1 **Hydraulic Shortcuts Increase the Connectivity of Arable Land Areas to**

2 **Surface Waters**

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Abstract

10 Surface runoff represents a major pathway for pesticide transport from agricultural areas to surface

11 waters. The influence of man-made structures (e.g. roads, hedges, ditches) on surface runoff

12 connectivity has been shown in various studies. In Switzerland, so-called hydraulic shortcuts (e.g.

13 inlets and maintenance manholes of road or field storm drainage systems) have been shown to

14 influence surface runoff connectivity and related pesticide transport. Their occurrence, and their

15 influence on surface runoff and pesticide connectivity have however not been studied systematically.

16 To address that deficit, we randomly selected 20 study areas (average size = 3.5 km^2) throughout the

17 Swiss plateau, representing arable cropping systems. We assessed shortcut occurrence in these study

18 areas using three mapping methods: field mapping, drainage plans, and high-resolution aerial images.

19 Surface runoff connectivity in the study areas was analysed using a 2x2 m digital elevation model and

20 a multiple-flow algorithm. Parameter uncertainty affecting this analysis was addressed by a Monte

21 Carlo simulation. With our approach, agricultural areas were divided into areas that are either directly

22 connected to surface waters, indirectly (i.e. via hydraulic shortcuts), or not connected at all. Finally,

23 the results of this connectivity analysis were scaled up to the national level using a regression model

24 based on topographic descriptors and were then compared to an existing national connectivity model.

25   Inlets of the road storm drainage system were identified as the main shortcuts. On average, we found

26   0.84 inlets and a total of 2.0 manholes per hectare of agricultural land. In the study catchments

27   between 43 and 74 % of the agricultural area is connected to surface waters via hydraulic shortcuts.

28   On the national level, this fraction is similar and lies between 47 and 60 %. Considering our empirical

29   observations led to shifts in estimated fractions of connected areas compared to the previous

30   connectivity model. The differences were most pronounced in flat areas of river valleys.

31   These numbers suggest that transport through hydraulic shortcuts is an important pesticide flow path

32   in a landscape where many engineered structures exist to drain excess water from fields and roads.

33   However, this transport process is currently not considered in Swiss pesticide legislation and

34   authorisation. Therefore, current regulations may fall short to address the full extent of the pesticide

35   problem. Overall, the findings highlight the relevance of better understanding the connectivity

36   between fields and receiving waters and the underlying factors and physical structures in the

37   landscape.

38

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., 2004b;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., 2004a;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

65 pesticide transport during subsequent rainfall events when intercepted pesticides are washed off the

66 roads.

67 However, such linear structures and the related connectivity effects exhibit substantial regional

68 differences due to natural conditions or various aspects of the farming systems. In contrast to other

69 countries, many roads in agricultural areas in Switzerland are drained by stormwater drainage systems

70 (Alder et al., 2015). Inlets of stormwater drainage systems are also found directly in fields (Doppler et

71 al., 2012;Prasuhn and Grünig, 2001). Since those stormwater drainage systems were reported to

72 shortcut surface runoff to surface waters, those structures were called *hydraulic shortcuts* or short-

73 circuits. Doppler et al. (2012) showed in a small Swiss agricultural catchment that hydraulic shortcuts

74 were creating connectivity of remote areas to surface waters and had a strong influence on pesticide

75 transport. Only 4.4 % of the catchment area was connected directly to surface waters, while 23 % was

76 connected indirectly (i.e. via hydraulic shortcuts). For the same catchment, Ammann et al. (2020)

77 showed that the uncertainty of a pesticide transport model could be reduced by 30 % by including

78 catchment-specific knowledge about hydraulic shortcuts and tile drainages.

79 The occurrence of hydraulic shortcuts and their influence on catchment connectivity has only been

80 studied for a few other catchments in Switzerland. Prasuhn and Grünig (2001) found that only 3.2 %

81 of the arable land in five small catchments were connected directly to surface waters, while 62 % were

82 connected indirectly. Consequently, 90 % of the sediment lost to surface waters was transported

83 through shortcuts.

