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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.

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 (54 %).

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. 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.

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1. Introduction

Agriculture has been shown to be a major source for pesticide contamination of surface waters (Stehle and Schulz 2015; Loague, Corwin, and Ellsworth 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 better.

Pesticides are lost to surface waters through various pathways from either point sources or diffuse sources. In current research, surface runoff (Holvoet, Seuntjens, and Vanrolleghem 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, Spliid, and Svensmark 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 hydrologically active (e.g. occurrence of surface runoff), and iii) they are connected to a water body.

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, Auerswald, and Van Oost 2011). 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, Quinn, and Hewett 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. In both studies, generalizing assumptions on the occurrence of hydraulic shortcuts were made (e.g. classification of roads as drained by shortcuts or as undrained, based on their size). Since only for small areas the occurrence of hydraulic shortcuts was effectively known, these assumptions are quite uncertain as also stated by Alder et al. (2015).

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. 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?

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 1 to Figure S 12 in the SI):

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.

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 (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 14).

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**

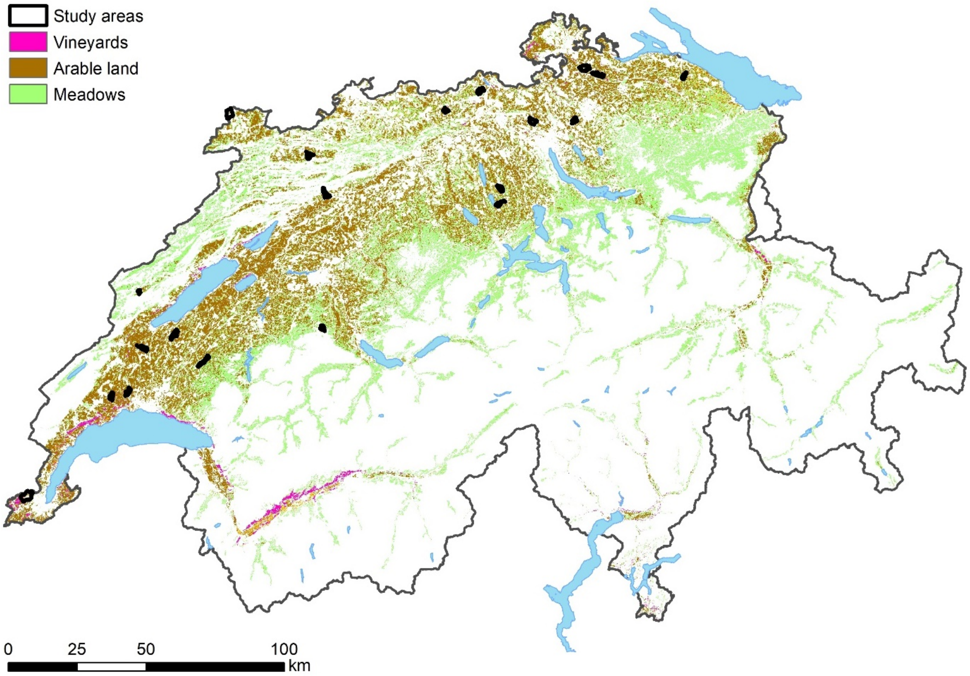

Figure 1: Study areas (black) and distribution of arable land (brown), vineyards (pink), and meadows (green) across Switzerland. Source: Swisstopo (2010); BFS (2014)

2.2. Assessment of hydraulic shortcuts

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 4). 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 1 to Table S 3).

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 4) 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 understand better 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

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). An area is defined as a CSA if 1) pesticides are applied on the area, 2) it is connected to surface waters, and 3) it is hydrologically active (i.e., generating fast flow processes transporting pesticides to streams). This model mainly focuses on the first two of these elements, while 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

