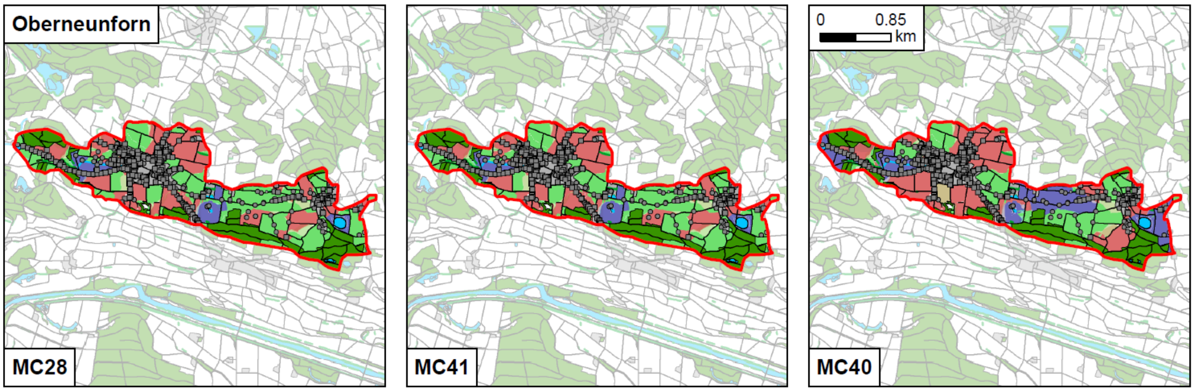

Lommiswil
MC28
MC41
0
0.7
km
MC40

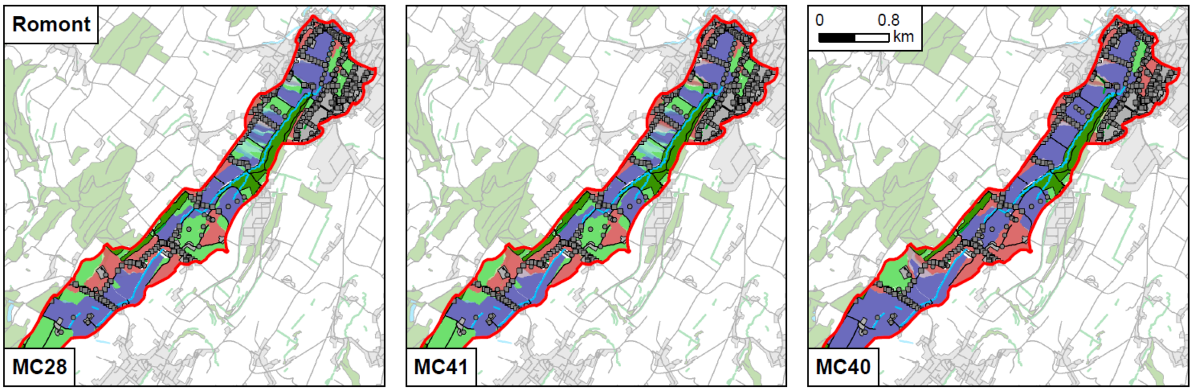

Meyrin
0
0.9
km
MC28
MC41
MC40

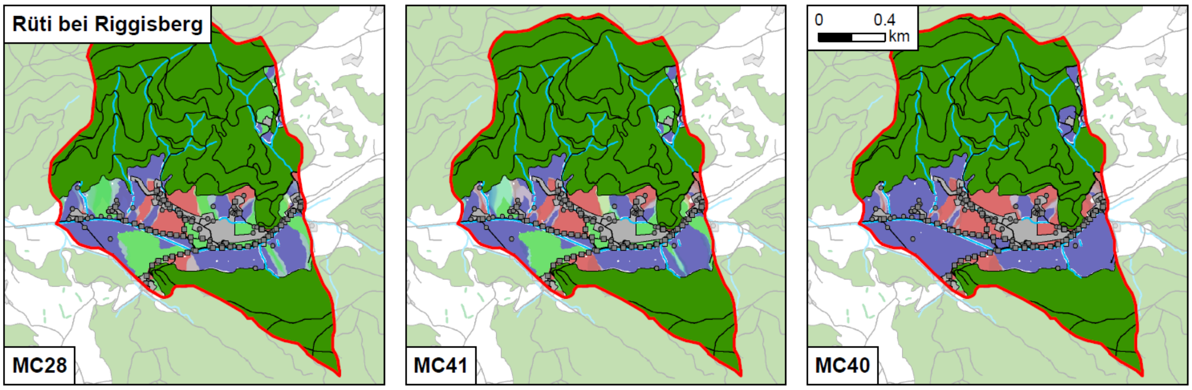

Molondin
0
0.75
km
MC28
MC41
MC40

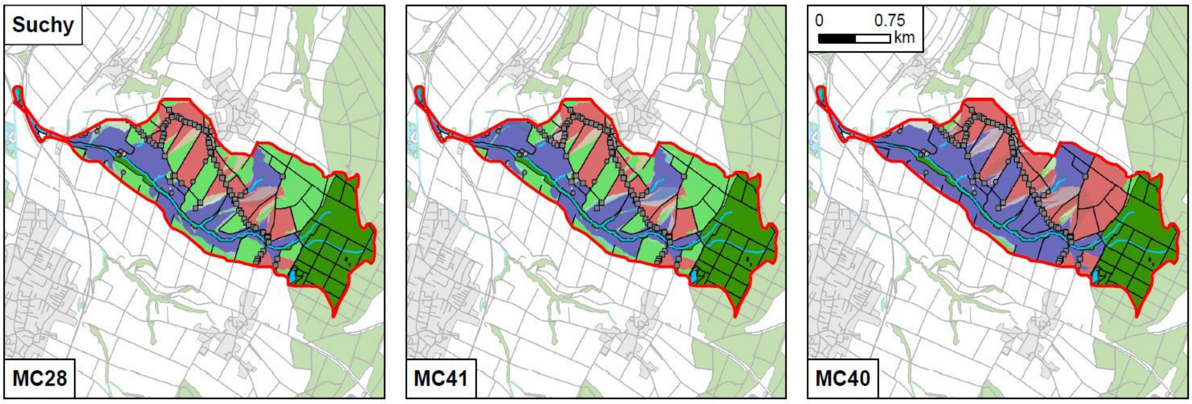

Müswangen
0
0.45
km
MC28
MC41
MC40

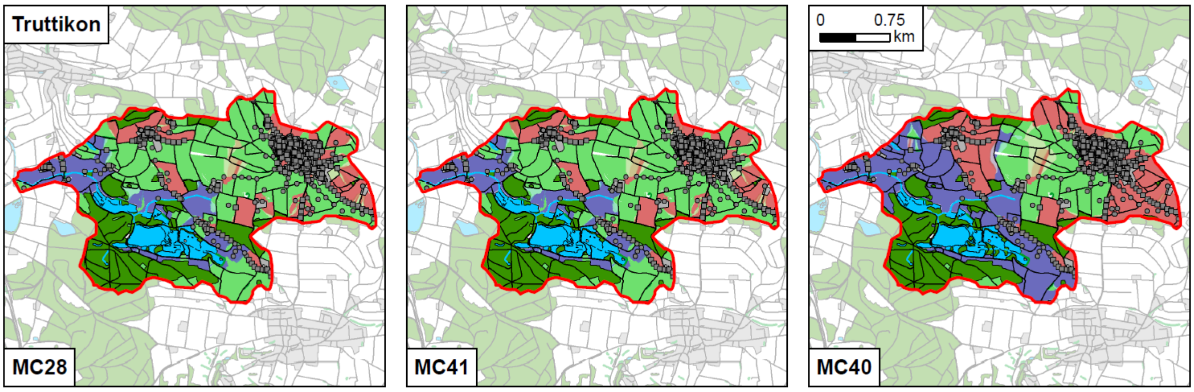

Nürensdorf
0
0.45
km
MC28
MC41
MC40

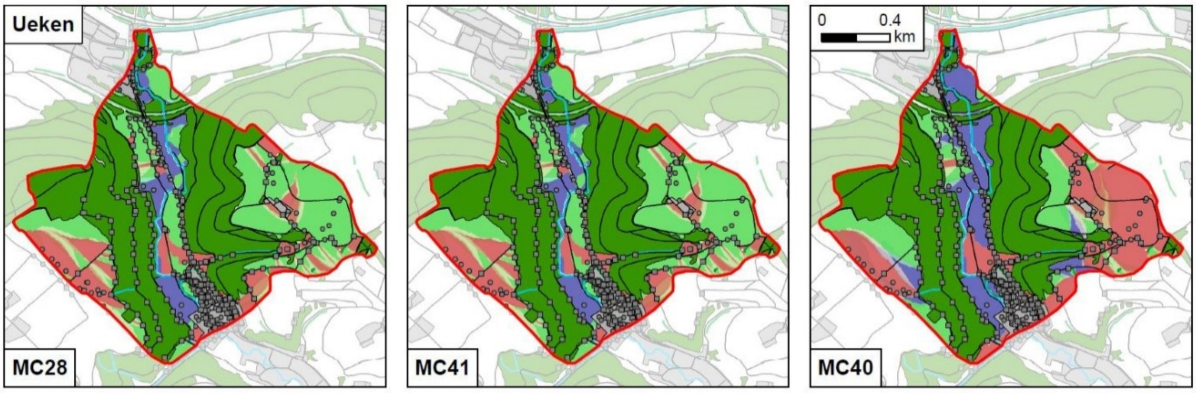

Oberneunforn
0 0.85 km
MC28
MC41
MC40

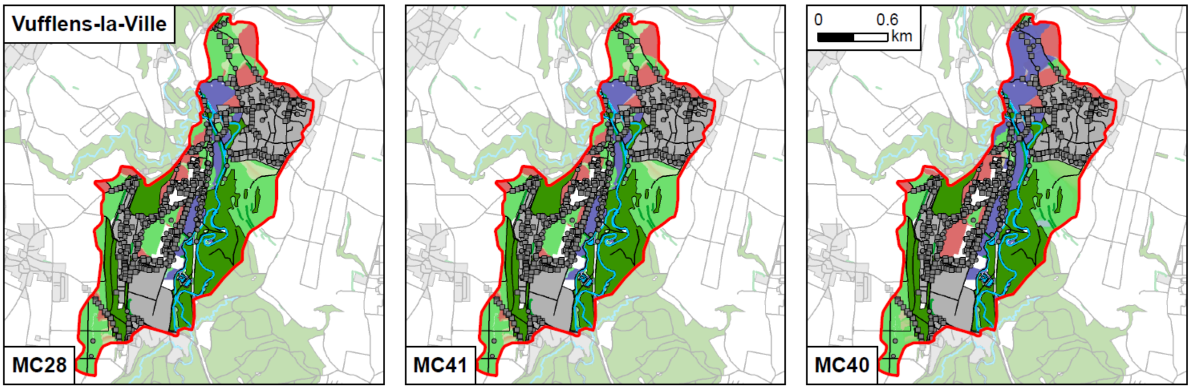

Romont
0 0.8 km
MC28
MC41
MC40


Rüti bei Riggisberg
0 0.4 km
MC28
MC41
MC40


Suchy
0 0.75 km
MC28
MC41
MC40


Truttikon
0 0.75 km
MC28
MC41
MC40


Ueken
0 0.4 km
MC28
MC41
MC40


Vufflens-la-Ville
0 0.6 km
MC28
MC41
MC40

S2.2.2. Monte Carlo Results: Directly, indirectly, and not connected areas

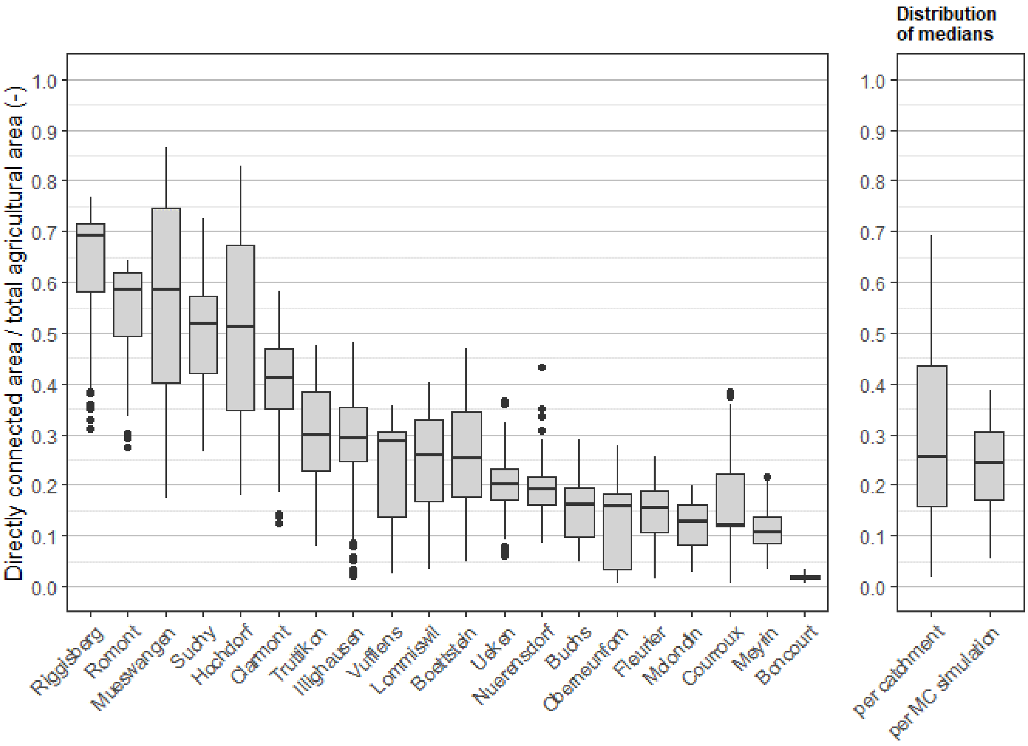


Figure S 19: Left: Directly connected area per total agricultural area (-) as calculated by the Monte Carlo analysis for each study area. Right: Distribution of medians of directly connected area per total agricultural area (-) per study area and per Monte Carlo simulation.

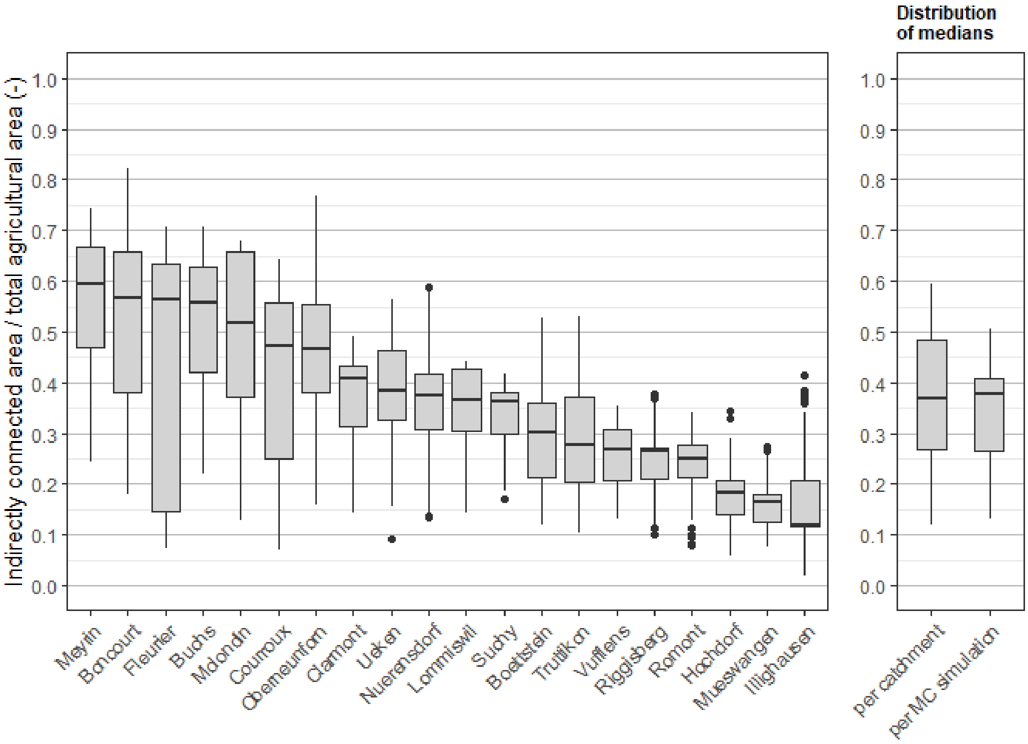


Figure S 20: Indirectly connected area per total agricultural area (-) as calculated by the Monte Carlo analysis for each study area. Right: Distribution of medians of indirectly connected area per total agricultural area (-) per study area and per Monte Carlo simulation.

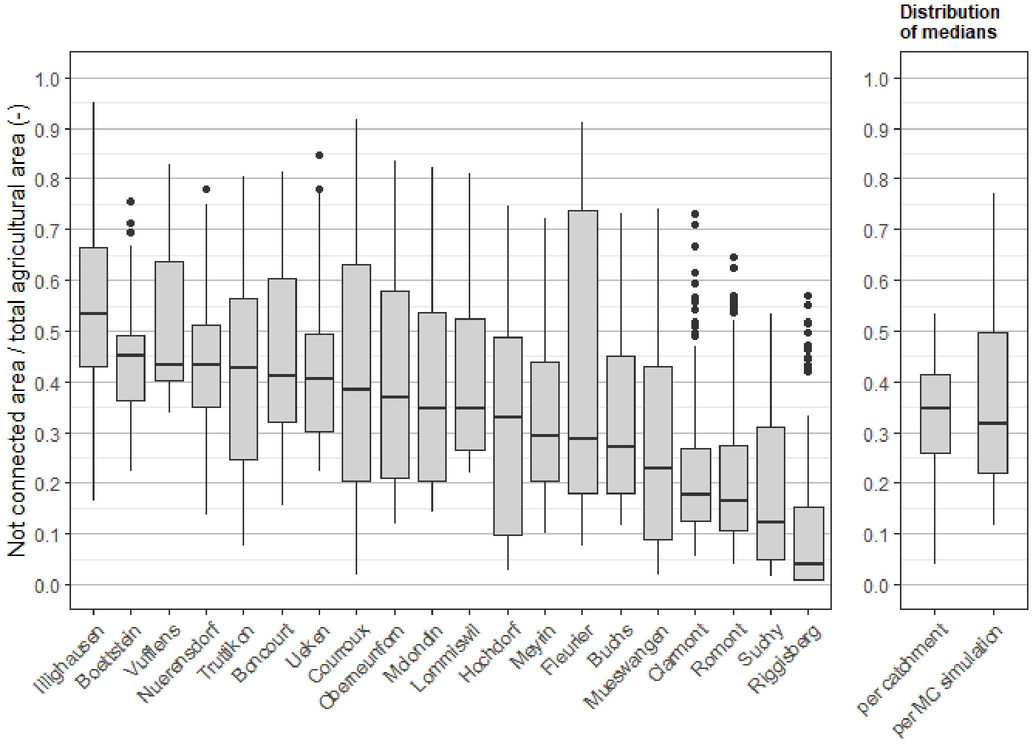


Figure S 21: Not connected area per total agricultural area (-) as calculated by the Monte Carlo analysis for each study area. Right: Distribution of medians of not connected area per total agricultural area (-) per study area and per Monte Carlo simulation.

S2.2.3. Correlation of connectivity fractions with catchment statistics

Table S 8: Correlation of catchment statistics with fractions of connected area connectivity. NECM: National erosion connectivity model, LSCM: Local surface runoff connectivity model.