84 To our knowledge, these two studies are the only ones systematically assessing the occurrence of

85 hydraulic shortcuts and their influence on (sediment) connectivity. However, since these studies only

86 covered a small total area in specific regions, it remains unknown if these findings are generally valid

87 for Swiss agricultural areas.

88 Two other studies in Switzerland addressed connectivity on a larger scale using a modelling approach.

89 Both indicated that more areas were connected through shortcuts than directly. Bug and Mosimann

90 (2011) estimated 12.5 % of the arable land in the canton of Basel-Landschaft to be connected directly

91 to surface waters, and 35 % to be connected indirectly. Later, Alder et al. (2015) created a national

92   connectivity map of erosion risk areas. They estimated that 21 % of the agricultural area is connected

93   directly to surface waters and 34 % indirectly. Since only for small areas the occurrence of hydraulic

94   shortcuts was effectively known, generalizing assumptions on the occurrence of hydraulic shortcuts

95   were made in both studies (e.g. classification of roads as drained by shortcuts or as undrained, based

96   on their size). As also stated by Alder et al. (2015), these assumptions are a major source of

97   uncertainty. Their influence on the estimated connectivity fractions remains unclear.

98   In summary, previous studies on hydraulic shortcuts were either restricted to small study areas in a

99   specific region, or were based on generalizing assumptions, lacking a spatially explicit consideration

100   of hydraulic shortcuts. This study aims for a systematic, spatially distributed, and representative

101   assessment of hydraulic shortcut occurrence on Swiss agricultural areas. Based on this assessment we

102   aim on quantifying the influence of hydraulic shortcuts on surface runoff connectivity and pesticide

103   transport. Additionally, we aim on estimating how additional data on the occurrence of shortcuts

104   influence the connectivity fractions reported by the existing national connectivity map. We focused

105   our study on arable land, since this is the largest type of agricultural land with common pesticide

106   application in Switzerland.

107   Our research questions therefore are:

108   1) How widespread do hydraulic shortcuts occur in Swiss arable land areas?

109   2) What is their relevance for surface runoff connectivity and for surface-runoff related pesticide

110   transport?

111   3) How are additional data on the occurrence of shortcuts influencing the connectivity predictions

112   at the national scale?

113

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 (km²)	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**