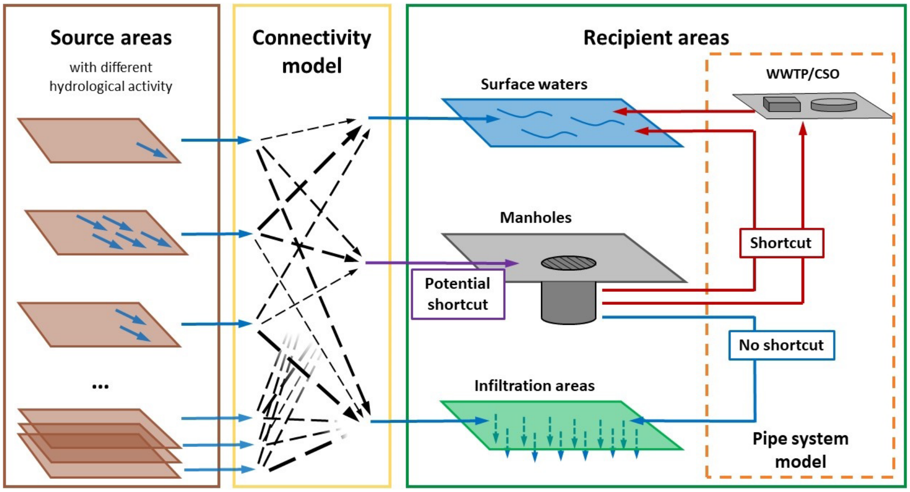

Figure 2: Structure of the surface runoff connectivity model

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, 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 (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, Liess, and Kattwinkel 2014; Dosskey, Eisenhauer, and Helmers 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

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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 13 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, Quinn, and Hewett 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”. Source areas with flow distances longer than the parameter *maximal flow distance* were then defined as not connected.

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). For the parameter *maximal flow distance,* all possible flow distances were evaluated.

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), and the maximal flow distance was not reduced (*maximal flow distance* = ∞). 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
Maximal flow distance	Calculation of all possible flow distances	-	2m ≤ x ≤ ∞	∞

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) for the source areas of the benchmark model. We calculated the TWI as follows, using the "Topographic Wetness Index" tool of the TauDEM model (Tarboton 1997):

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

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, we developed a model for extrapolating the results from our study areas (local surface runoff connectivity model, LSCM) to the national scale.

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. Catchment statistics included fraction of forests, fraction of agricultural area, road density (total, paved, unpaved), water body density (total, rivers, lakeshores), mean annual precipitation, mean slope of agricultural areas, and area fractions (direct, indirect, not connected) as reported by the national erosion connectivity model (NECM) (Alder et al. 2015). Details on the datasets used for calculating those catchment statistics can be found in Table S 5 of the supporting information.

We created a linear regression between each of those catchment statistics to the 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. The resulting modelling approach is shown in Figure 3. Mathematical details are provided in the SI (chapter S1.5).

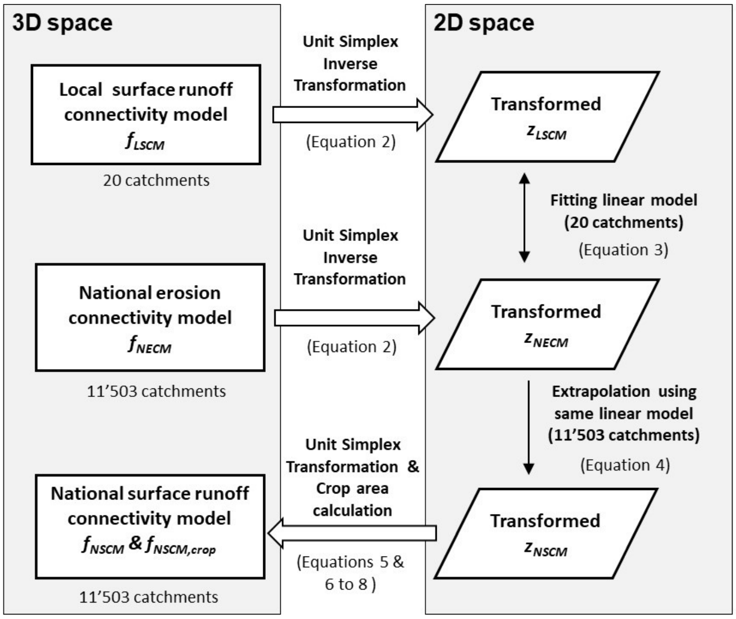

Figure 3: Extrapolation of the local surface runoff connectivity model (LSCM) to the national scale (NSCM) using a unit simplex transformation approach.

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 high-resolution datasets of crop areas yet available in Switzerland, 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 areas with rare pesticide application, such as meadows, which are not expected to act as source areas (except in special cases such as fighting weeds such as bitter dock (*Rumex obtusifolius L.*)).

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). 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 (min: 66 %, max: 100 %; Table 4). Only very few inlets (2.8 %) are found directly on fields. In contrast, maintenance manholes are found much more often on fields (mean: 21 %, min: 0 %, max: 42 %) and therefore less often on paved or unpaved roads (mean: 52 %, min: 39 %, max: 88 %). The fractions of inlets and maintenance

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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 ($R^2 = 0.37$, $p = 0.005$). Details can be found in 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	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 %