Variable	**Fraction directly connected $f_{LSCM,dir}$ (-)**			**Fraction indirectly connected $f_{LSCM,indir}$ (-)**			**Fraction not connected $f_{LSCM,nc}$ (-)**		
	R^2	**Slope**	**P**	**R^2**	**Slope**	**P**	**R^2**	**Slope**	**P**
NECM: Directly connected agricultural area per total agricultural area $f_{NECM,dir}$ (-)	0.71	1.0E+00	**< 0.001** ***	-	-	-	-	-	-
NECM: Indirectly connected agricultural area per total agricultural area $f_{NECM,indir}$ (-)	-	-	-	0.52	6.0E-01	**< 0.001** ***	-	-	-
NECM: Not connected agricultural area per total agricultural area $f_{NECM,nc}$ (-)	-	-	-	-	-	-	0.26	4.0E-01	**0.022** *
Surface water body density (m^{-1})	0.51	2.2E+02	**< 0.001** ***	0.35	-1.4E+02	**0.006** **	0.14	-7.6E+01	**0.10** *
Paved road density (m^{-1})	0.20	-2.2E+01	**0.049** *	0.19	1.7E+01	0.053 -	0.04	6.5E+00	0.41 -
Inlet density (ha^{-1})	0.07	-1.3E-01	0.28 -	0.10	1.2E-01	0.17 -	0.00	1.0E-02	0.90 -
Manhole density (ha^{-1})	0.15	4.0E+02	0.09 -	0.07	-2.0E+02	0.27 -	0.07	-1.8E+02	0.27 -
Yearly rainfall (mm/year)	0.10	-5.2E-02	0.17 -	0.06	3.2E-02	0.28 -	0.04	2.0E-02	0.43 -
Total road density (m^{-1})	0.05	2.6E-01	0.35 -	0.05	-2.0E-01	0.33 -	0.00	-4.5E-02	0.80 -
Subsurface waterbody density (m^{-1})	0.11	-7.5E+00	0.14 -	0.04	3.3E+00	0.40 -	0.10	4.5E+00	0.18 -
Fraction of agricultural area (-)	0.00	2.6E+01	0.94 -	0.03	-1.7E+02	0.48 -	0.03	1.7E+02	0.43 -
Unpaved road density (m^{-1})	0.15	4.4E-04	0.09 -	0.02	-1.2E-04	0.55 -	0.18	-3.2E-04	0.063 -
Lake shore density (m^{-1})	0.03	1.3E-02	0.49 -	0.02	7.7E-03	0.60 -	0.13	-1.9E-02	0.13 -
Slope on agricultural areas (°)	0.04	-5.8E+00	0.41 -	0.00	2.2E-01	0.97 -	0.09	6.0E+00	0.19 -

S2.2.4. Sensitivity analysis

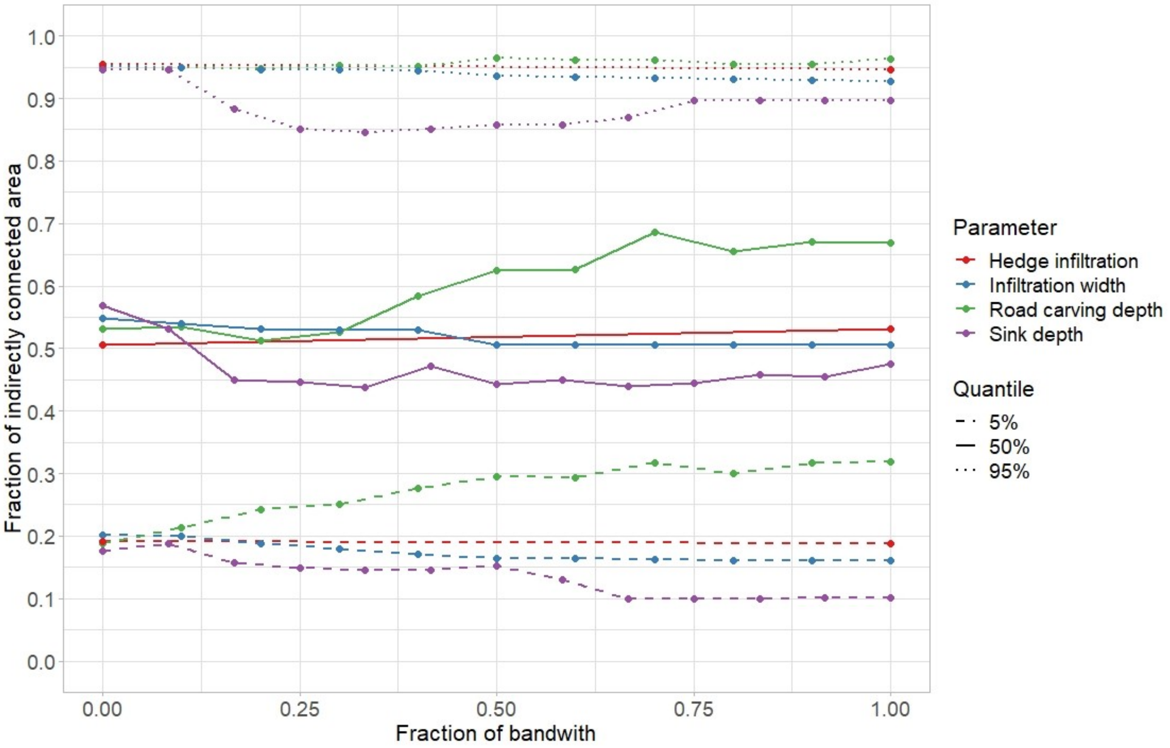


Figure S 22: Sensitivity analysis for shortcut definition A. The y-axis shows the fraction of indirectly connected area per total connected area. The parameters were varied within the following bandwidths. Hedge infiltration [no; yes], infiltration width [6 m; 100 m], road carving depth [0 cm; 100 cm], sink depth [0 cm; 100 cm]