131
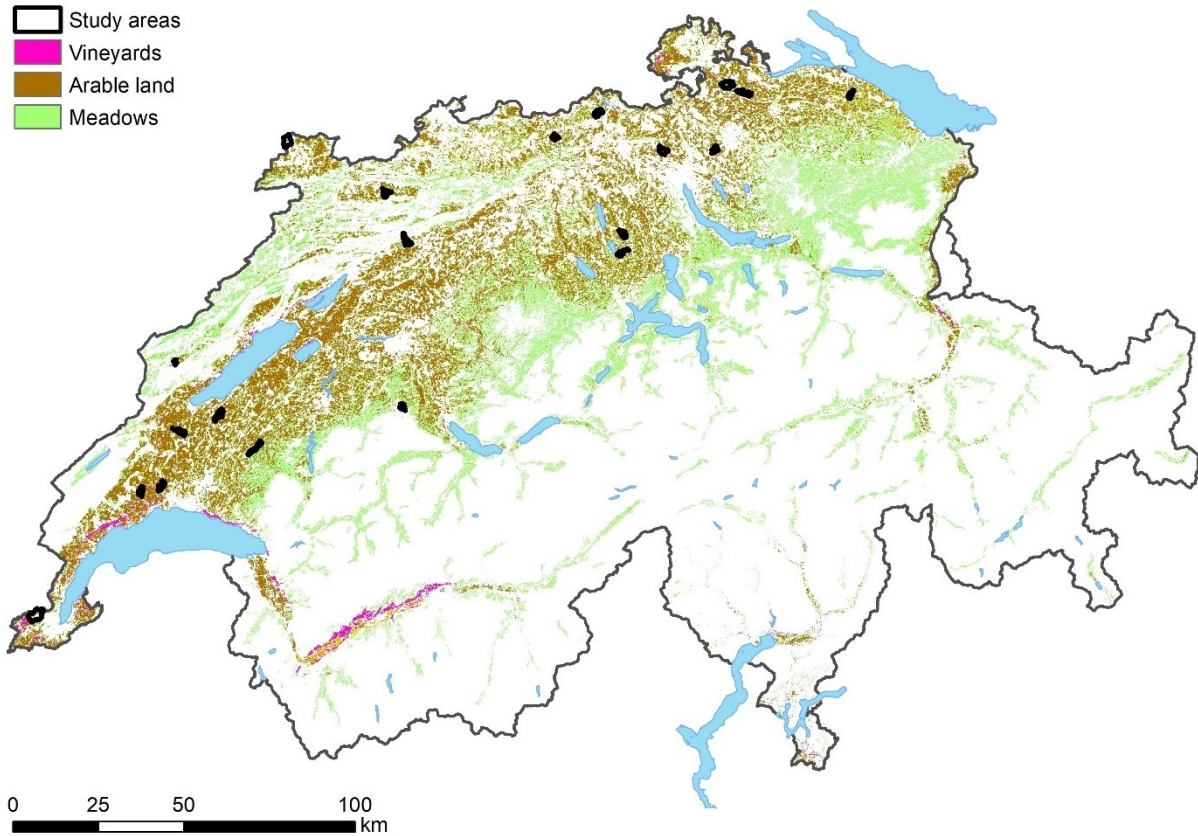
132

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

135

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

143   B)   Maintenance manholes of storm drainage systems or tile drainage system on roads, farm

144   tracks and crop areas

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

146   If one of these structures is present, we defined this as a *potential shortcut*. If surface runoff can enter

147   the structure and if the structure is drained to surface waters or to a wastewater treatment plant, this is

148   defined as a *real shortcut*. Other processes that are sometimes referred to as hydraulic shortcuts (e.g.

149   tile drains) are not considered in this study. Tile drains have already received considerable attention in

150   pesticide research and the transport to tile drains includes flow through natural soil structures.

151   **Shortcut location and type**

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

153   different methods.

154   i) *Field survey*: Field surveys were performed between August 2017 and May 2018 (details see Table

155   S 5). In a subpart of each study area, we walked along roads and paths and mapped all the potential

156   shortcut structures. The starting point was selected randomly, and we mapped as much as we could

157   within one day. Consequently, the field survey data only cover a part of the catchment. For each of the

158   potential shortcuts we recorded its location, as well as a set of properties using a smartphone and the

159   app "Google My Maps". This included a specification of the type of the shortcut (e.g. inlet, inspection

160   chamber, ditches, channel drains), its lid type (e.g. grid, sealed lid, lid with small openings), and its lid

161   height relative to the ground surface. A list of all possible types can be found in the supporting

162   information (Table S 2 to Table S 4).

163   ii) *Drainage plans*: For all municipalities covering more than 5 % of a study area we asked the

164   responsible authorities to provide us with their plans of the road storm drainage systems and the

165   agricultural drainage systems. For 38 and 26 of the 46 municipalities concerned we received road

166   storm drainage system plans and tile drainage system plans, respectively. Reasons for missing data are

167   either that the responsible authorities did not respond or that data on the drainage systems were not

168   available. From the plans, we extracted the locations of shortcuts and, if available, the same properties

169   were specified as in the field survey.

170 iii) A*erial images*: Between August 2017 and August 2018 (details see Table S 5) we acquired aerial

171 images of the study areas with a ground resolution of 2.5 to 5 cm. We used a fixed-wing UAV (eBee,

172 Sensefly, Cheseaux-sur-Lausanne) in combination with a visible light camera (Sony DSC-WX220,

173 RGB). The study areas were fully covered by the UAV imagery, with the exception of larger

174 settlement areas, forests, and lakes, and of no-fly zones for drones (e.g. airports). The UAV images

175 were processed to one georeferenced aerial image per study area using the software Pix4Dmapper 4.2.

176 In the no-fly zones of the study areas Meyrin (Geneva), Buchs (Zürich), and Nürensdorf (Zürich) we

177 used aerial images provided by the cantons of Geneva (Etat de Genève, 2016) and Zürich (Kanton

178 Zürich, 2015). Ground resolutions were 5 cm, and 10 cm respectively. Using ArcGIS 10.7, we gridded

179 the aerial images, scanned by eye through each of the grid cells, and marked all potential shortcut

180 structures manually. If observable from the aerial image, the same properties as for the field survey

181 were specified for each potential shortcut structure.