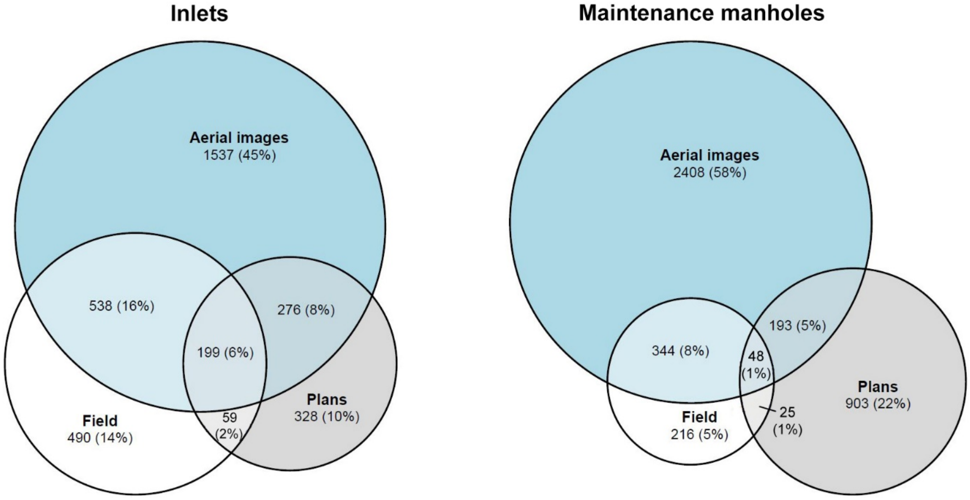
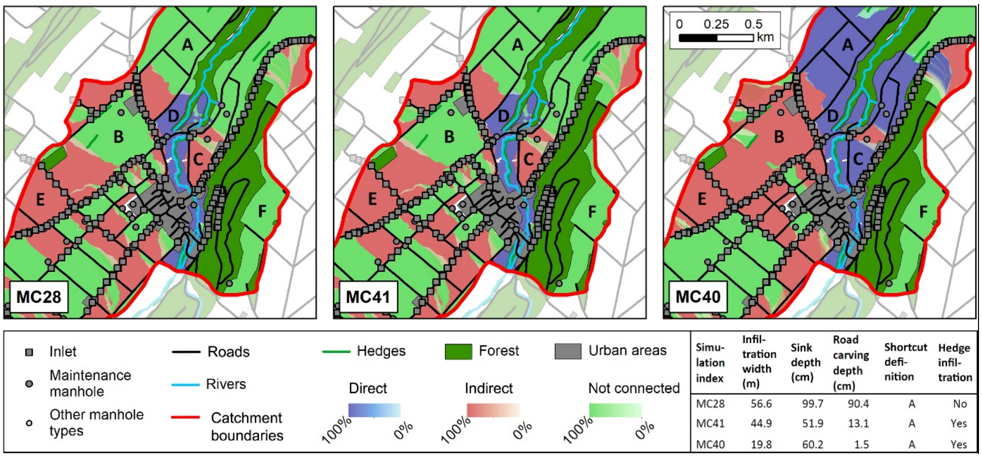


Figure 4: Number of inlets (left) and maintenance manholes (right) identified by the different mapping methods.

3.2. Surface runoff connectivity

3.2.1. Study areas

Based on the Monte Carlo analysis of the surface runoff connectivity model, we estimated 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. While certain areas change their classification depending on the model parametrisation (e.g. letters A to C), for other parts of the catchment, the results of the MC simulations are very consistent (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).



Simulation index	Infiltration width (m)	Sink depth (cm)	Road carving depth (cm)	Shortcut definition	Hedge infiltration
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: Directly connected (blue), indirectly connected (red) and not connected (green) areas resulting from three example Monte Carlo (MC) simulations for a part of the study area Molondin. 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.