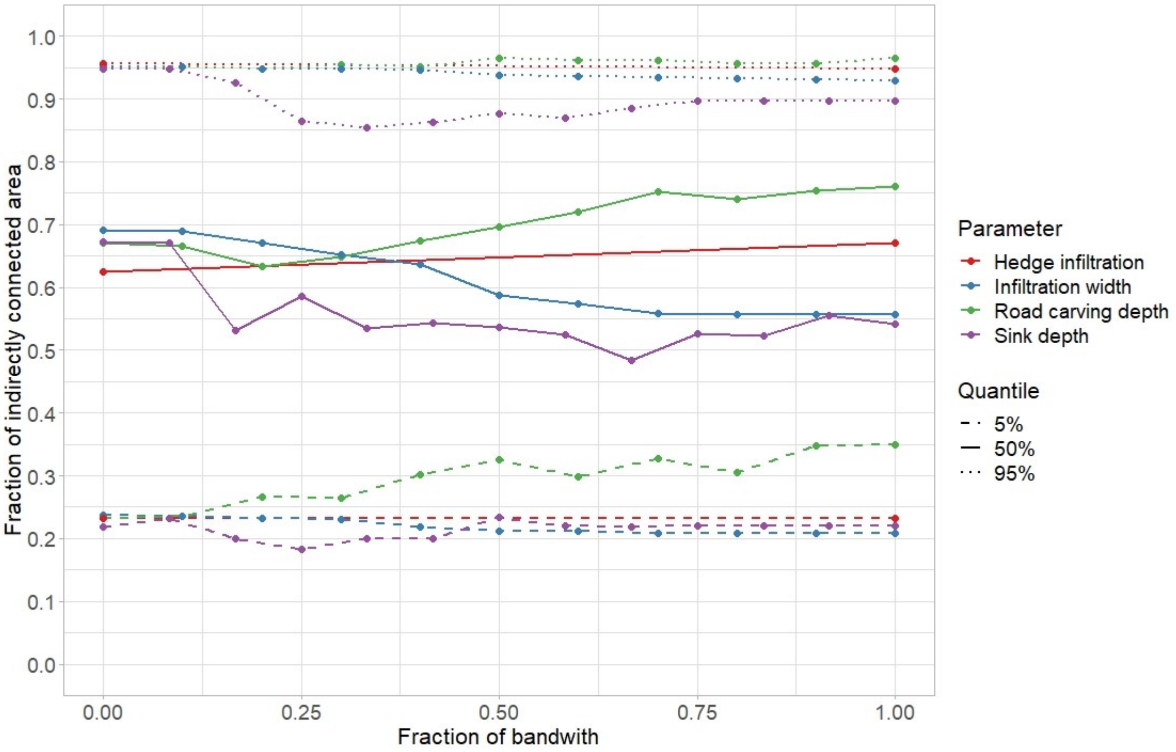


Figure S 23: Sensitivity analysis for shortcut definition B. The y-axis shows the fraction of indirectly connected area per total connected area. The parameters were varied within the following bandwidths. Hedge infiltration [no; yes], infiltration width [6 m; 100 m], road carving depth [0 cm; 100 cm], sink depth [0 cm; 100 cm]

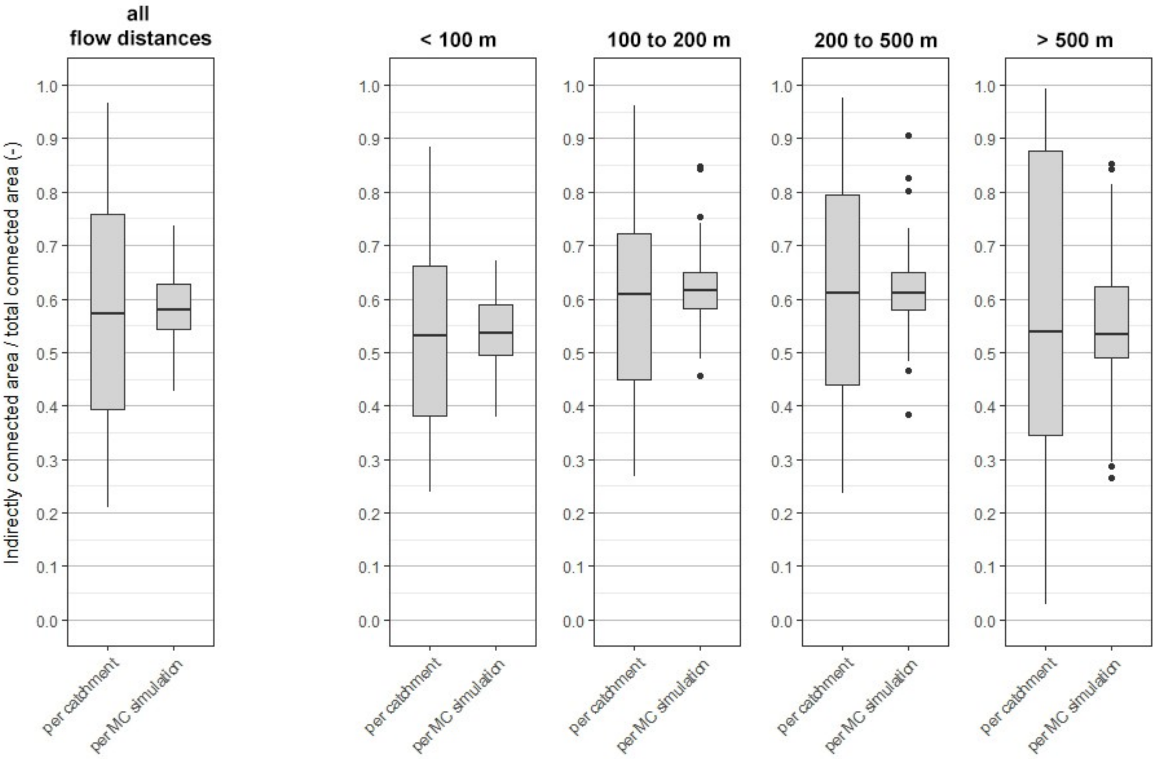


Figure S 24: Influence of flow distance on Monte Carlo results. Distribution of medians of indirectly connected area per total connected area (-) per study area and per Monte Carlo simulation for different flow distances. Left: Consideration of all flow distances. Right: Consideration of flow distances of smaller than 100 m, 100 to 200 m, 200 to 500 m, and larger than 500 m, respectively.

S2.2.5. Distribution of slope and wetness index

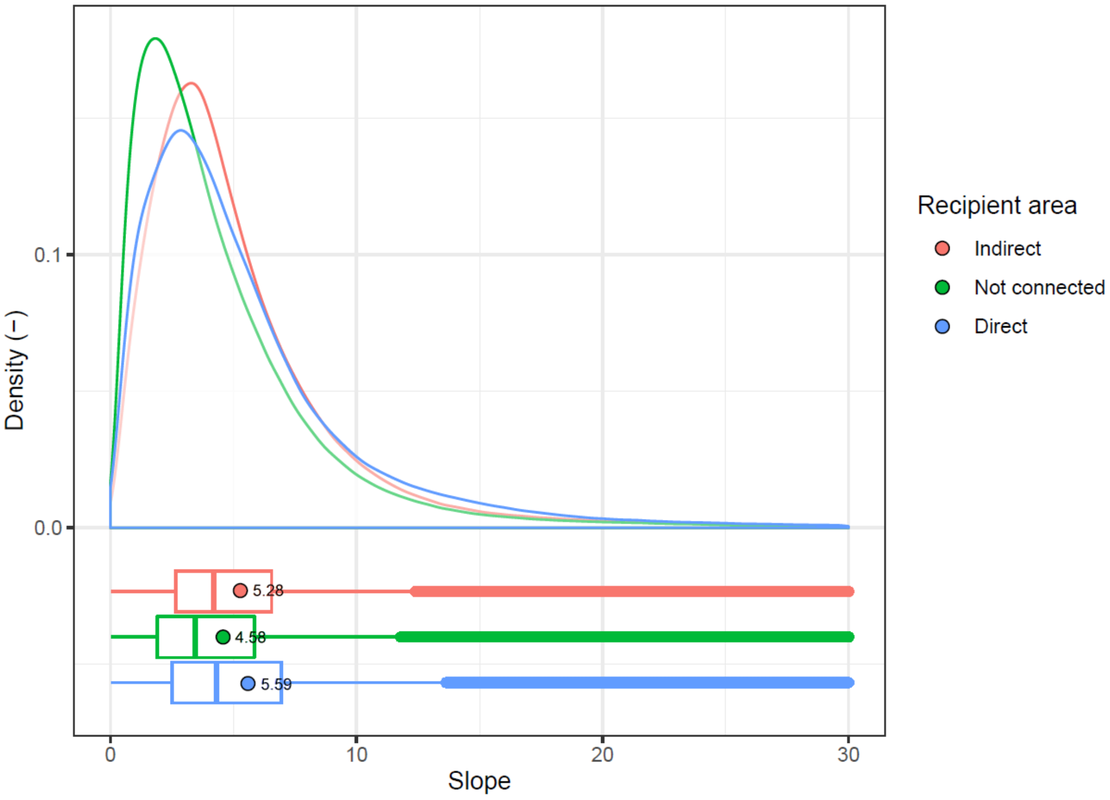


Figure S 25: Slope distribution (degrees) on different source area types

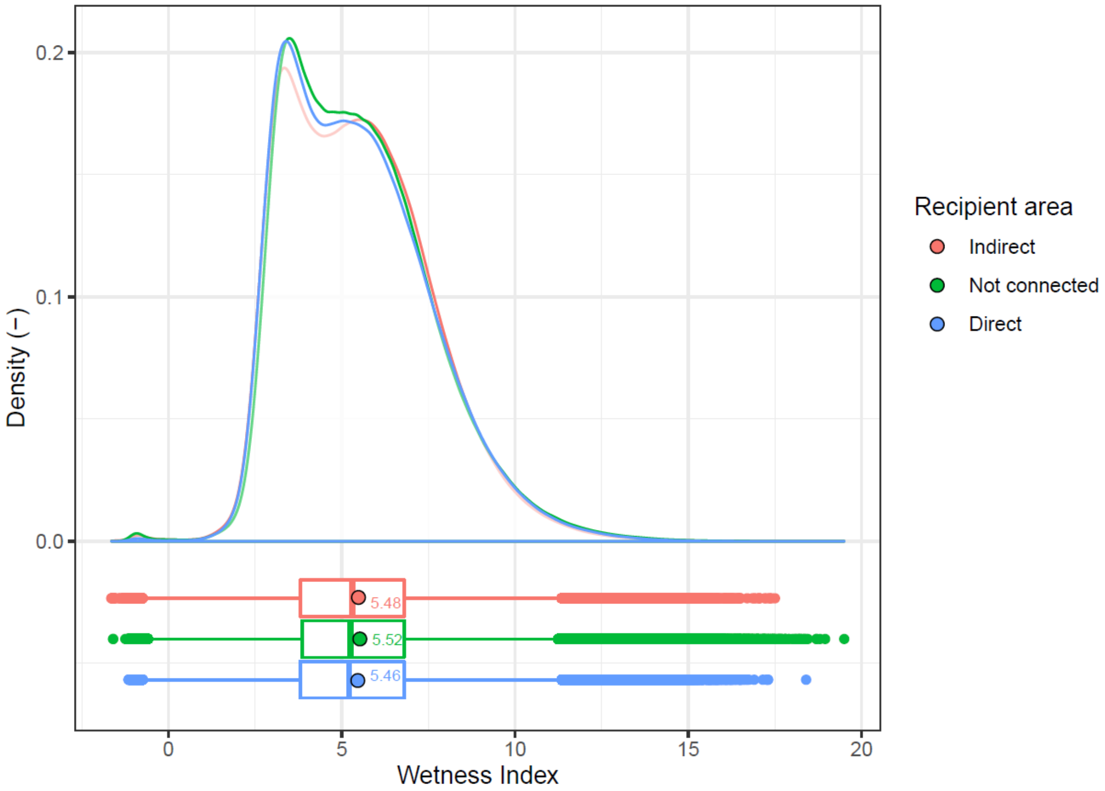


Figure S 26: Topographic wetness index distribution (-) on different source area types