182 We combined the three datasets originating from the three methods to a single dataset. If a potential

183 shortcut structure was only found by one of the mapping methods, its location and type were used for

184 the combined dataset. If it was found by more than one of the mapping methods, we used the location

185 and type of the mapping method that we expected to be the most accurate. For the location

186 information, this is UAV imagery, before field survey, and maps. For the type specification, this is

187 field survey, before UAV imagery, and maps.

188 **Assigning shortcuts to different landscape elements**

189 In order to better understand where hydraulic shortcuts occur the most, we assigned them to different

190 landscape elements. Using the topographic landscape model of Switzerland "swissTLM3D"

191 (Swisstopo, 2010) we defined five landscape elements: Paved roads, unpaved roads, fields,

192 settlements, and other areas (e.g. railways, other traffic areas, forests, water bodies, wetlands, single

193 buildings). For all landscape elements except roads and railways, shortcuts were assigned to their

194 landscape elements by a simple intersection. However, shortcuts belonging to road or railway drainage

195 systems are in many cases not placed on the road or railway directly, but on the adjacent agricultural

196 land or settlement. Therefore, shortcuts were assigned to the landscape elements road or railway if

197 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, see introduction). It mainly focuses on the first two elements of the CSA concept (pesticide application and connectivity to surface waters), 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.

224 **Model structure**
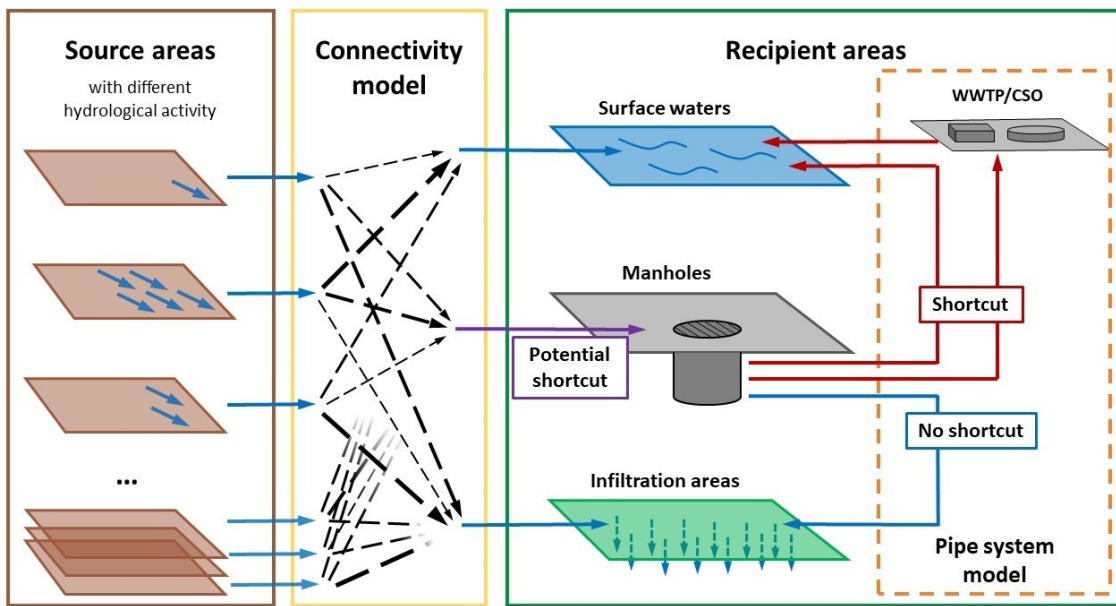
228 ***Source areas.*** All crop areas on which pesticides are applied should in theory be considered as source

229 areas. However, a highly resolved spatial dataset of land in a crop rotation for our study areas is

230 lacking. Therefore, we considered the total extent of agricultural areas (i.e. arable land,

231 meadows/pastures, vineyards, orchards, and gardening) as source areas, since those areas could be