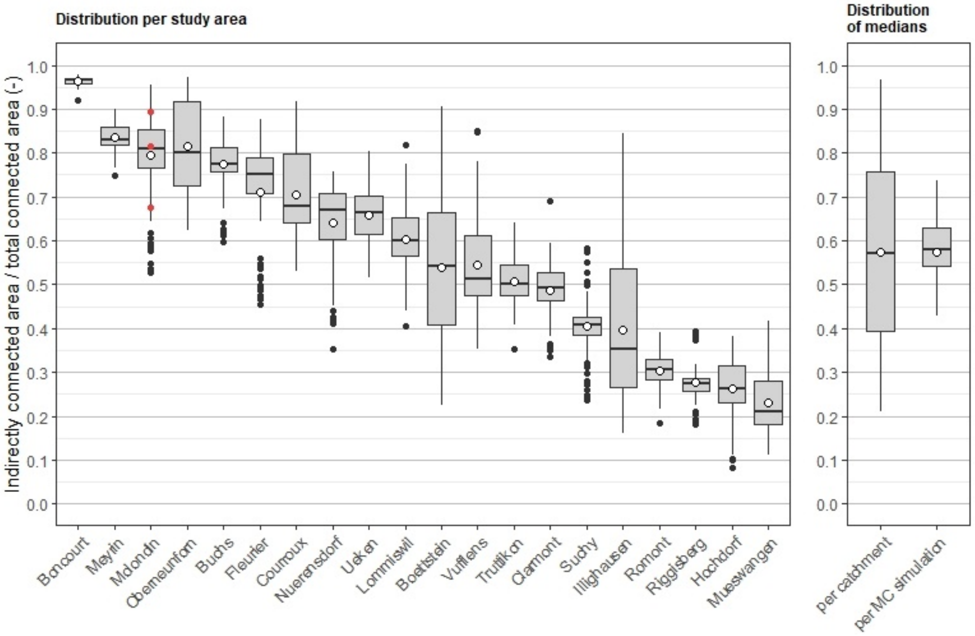


Figure 6: Left: Fractions of indirectly connected areas per total connected areas as calculated by the Monte Carlo analysis for each study area. White dots indicate the means of the distributions. The red dots indicate the results of the example Monte Carlo simulations (MC28, MC41, and MC 40) shown in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

However, this fraction varies strongly between the study areas, 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

In the previous section, variation due to model parameter uncertainty was addressed globally by analysing the variation of Monte Carlo simulation results. To analyse which model parameters have the largest influence on our model results, we tested the local model parameter sensitivity on our benchmark model. Our results show that 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. Detailed results can be found in Figure S 22 and Figure S 23 in the supporting information. We also analysed how the fraction of indirect to total connected areas changed with flow distance. However, the sensitivity was rather small (details see Figure S 24).

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.

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). As depicted in Figure 7, the differences in the mean and standard deviation of directly connected and not connected area fractions were strongly reduced by this transformation in our study areas. Differences in mean and standard deviation of indirectly connected area fractions were already small before the transformation and did not change substantially.

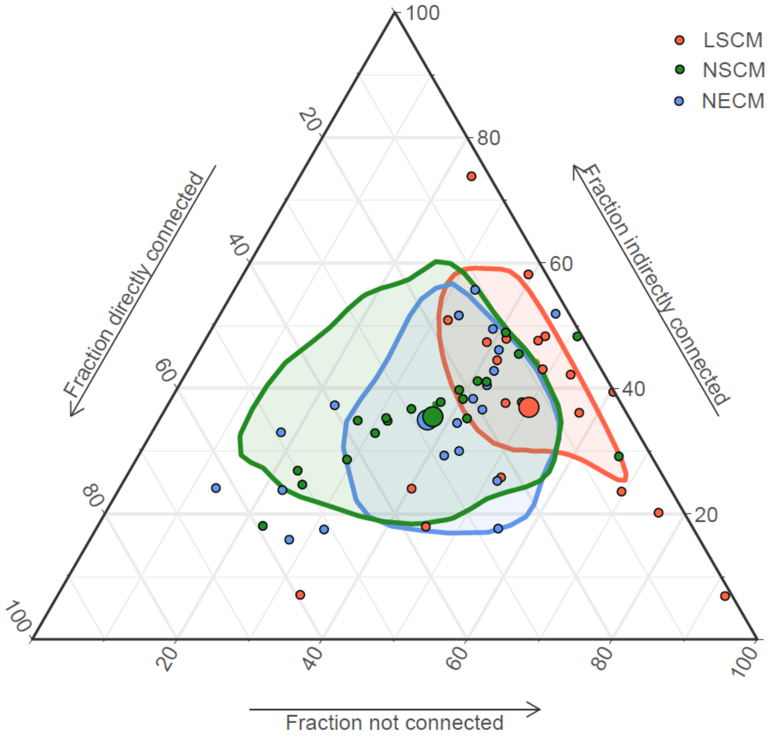


Figure 7: Fractions of directly connected (f_{dir}), indirectly connected (f_{indir}), and not connected areas (f_{nc}) per total agricultural area for the local surface runoff connectivity model (LSCM, blue), national erosion connectivity model (NECM, red), and national surface runoff connectivity model (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.

Using the transformation derived from our study areas, we extrapolated the results of the local surface runoff connectivity model to the national scale, resulting in a national surface runoff connectivity model (NSCM) aggregated to the catchment scale. It covers all catchments of the valley zones, hill zones and lower elevation mountain zones. Using land use data, we additionally calculated the fraction of agricultural crop area per total agricultural area of each catchment. Multiplication of this fraction with the NSCM resulted in 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 (details see Figure S 27). 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. From the total connected crop area, 54 % are connected indirectly. These results are similar to those obtained for the 20 study areas (see above). Mean fractions of directly and indirectly connected 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 area is a bit larger (+3 %). The fraction of indirectly connected crop area per total connected crop area is slightly smaller (-2.6 %).