S2.3. Surface runoff connectivity: Extrapolation to national level

S2.3.1. National area fractions

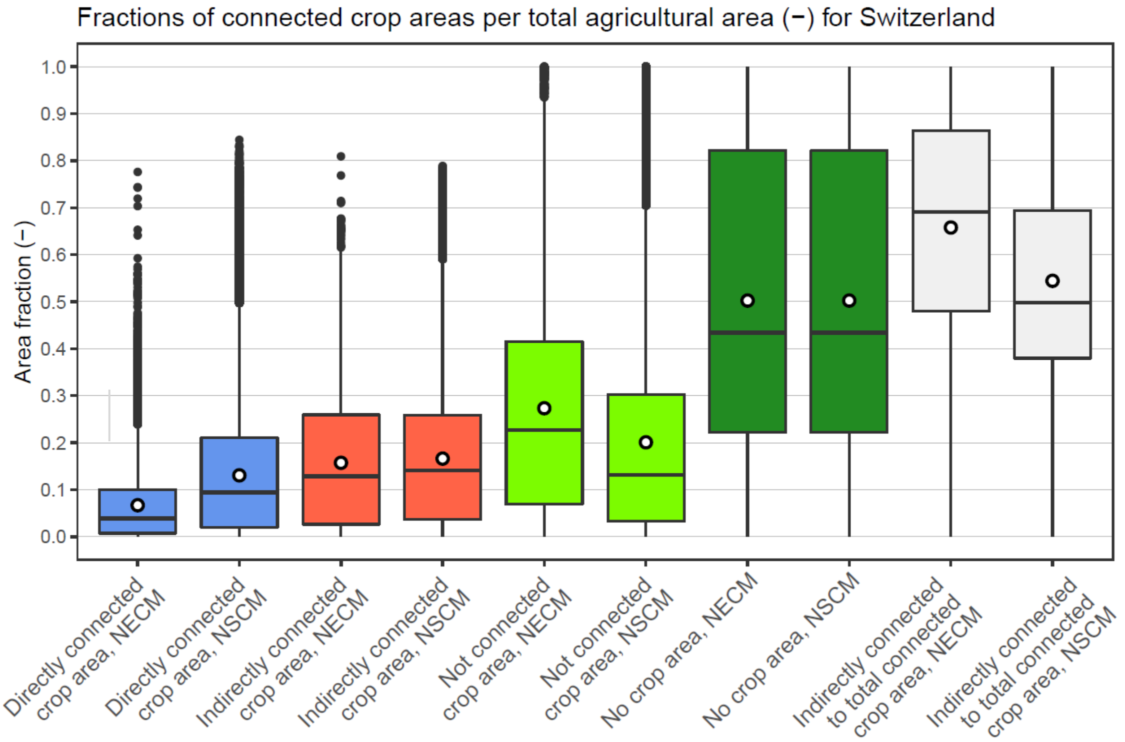


Figure S 27: Modelled area fractions by the NECM and the NSCM: Directly, indirectly, and not connected crop areas per total agricultural area, non-cropping area per total agricultural area, and indirectly connected crop area per total connected crop area for all catchments in Switzerland.

Table S 9: Statistics of modelled area fraction by the NECM and the NSCM. For the NSCM, the mean, the 5% quantile and the 95% quantile of the mean fractions resulting from the MC simulations is given. Additionally, the mean, the 5% quantile and the 95% quantile of the mean fractions resulting from the bootstrapping approach is given.

Statistic	**Fraction of directly connected crop area $f_{crop,dir}$**	**Fraction of indirectly connected crop area $f_{crop,indir}$**	**Fraction of not connected crop area $f_{crop,nc}$**	**No crop area**	**Fraction of indirectly per total connected area $f_{fracindir}$**
NECM	6.7%	16%	27%	50%	66%
NSCM: Mean (5% quantile; 95% quantile) of mean per MC simulation	13% (6.9%; 18%)	17% (7.0%; 24%)	20% (8.8%; 36%)	50% (50%; 50%)	54% (47%; 60%)
NSCM: Mean (5% quantile; 95% quantile) of mean per bootstrap simulation	14% (11%; 16%)	15% (13%; 17%)	21% (19%; 24%)	50% (50%; 50%)	49% (42%; 55%)

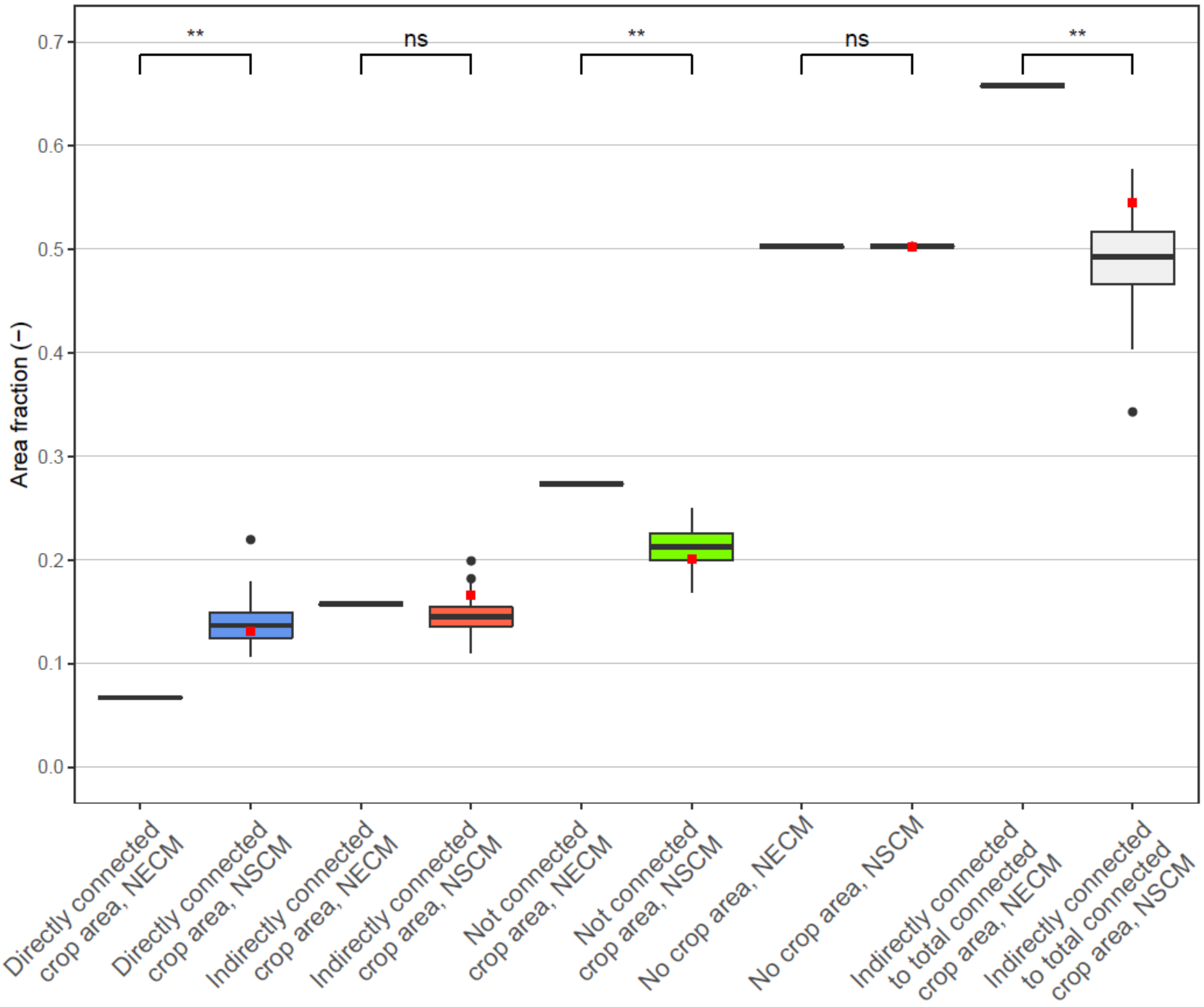


Figure S 28: Mean area fractions reported by the NECM and distribution of the bootstrapped mean area fractions reported by the NSCM. Directly, indirectly, and not connected crop areas per total agricultural area, non-cropping area per total agricultural area, and indirectly connected crop area per total connected crop area for all catchments in Switzerland. The red squares report the means reported by the NSCM without using a bootstrapping approach. The black lines on the top of the plot indicate if the mean fraction reported by the NECM is significantly different from the distribution of means reported by the bootstrapping approach (**: $p < 0.01$, ns: not significant). Significance values were determined from the empirical cumulative distribution of the bootstrapped means.

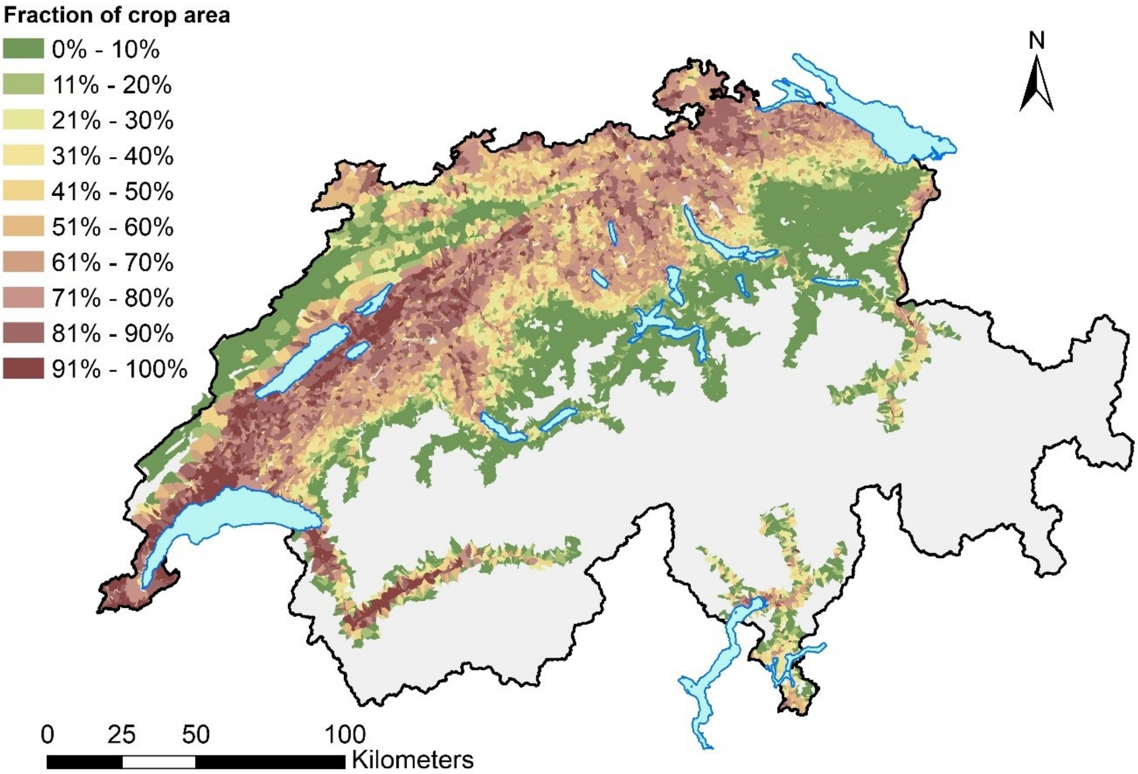


Figure S 29: Fraction of crop area (arable land, vineyards, orchards, horticulture) per total agricultural area per catchment. Source of background map: Swisstopo (2010)