232 derived in high resolution. The extent of agricultural areas was defined by subtracting all non-

233 agricultural areas (forests, water bodies, urban areas, traffic areas, and other non-agricultural areas) as

234 defined by the national topographical landscape model SwissTLM3D (Swisstopo, 2010) from the total

235 area of each study area. According to the Swiss proof of ecological performance (PEP), pesticide

236 usage within a distance of 6 m from a river, and within 3 m from hedges and forests is prohibited. The

237 extent of agricultural areas was reduced accordingly except along forests (parameters *river spray*

238 *buffer*, *hedge spray buffer*).

239 ***Recipient areas.*** Surface runoff generated on a source area and routed through the landscape can end

240 up in three different types of landscape elements, referred to as recipient areas: Surface waters,

241 infiltration areas (i.e. forests, hedges, internal sinks), and shortcuts. The extent of surface waters

242 (rivers that have their course above the surface, lakes, and wetlands), was defined by the

243 SwissTLM3D model as was the extent of forests and hedges. Since forests and hedges are known to

244   infiltrate surface runoff (Sweeney and Newbold, 2014;Schultz et al., 2004;Bunzel et al., 2014;Dosskey

245   et al., 2005) we assumed that forests with a certain width (parameter *infiltration width*) act as an

246   infiltration area. Hedges were assumed either to act as infiltrations areas, or to have no effect on

247   surface runoff. Accordingly, the parameter *hedge infiltration*, was varied between yes (hedges act as

248   infiltration areas) and no (hedges don't act as an infiltration areas).

249   Internal sinks in the landscape were defined using the 2x2m digital elevation model (Swisstopo, 2018).

250   All sinks larger than two raster cells and deeper than a certain depth (parameter *sink depth*) were

251   defined as internal sinks. All other sinks were filled completely.

252   Shortcuts were defined in two different ways (parameter *shortcut definition*): In definition A, all inlets,

253   ditches, and channel drains were considered as potential shortcuts. In definition B, manholes lying in

254   internal sinks were additionally considered as potential shortcuts. Potential shortcuts were defined to

255   act as real shortcuts if they are known to discharge to surface waters or wastewater treatment plants.

256   From the drainage plans of the municipalities, we know that most of the inlets discharge into either a

257   surface water body or a wastewater treatment plant. Therefore, also potential shortcuts with unknown

258   drainage location were assumed to act as real shortcuts. Potential shortcuts discharging into forests or

259   infiltration structures were assumed not to act as shortcuts and were not used in the model. Shortcut

260   recipient areas were defined as the raster cells of the digital elevation model on which the shortcut is

261   located and all the cells directly surrounding it (see Figure S 14 in the SI).

262   ***Connectivity model***. For modelling connectivity we used the TauDEM model (Tarboton, 1997) which

263   is based on a D-infinity flow direction approach. As an input we used a 2x2m digital elevation model

264   (DEM) (Swisstopo, 2018). This DEM was modified as follows: We assumed that only those internal

265   sinks that were defined as sink recipient areas (see above) effectively act as sinks. Therefore, firstly,

266   all sinks were filled, and sink recipient areas were carved 10 m into the DEM. Secondly, all other

267   recipient areas (shortcuts, forests, hedges, surface waters) were carved between 10 and 50 m into the

268   DEM. Carving the recipient areas into the DEM ensured that surface runoff reaching a recipient area

269   was not routed further on to another recipient area. Thirdly, to account for the effect of roads

270   accumulating surface runoff (Heathwaite et al., 2005), roads were carved into the DEM by a given

271   depth defined by the parameter *road carving depth*.

272 The modified DEM, the source areas, and the recipient areas were used as an input into the TauDEM

273 tool "D-Infinity upslope dependence". Like this, each raster cell belonging to a source area was

274 assigned with a probability to be drained into one of the three types of recipient areas.

275 The connectivity of a source area may depend on the flow distance to surface waters. For longer flow

276 distances, water has a higher probability to infiltrate before it reaches a surface water. Therefore, for

277 each source area raster cell, we calculated the flow distance to its recipient area using the tool "D-

278 infinity distance down".