Compared to the national erosion connectivity model (NECM), the national surface runoff connectivity model (NSCM) shows lower fractions of not connected crop areas (-7.2 %), but higher fractions of directly connected crop areas (+6.2 %). The fractions of indirectly connected areas are approximately the same between the two models (+1 %). Consequently, the fraction of indirectly connected per total connected crop area is lower in the NSCM (-11 %).

Fractions of indirectly connected crop area per total agricultural area for all Swiss catchments in the valley zones, hill zones and lower elevation mountain zones are shown in Figure 8. This map corresponds to a risk map of pesticide transport via hydraulic shortcuts from agricultural areas to surface waters. Areas of high risk for indirect pesticide transport are mainly found in the valley and hill zones of the Swiss midlands, as well as in the Rhone valley. In higher zones (low mountain zones), agricultural areas mainly consist of grassland (see Figure S 28). Therefore, higher zones pose a low risk for pesticide transport, although their fraction of indirectly connected agricultural area can be very high in certain regions, such as the Jura region (see Figure S 30 in the supporting information). However, these regions still pose a risk for indirect transport of other pollutants, such as eroded soil or nitrate to surface waters.

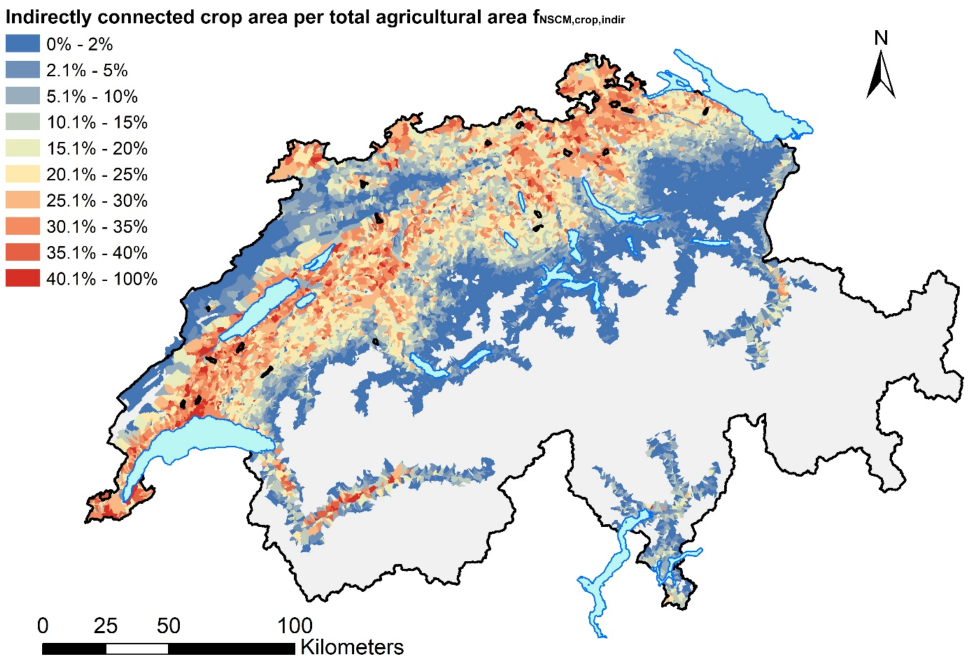


Figure 8: Fraction of indirectly connected crop area per total agricultural area $f_{NSCM,crop,indir}$ for all Swiss catchments in the valley zones, hill zones and lower elevation mountain zones. Study areas are marked with black lines. Grey areas represent higher elevation mountain zones that were excluded from the analysis. 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 in the catchment are ditches at the boundary between a ditches and a 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

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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 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 would 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 highlights that sinks can 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).

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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, Zinko, and Seibert 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 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 are unlikely. Nevertheless, in Switzerland, a national plot-specific crop type geodataset is currently being developed. In the future, this dataset could give further insight into this question.

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.

Extrapolation to the national level

For extrapolating the results of our study areas to the national level, we used the national erosion connectivity model (NECM) (Alder et al. 2015) since this dataset correlated best with the results of the local connectivity model (LSCM). Alder et al. (2015) pointed out that the largest uncertainty of the NECM is the classification of roads as drained or undrained, which was based on generalising assumptions. The national surface runoff connectivity model (NSCM) combines the advantages of the LSCM (consideration of field data on effective shortcut locations) and the NECM (modelling shortcuts on the national scale). In addition, the NSCM also includes statistical information on crops grown per catchment, which is not the case for the NECM. The result is an improved estimation of surface runoff connectivity for crop areas on the national scale.