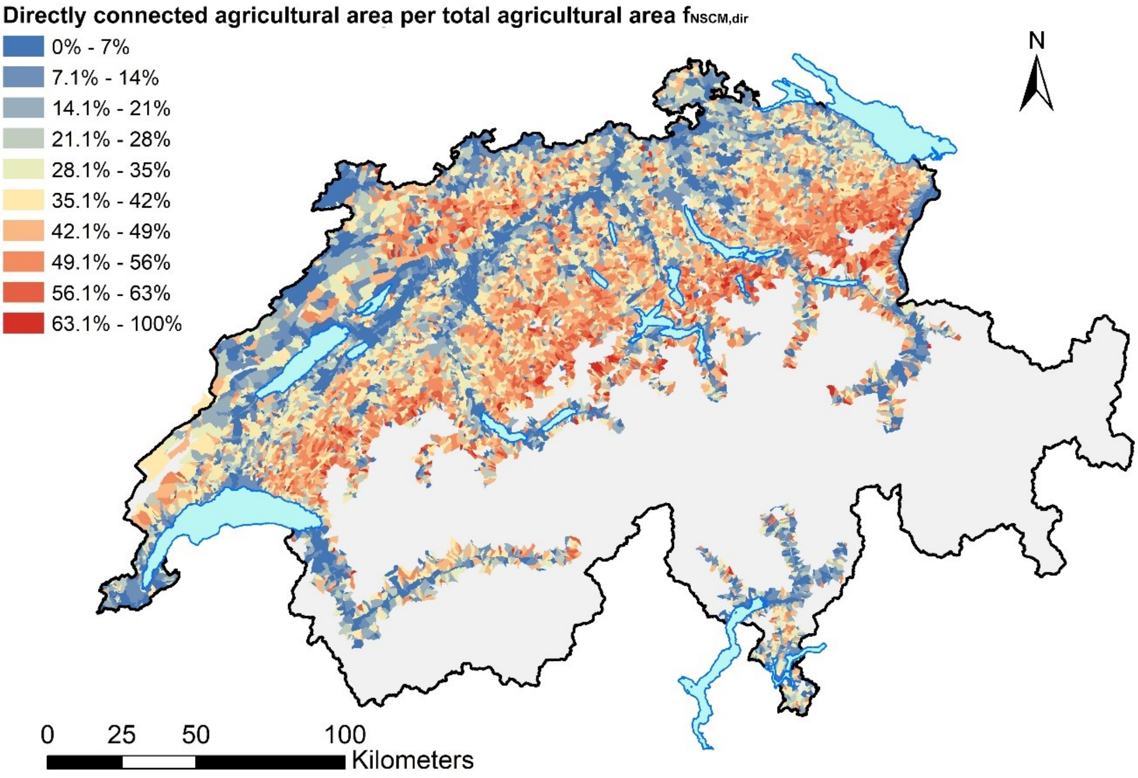


Figure S 30: Fraction of directly connected agricultural area per total agricultural area per catchment $f_{NSCM,dir}$. Source of background map: Swisstopo (2010)

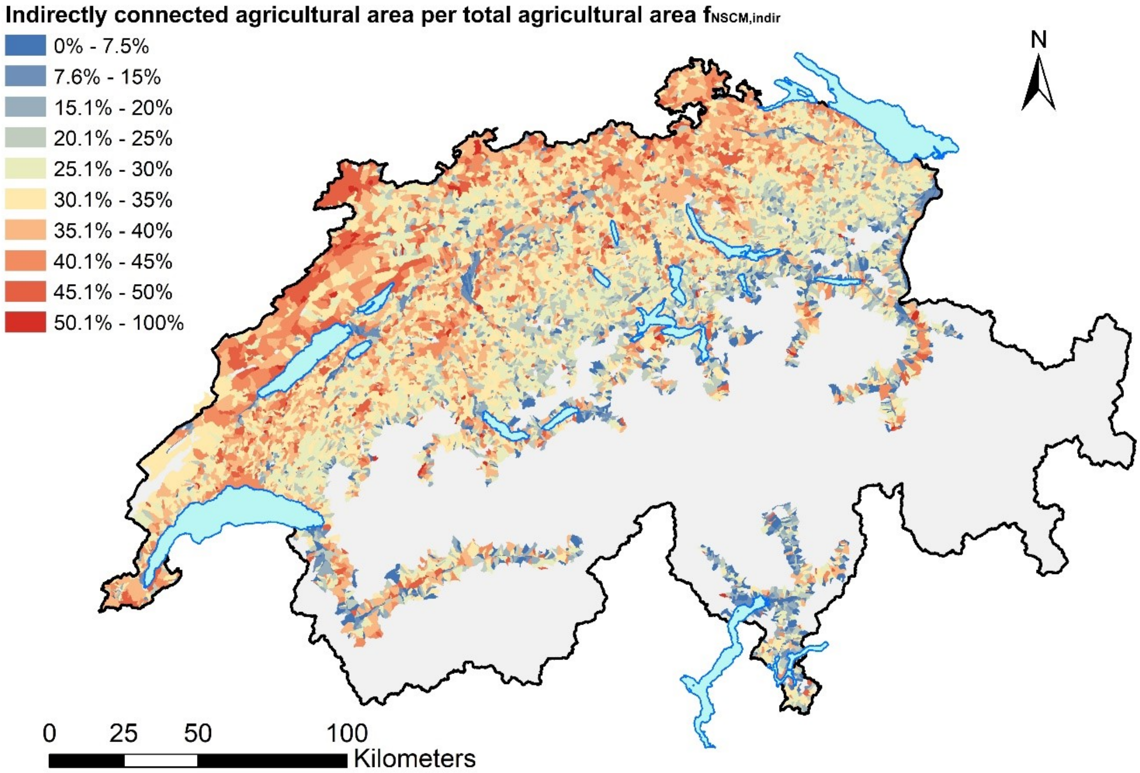


Figure S 31: Fraction of indirectly connected agricultural area per total agricultural area per catchment $f_{NSCM,indir}$. Source of background map: Swisstopo (2010)

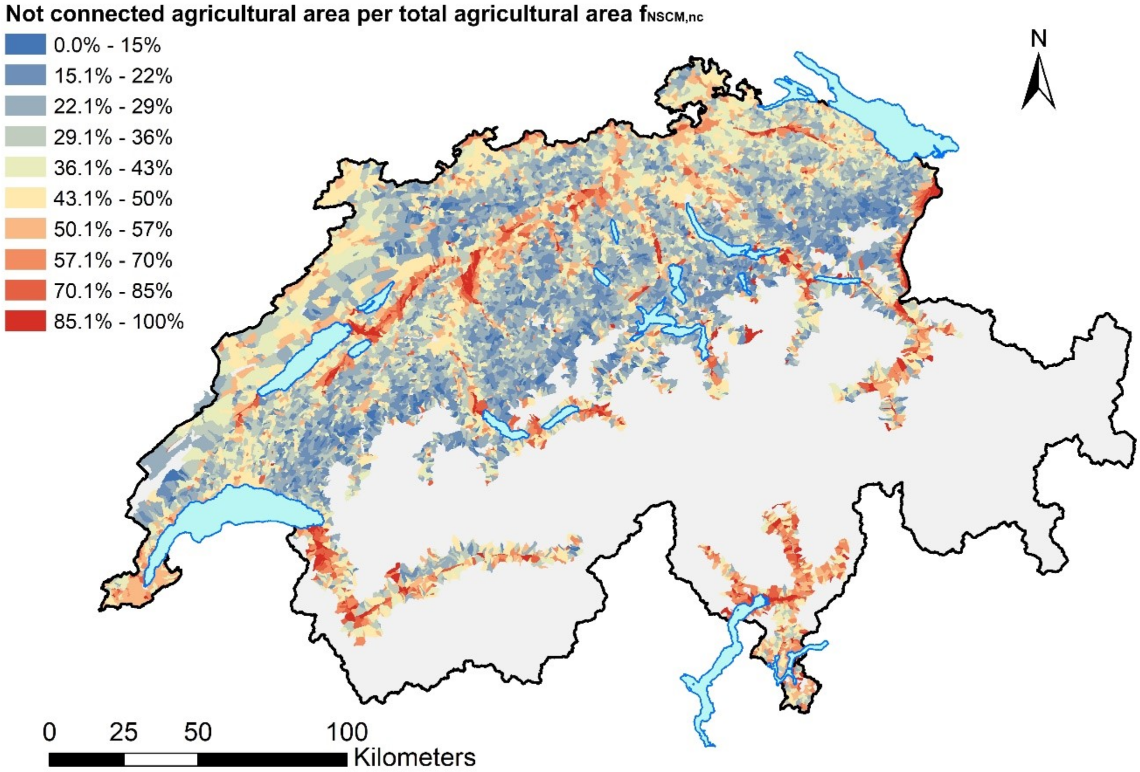


Figure S 32: Fraction of not connected agricultural area per total agricultural area per catchment $f_{NSCM,nc}$. Source of background map: Swisstopo (2010)

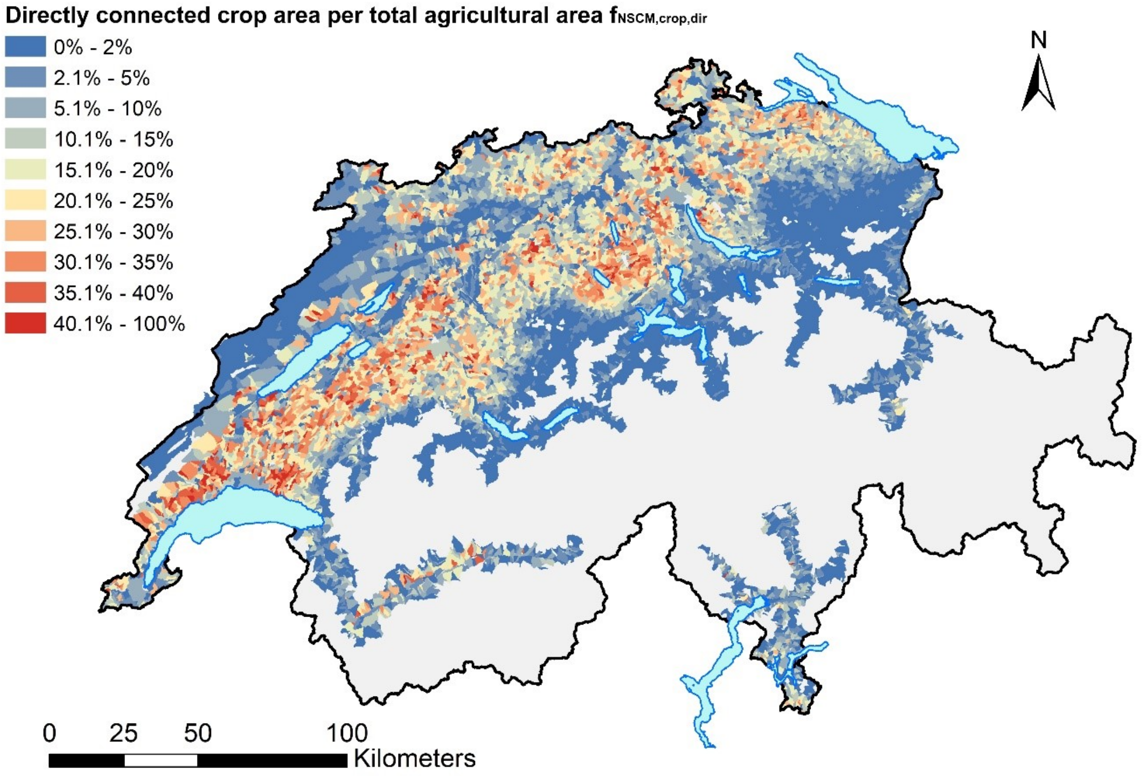


Figure S 33: Fraction of directly connected crop area per total agricultural are per catchment $f_{NSCM,crop,dir}$. Source of background map: Swisstopo (2010)