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, Spycher, and Daniel 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.

In contrast to the NECM, which reports connectivity on a 2x2 m raster, the NSCM is aggregated to the catchment scale. Therefore, it cannot be used as an instrument for pinpointing critical source areas within in a catchment, as this is the case for the NECM. However, the NSCM can indicate the risk posed to the receiving waters of all Swiss catchments by direct or indirect surface runoff from crop areas. Authorities could therefore use the NSCM to select high-risk catchments and prioritize measures. Additionally, our results on the occurrence of hydraulic shortcuts could be used to improve the current version of the NECM.

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 may be important for connecting fields with the stream network (Lefrancq et al. 2013; Gassmann, Lange, and Schuetz 2012; Bug and Mosimann 2011). 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 that approximately half of the surface runoff related pesticide transport is occurring indirectly. This gap between legislation on direct and indirect transport was already pointed out by Alder et al. (2015) for soil erosion.

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, drainage of shortcuts to infiltration basins, removal of shortcuts).

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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.

Finally, pesticide transport via hydraulic shortcuts should 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

Our results 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, Spycher, and Daniel 2015). Therefore, an assessment of hydraulic shortcut relevance in vineyards is needed.

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. In Switzerland, these deposits are expected to be washed off during rain events and to be transported to surface waters via hydraulic shortcuts. Further research should aim on quantifying the amounts of spray drift deposited on roads and transported to surface waters via hydraulic shortcuts.

Although model estimations can give insight of pesticide transport via hydraulic shortcuts on a large scale, they have not been validated in the field. Targeted measurements on pesticide transport through shortcuts are needed to provide evidence on the quantitative relevance of this flow path.

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 connectivity analyses suggests that on average, around half of the surface runoff connectivity and related pesticide transport to surface waters from arable land is caused by hydraulic shortcuts. 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 national surface runoff connectivity model developed in this study identifies high-risk catchments for pesticide transport to surface waters via hydraulic shortcuts.

Overall, the findings highlight the relevance of better understanding the connectivity between fields and the receiving water and the underlying factors and physical structures in the landscape. Further research should aim on analysing the effect of hydraulic shortcuts on surface runoff on other types of agricultural crops, such as orchards or vineyards. In addition, the current type of landscape analysis should be complemented by measurements on actual pesticide concentrations and loads in hydraulic shortcuts in the field.

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 (geodataset)
- Aerial images
- Shortcut locations (geodataset)
- 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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References

Accinelli, C., A. Vicari, P. R. Pisa, and P. Catizone. 2002. 'Losses of atrazine, metolachlor, prosulfuron and triasulfuron in subsurface drain water. I. Field results', *Agronomie*, 22: 399-411.

Alder, S., V. Prasuhn, H. Liniger, K. Herweg, H. Hurni, A. Candinas, and H. U. Gujer. 2015. 'A high-resolution map of direct and indirect connectivity of erosion risk areas to surface waters in Switzerland-A risk assessment tool for planning and policy-making', *Land Use Policy*, 48: 236-49.

Ammann, L., T. Doppler, C. Stamm, P. Reichert, and F. Fenicia. 2020. 'Characterizing fast herbicide transport in a small agricultural catchment with conceptual models', *Journal of Hydrology*, 586.

Ayele, G. T., S. S. Demissie, M. A. Jemberrie, J. Jeong, and D. P. Hamilton. 2020. 'Terrain Effects on the Spatial Variability of Soil Physical and Chemical Properties', *Soil Systems*, 4.

BAFU, Bundesamt für Umwelt. 2012. "Einzugsgebietsgliederung Schweiz (EZGG-CH), Topographische Einzugsgebiete der Schweizer Gewässer." In, edited by Bundesamt für Umwelt BAFU. Bern: Bundesamt für Umwelt BAFU.

Beketov, M. A., B. J. Kefford, R. B. Schafer, and M. Liess. 2013. 'Pesticides reduce regional biodiversity of stream invertebrates', *Proceedings of the National Academy of Sciences of the United States of America*, 110: 11039-43.

BFS, Bundesamt für Statistik. 2014. "Arealstatistik nach Nomenklatur 2004." In, edited by Bundesamt für Statistik BFS.

Bug, J., and T. Mosimann. 2011. 'Modellierung des Gewässeranschlusses von erosionsaktiven Flächen', *Naturschutz und Landschaftsplanung*, 43.

Bunzel, K., M. Liess, and M. Kattwinkel. 2014. 'Landscape parameters driving aquatic pesticide exposure and effects', *Environmental Pollution*, 186: 90-97.