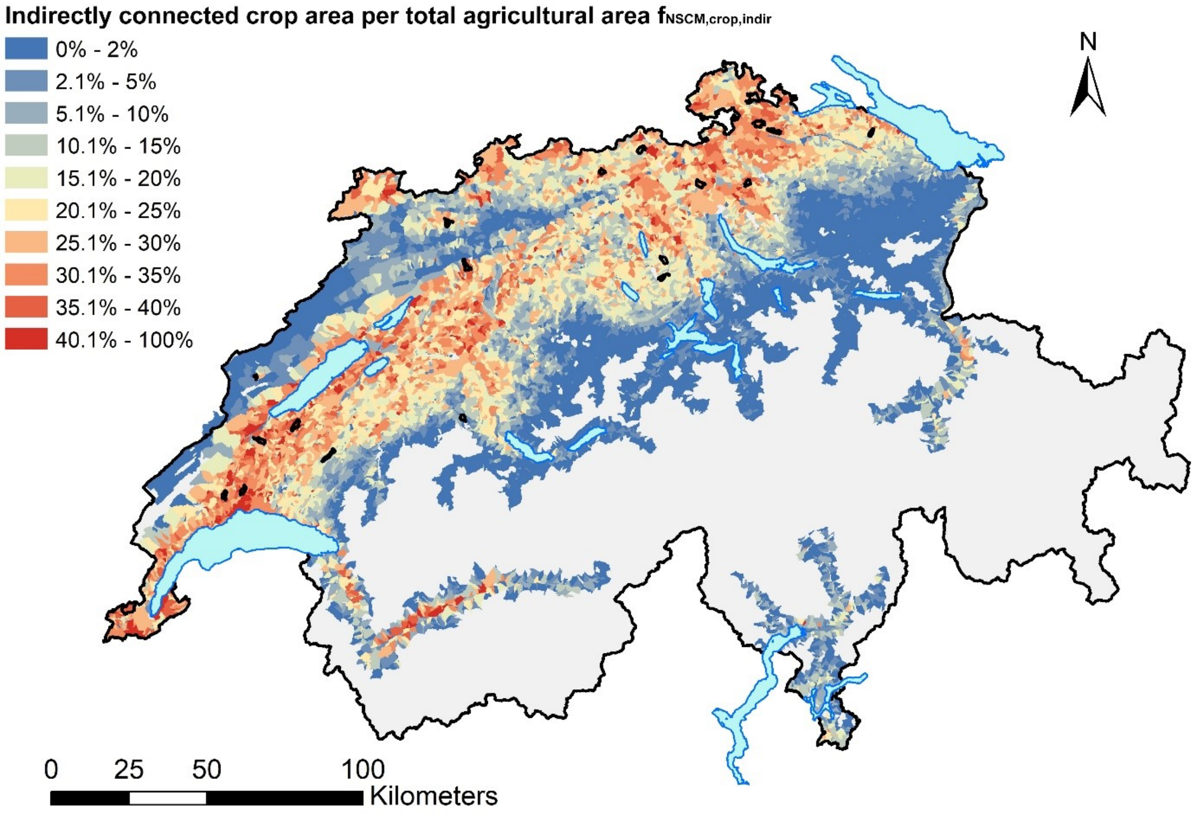


Figure S 34: Fraction of indirectly connected crop area per total agricultural are per catchment $f_{NSCM,crop,dir}$. Source of background map: Swisstopo (2010)

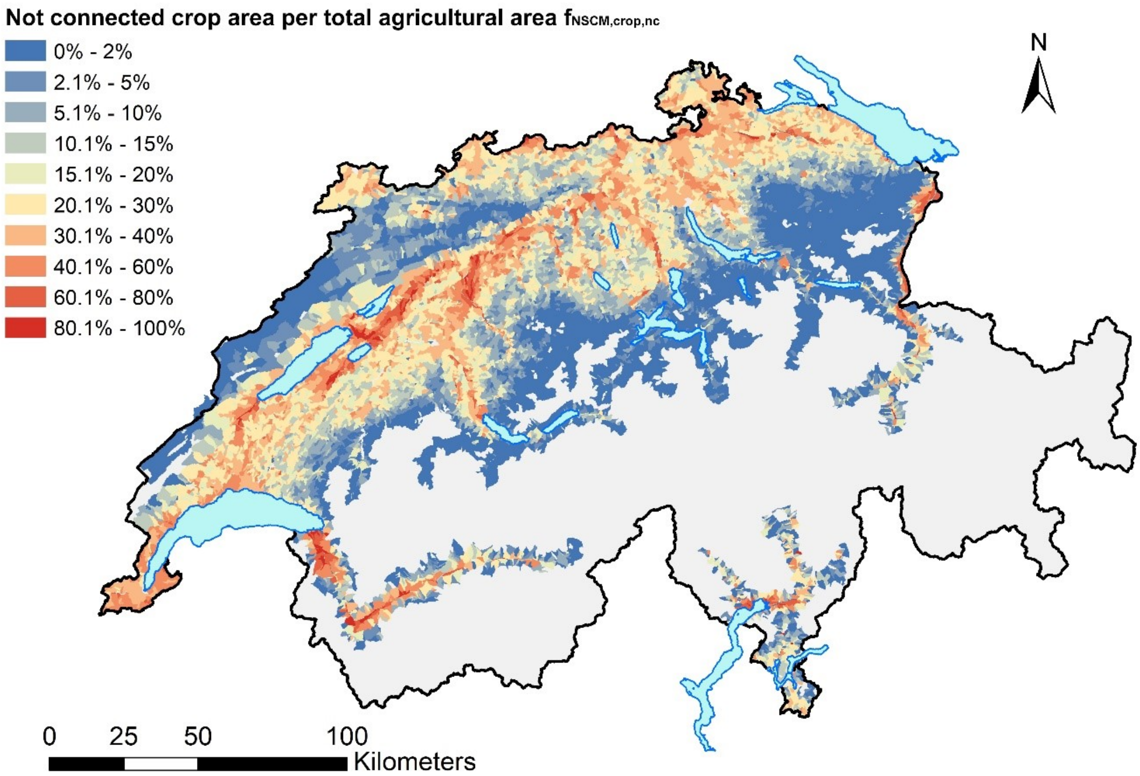


Figure S 35: Fraction of not connected crop area per total agricultural area per catchment $f_{NSCM,crop,nc}$. Source of background map: Swisstopo (2010)

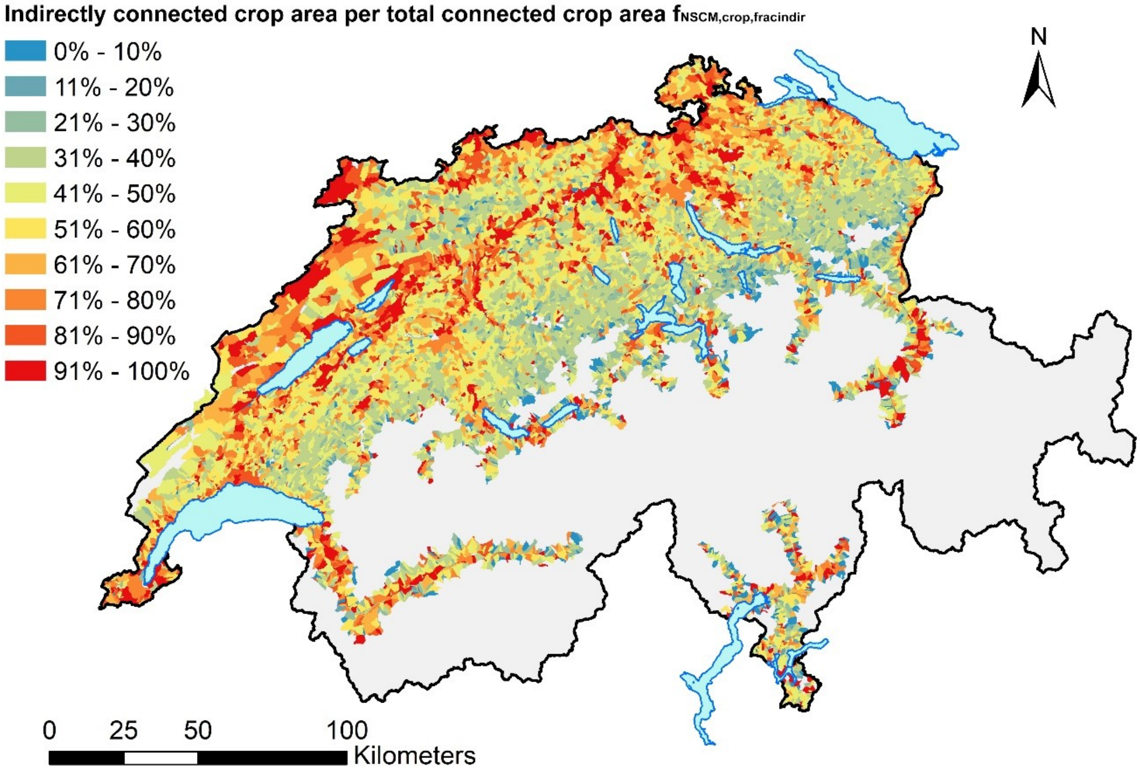


Figure S 36: Fraction of indirectly connected crop area per total connected crop area $f_{NSCM,drop,fracindir}$. Source of background map: Swisstopo (2010)

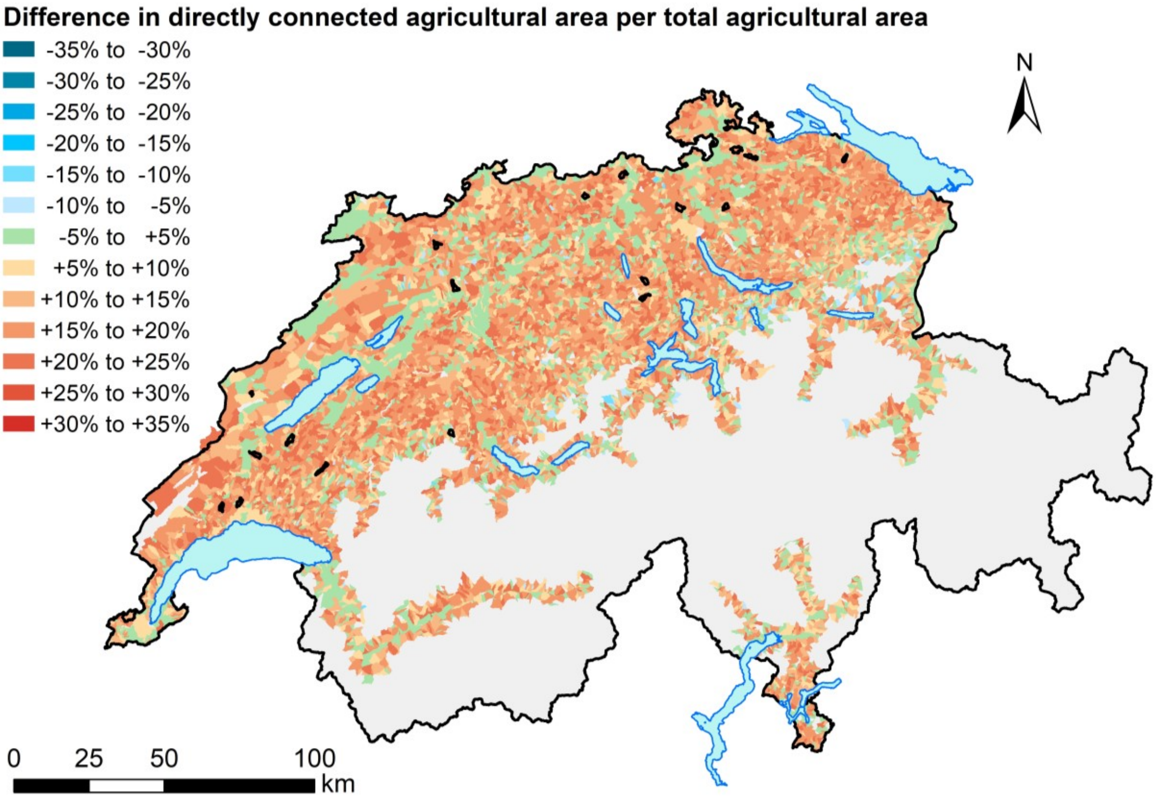


Figure S 37: Difference between the fractions of directly connected agricultural area per total agricultural area reported by the NSCM and the NECM ($f_{NSCM,dir} - f_{NECM,dir}$). Source of background map: Swisstopo (2010)

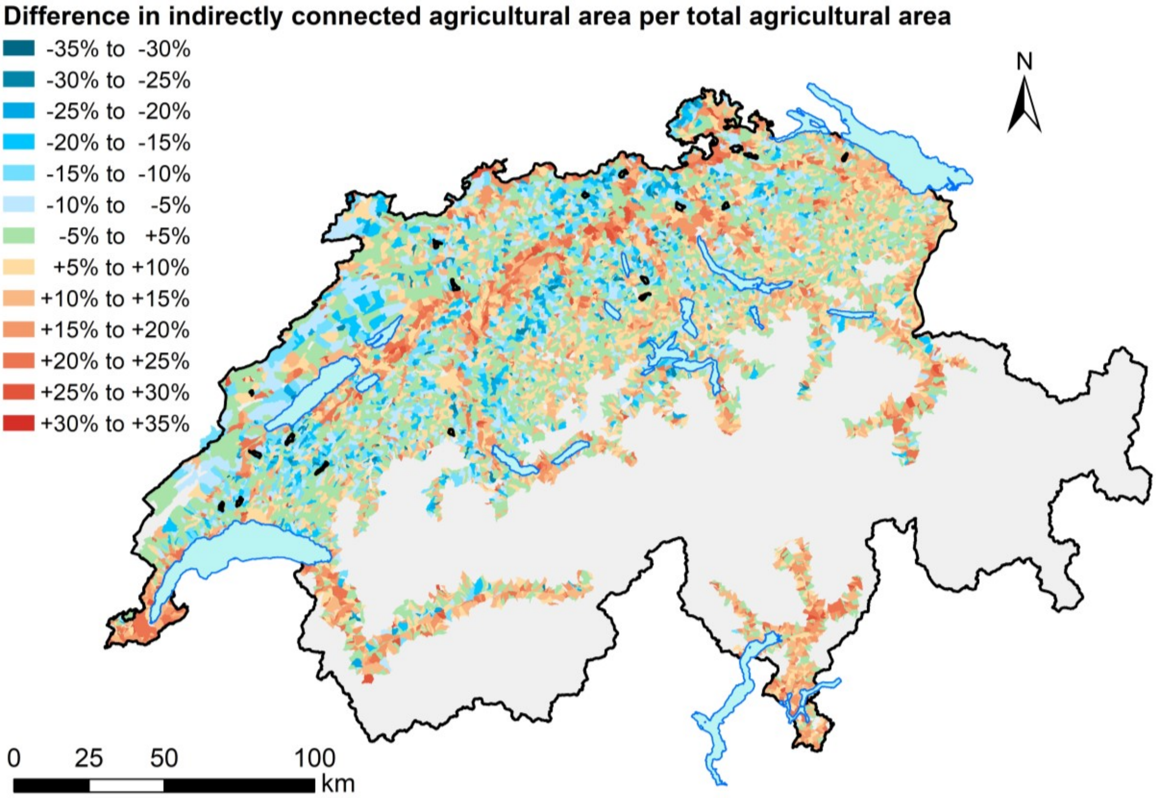


Figure S 38: Difference between the fractions of indirectly connected agricultural area per total agricultural area reported by the NSCM and the NECM ($f_{NSCM,indir} - f_{NECM,indir}$). Source of background map: Swisstopo (2010)

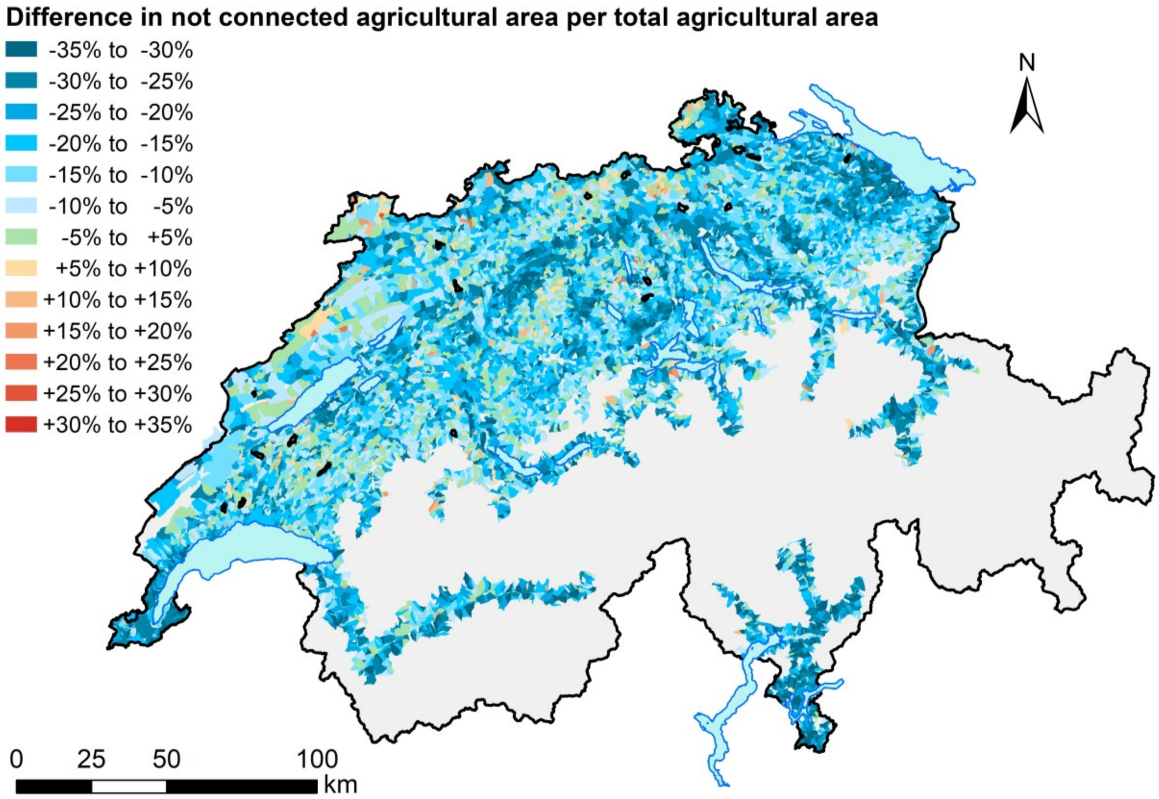


Figure S 39: Difference between the fractions of not connected agricultural area per total agricultural area reported by the NSCM and the NECM ($f_{NSCM,nc}$ - $f_{NECM,nc}$). Source of background map: Swisstopo (2010)

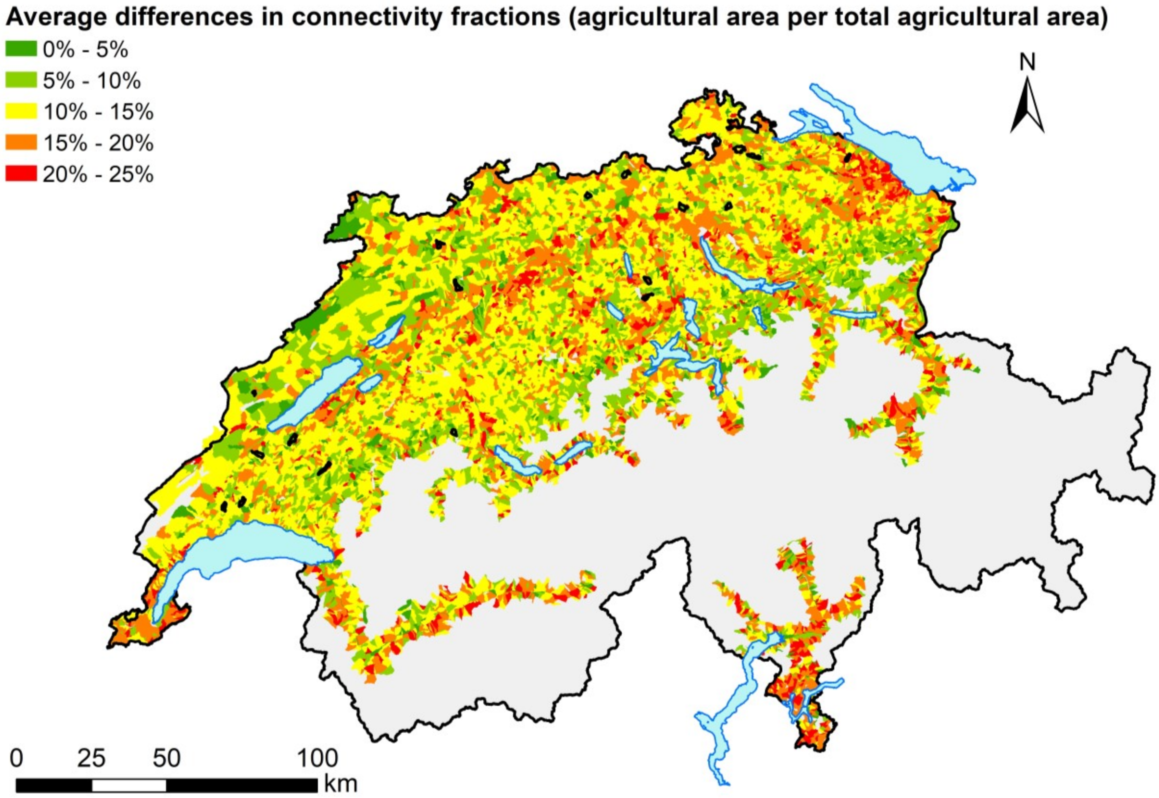


Figure S 40: Average difference in connectivity fractions of agricultural areas reported by the NSCM and the NECM: $\Delta f_{crop} = ((f_{NSCM,dir} - f_{NECM,dir}) + (f_{NSCM,indir} - f_{NECM,indir}) + (f_{NSCM,nc} - f_{NECM,nc}))/3$. The map shows data for all Swiss catchments in the valley zones, hill zones and lower elevation mountain zones. Grey areas represent higher elevation

mountain zones that were excluded from the analysis. Study areas are marked with black lines. Source of background map: Swisstopo (2010)