Carlsen, S. C. K., N. H. Spliid, and B. Svensmark. 2006. 'Drift of 10 herbicides after tractor spray application. 2. Primary drift (droplet drift)', *Chemosphere*, 64: 778-86.

Carluer, Nadia, and Ghislain De Marsily. 2004. 'Assessment and modelling of the influence of man-made networks on the hydrology of a small watershed: implications for fast flow components, water quality and landscape management', *Journal of Hydrology*, 285: 76-95.

De Baan, L. 2020. 'Sensitivity analysis of the aquatic pesticide fate models in SYNOPS and their parametrization for Switzerland', *Science of the Total Environment*, 715.

De Baan, L., S. Spycher, and O. Daniel. 2015. 'Einsatz von Pflanzenschutzmitteln in der Schweiz von 2009 bis 2012', *Agrarforschung Schweiz*, 6: 45-55.

Dehotin, J., P. Breil, I. Braud, A. de Lavenne, M. Lagouy, and B. Sarrazin. 2015. 'Detecting surface runoff location in a small catchment using distributed and simple observation method', *Journal of Hydrology*, 525: 113-29.

Doppler, Tobias, L. Camenzuli, G. Hirzel, M. Krauss, A. Lück, and Christian Stamm. 2012. 'Spatial variability of herbicide mobilisation and transport at catchment scale: insights from a field experiment', *Hydrology and Earth System Sciences*, 16: 1947-67.

Dosskey, M. G., D. E. Eisenhauer, and M. J. Helmers. 2005. 'Establishing conservation buffers using precision information', *Journal of Soil and Water Conservation*, 60: 349-54.

Etat de Genève, Direction de l'information du territoire (DIT). 2016. "Orthophotos 2016 (5cm) hivers." In, edited by Direction de l'information du territoire (DIT) Etat de Genève. Etat de Genève, Direction de l'information du territoire (DIT).

Fiener, P., K. Auerswald, and K. Van Oost. 2011. 'Spatio-temporal patterns in land use and management affecting surface runoff response of agricultural catchments-A review', *Earth-Science Reviews*, 106: 92-104.

Gassmann, M., J. Lange, and T. Schuetz. 2012. 'Erosion modelling designed for water quality simulation', *Ecohydrology*, 5: 269-78.

Gomides Freitas, Luciana, Heinz Singer, Stephan R. Müller, René P. Schwarzenbach, and Christian Stamm. 2008. 'Source area effects on herbicide losses to surface waters - A case study in the Swiss Plateau', *Agriculture, Ecosystems and Environment*, 128: 177-84.

Heathwaite, A. L., P. F. Quinn, and C. J. M. Hewett. 2005. 'Modelling and managing critical source areas of diffuse pollution from agricultural land using flow connectivity simulation', *Journal of Hydrology*, 304: 446-61.

Holvoet, Kathrin M. A, Piet Seuntjens, and Peter A. Vanrolleghem. 2007. 'Monitoring and modeling pesticide fate in surface waters at the catchment scale', *Ecological Modelling*, 207: 53-64.

Jankowfsky, S., F. Branger, I. Braud, J. Gironas, and F. Rodriguez. 2013. 'Comparison of catchment and network delineation approaches in complex suburban environments: application to the Chaudanne catchment, France', *Hydrological Processes*, 27: 3747-61.

Kanton Zürich, Amt für Raumentwicklung. 2015. "Orthofoto des Kantons Zürich Sommer RGB 2014/15." In. Geographisches Informationssystem GIS-ZH: Kanton Zürich, Amt für Raumentwicklung.

Kirchhofer, Walter, and Boris Sevruk. 1992. "Mean Annual Corrected Precipitation Depths 1951-1980." In, edited by Geographisches Institut der Universität Bern. Bern: Bundesamt für Landestopographie.

Larsbo, M., M. Sandin, N. Jarvis, A. Etana, and J. Kreuger. 2016. 'Surface Runoff of Pesticides from a Clay Loam Field in Sweden', *Journal of Environmental Quality*, 45: 1367-74.

Lefrancq, M., G. Imfeld, S. Payraudeau, and M. Millet. 2013. 'Kresoxim methyl deposition, drift and runoff in a vineyard catchment', *Science of the Total Environment*, 442: 503-08.

Lefrancq, M., A. Jadas-Hecart, I. La Jeunesse, D. Landry, and S. Payraudeau. 2017. 'High frequency monitoring of pesticides in runoff water to improve understanding of their transport and environmental impacts', *Science of the Total Environment*, 587: 75-86.

Leu, Christian, Heinz Singer, Christian Stamm, Stephan R. Müller, and René P. Schwarzenbach. 2004a. 'Simultaneous Assessment of Sources, Processes, and Factors Influencing Herbicide Losses to Surface Waters in a Small Agricultural Catchment', *Environmental Science & Technology*, 38: 3827-34.

———. 2004b. 'Variability of Herbicide Losses from 13 Fields to Surface Water within a Small Catchment after a Controlled Herbicide Application', *Environmental Science & Technology*, 38: 3835-41.

Loague, K., D. L. Corwin, and A. T. Ellsworth. 1998. 'Feature: the challenge of predicting nonpoint source pollution', *Environ Sci Technol*, 32: 130A-3A.

Luo, G. J., S. J. Wang, X. Y. Bai, X. M. Liu, and A. Y. Cheng. 2016. 'Delineating small karst watersheds based on digital elevation model and eco-hydrogeological principles', *Solid Earth*, 7: 457-68.

Malaj, E., P. C. von der Ohe, M. Grote, R. Kuhne, C. P. Mondy, P. Usseglio-Polatera, W. Brack, and R. B. Schafer. 2014. 'Organic chemicals jeopardize the health of freshwater ecosystems on the continental scale', *Proceedings of the National Academy of Sciences of the United States of America*, 111: 9549-54.

Matsumoto, Makoto, and Takuji Nishimura. 1998. 'Mersenne Twister: A 623-Dimensionally Equidistributed Uniform Pseudo-Random Number Generator', *ACM Transactions on Modeling and Computer Simulation*, 8: 3-30.

Payraudeau, S., P. Junker, G. Imfeld, and C. Gregoire. 2009. 'Characterizing hydrological connectivity to identify critical source areas for pesticides losses', *18th World Imacs Congress and Modsim09 International Congress on Modelling and Simulation*: 1879-85.

Pionke, H. B., W. J. Gburek, A. N. Sharpley, and R. R. Schnabel. 1995. 'Flow and nutrient export patterns for an agricultural hill-land watershed', *Clean Water - Clean Environment - 21st Century, Team Agriculture - Working to Protect Water Resources, Conference Proceedings, Vol Ii: Nutrients*, 95: 167-70.

Prasuhn, V., and K. Grünig. 2001. 'Evaluation der Ökomassnahmen - Phosphorbelastung der Oberflächengewässer durch Bodenerosion', *Schriftenreihe der FAL*, 37: 1-152.

Reichenberger, S., M. Bach, A. Skitschak, and H. G. Frede. 2007. 'Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness; A review', *Science of the Total Environment*, 384: 1-35.

Sandin, M., K. Piikki, N. Jarvis, M. Larsbo, K. Bishop, and J. Kreuger. 2018. 'Spatial and temporal patterns of pesticide concentrations in streamflow, drainage and runoff in a small Swedish agricultural catchment', *Science of the Total Environment*, 610: 623-34.

Schultz, R. C., T. M. Isenhart, W. W. Simpkins, and J. P. Colletti. 2004. 'Riparian forest buffers in agroecosystems - lessons learned from the Bear Creek Watershed, central Iowa, USA', *Agroforestry Systems*, 61-2: 35-50.

Schulz, Ralf. 2001. 'Comparison of spray drift- and runoff-related input of azinphos-methyl and endosulfan from fruit orchards into the Lourens River, South Africa', *Chemosphere*, 45: 543-51.

Sorensen, R., U. Zinko, and J. Seibert. 2006. 'On the calculation of the topographic wetness index: evaluation of different methods based on field observations', *Hydrology and Earth System Sciences*, 10: 101-12.

Stehle, S., and R. Schulz. 2015. 'Agricultural insecticides threaten surface waters at the global scale', *Proceedings of the National Academy of Sciences of the United States of America*, 112: 5750-55.

Sweeney, B. W., and J. D. Newbold. 2014. 'Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and Organisms: A Literature Review', *Journal of the American Water Resources Association*, 50: 560-84.

Swisstopo. 2010. "Topografisches Landschaftsmodell TLM: swissTLM3D." In, edited by Swisstopo. Wabern.

———. 2018. "The high precision digital elevation model of Switzerland." In, edited by Swisstopo. Wabern: Swisstopo.

———. 2019. "The high precision digital elevation model of Switzerland." In, edited by swisstopo. Wabern: swisstopo.

Tarboton, D. G. 1997. 'A new method for the determination of flow directions and upslope areas in grid digital elevation models', *Water Resources Research*, 33: 309-19.

Vischetti, Costantino, Alessandra Cardinali, Elga Monaci, Marco Nicelli, Federico Ferrari, Marco Trevisan, and Ettore Capri. 2008. 'Measures to reduce pesticide spray drift in a small aquatic ecosystem in vineyard estate', *Science of the Total Environment*, 389: 497-502.