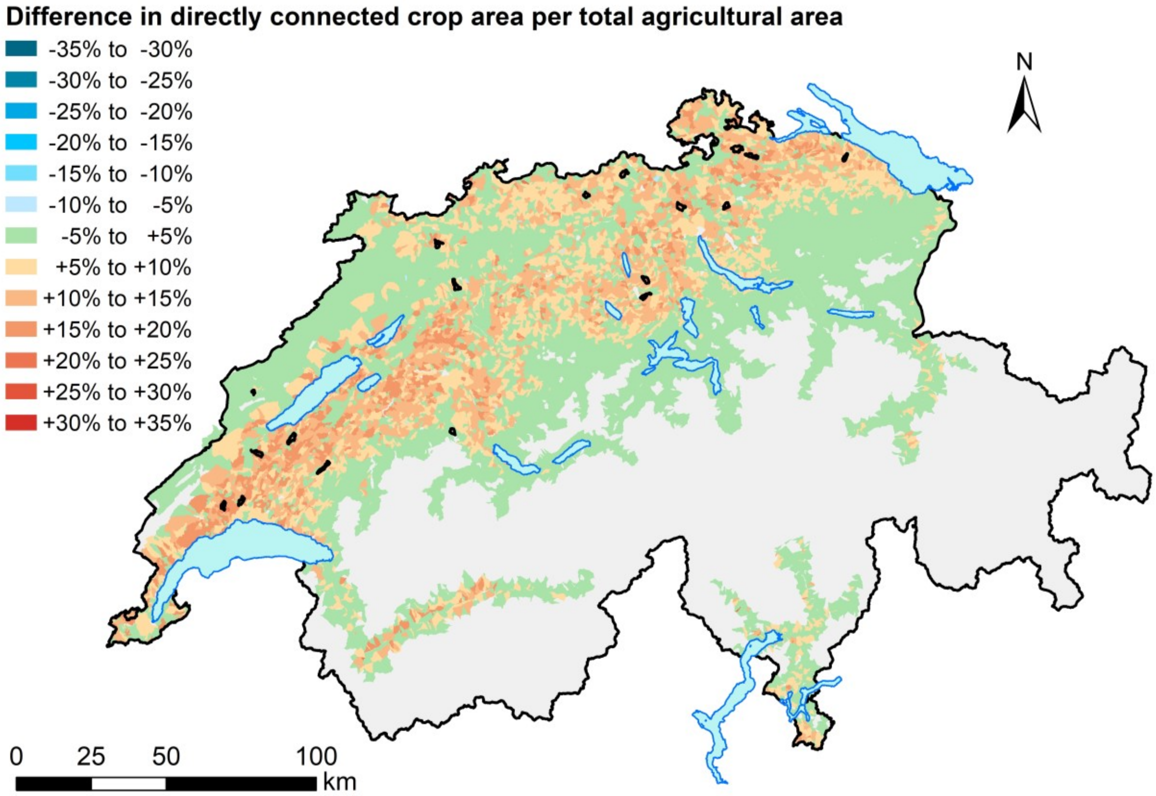


Figure S 41: Difference between the fractions of directly connected crop area per total agricultural area reported by the NSCM and the NECM ($f_{NSCM,crop,dir}$ - $f_{NECM,crop,dir}$). Source of background map: Swisstopo (2010)

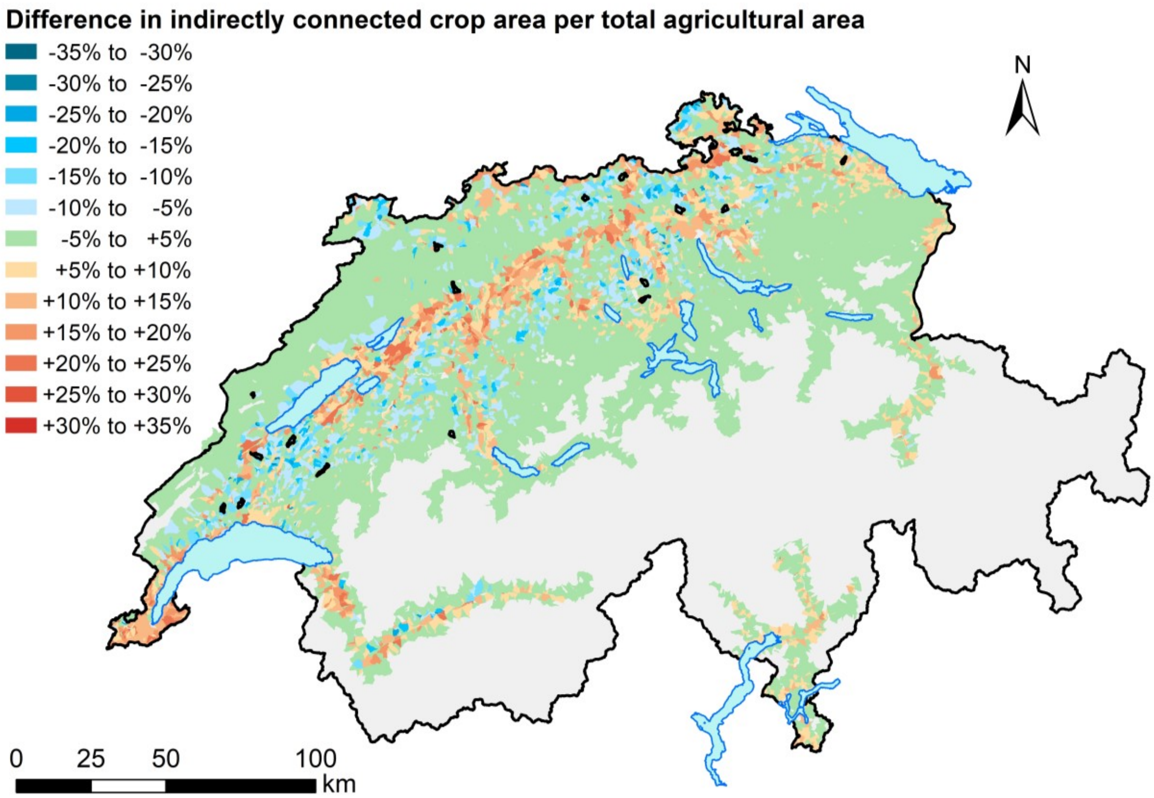


Figure S 42: Difference between the fractions of indirectly connected crop area per total agricultural area reported by the NSCM and the NECM ($f_{NSCM,crop,indir}$ - $f_{NECM,crop,indir}$). Source of background map: Swisstopo (2010)

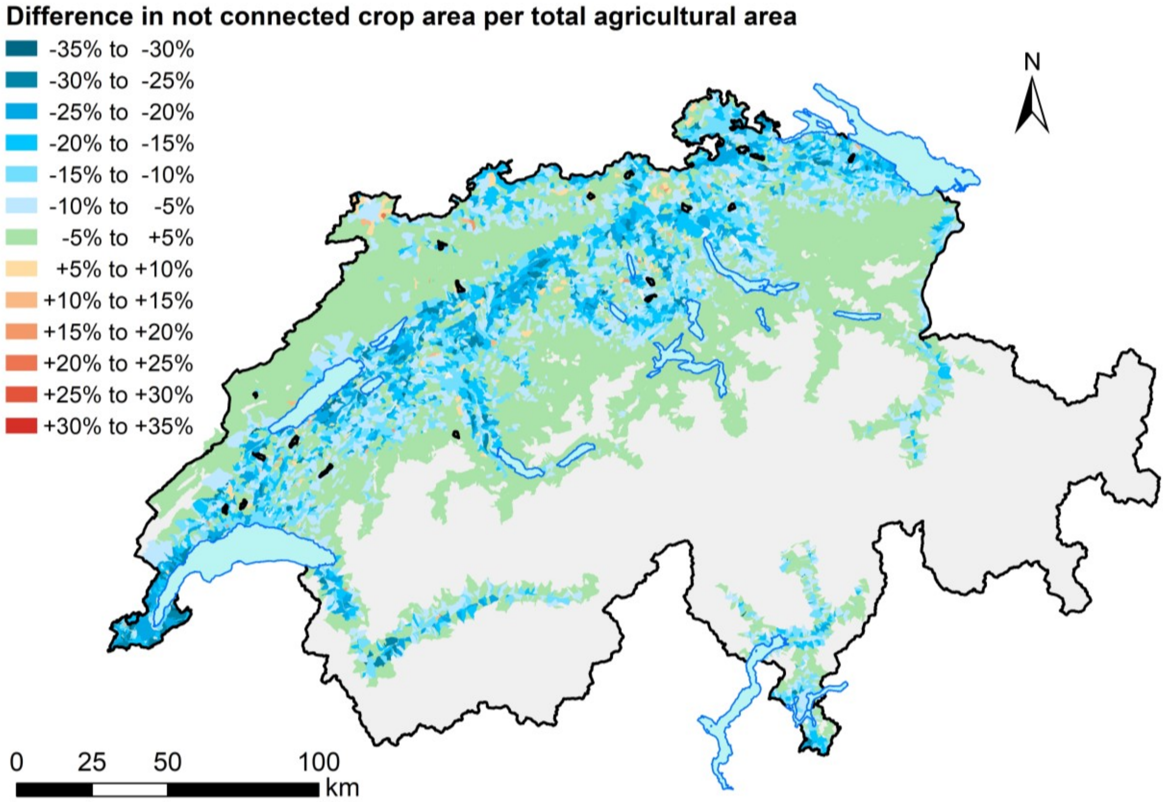


Figure S 43: Difference between the fractions of not connected crop area per total agricultural area reported by the NSCM and the NECM ($f_{NSCM,crop,nc}$ - $f_{NECM,crop,nc}$). Source of background map: Swisstopo (2010)

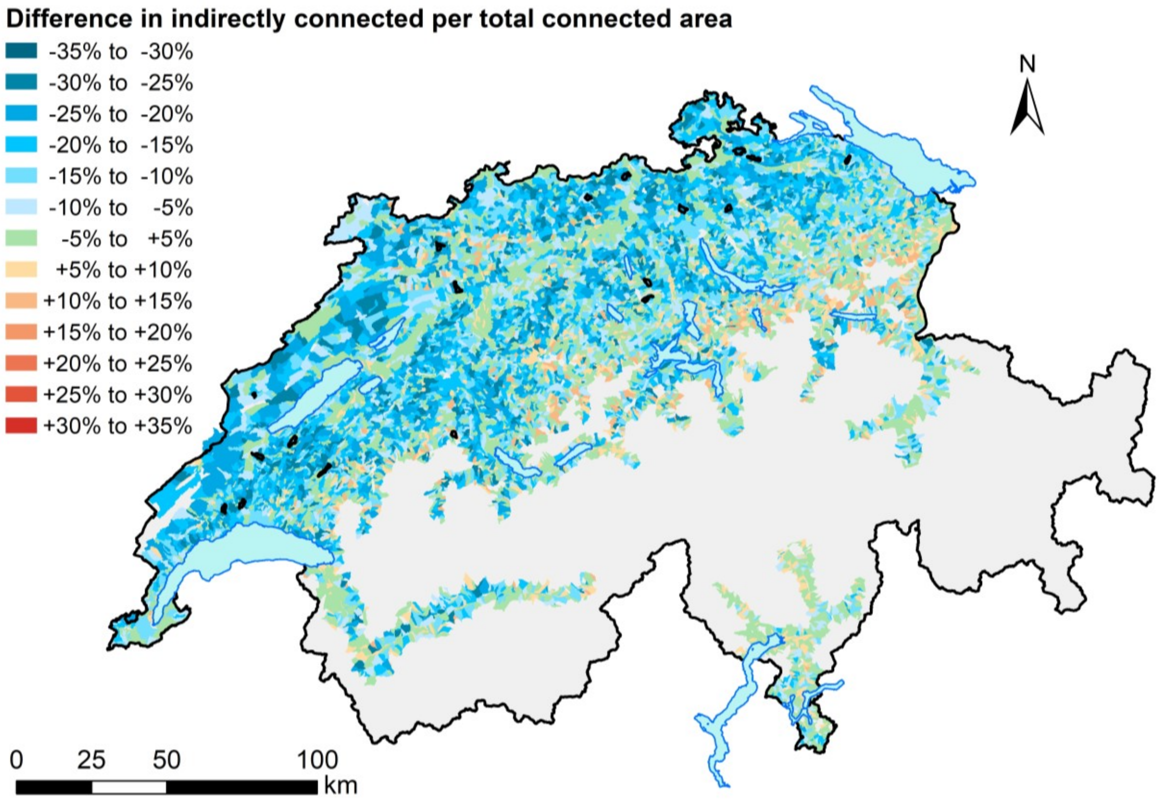


Figure S 44: Difference between the fractions of indirectly connected per total connected area reported by the NSCM and the NECM ($f_{NSCM,fracindir}$ - $f_{NECM, fracindir}$). Source of background map: Swisstopo (2010)