Model parametrization and sensitivity analyses

280 The model parameters mentioned in the section above vary in space and time. Since this variability

281 could not be addressed with the selection of a single parameter value, we performed a Monte Carlo

282 simulation with 100 realizations. The probability distributions of the parameters are provided in Table

283 2. The bounds or categories of these distributions were based on our prior knowledge about the

284 hydrological processes involved, about structural aspects (e.g. depths of sinks), and on our experience

285 from field mapping. The parameters *river spray buffer* and *hedge spray buffer* were assumed constant

286 according to the guidelines of the Swiss proof of ecological performance (PEP).

287 To assess the influence of single parameters on our modelling results, we performed a local sensitivity

288 analysis against a benchmark model (one realization of the model with a specific parameter set, see

289 Table 2). When selecting the benchmark model parameter set, we kept the changes in the digital

290 elevation model small (i.e. *road carving depth* = 0 cm, *sink depth* = 10 cm). For the other model

291 parameters, we selected the values that we assumed to be the most probable in reality. For the local

292 sensitivity analysis, each of the model parameters was varied individually within the same boundaries

293 as for the Monte Carlo analysis.

294 **Table 2: Summary of parameter distributions used for the Monte Carlo analysis and parameter values used as a**
295 **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

296

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).

314   For other variables (e.g. crop type, rain intensity), there is no indication for such systematic

315   differences. Therefore, we assumed that they do not differ systematically between areas draining to

316   different recipient areas.

317

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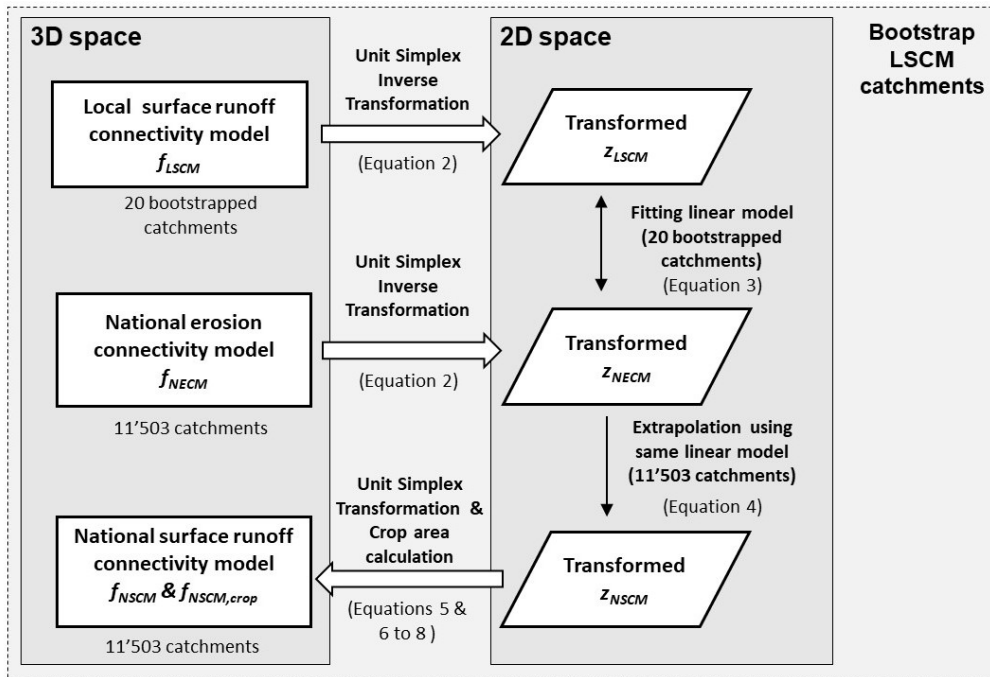
Figure 3: Extrapolation of the local surface runoff connectivity model (LSCM) to the national scale (NSCM) using a unit simplex transformation approach.

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 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 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.

357   The fractions of directly, indirectly, and not connected crop areas per total agricultural area per

358   catchment c ($f_{NSCM,crop,c}$) were calculated as follows:

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

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

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

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

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

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

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

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

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

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

369

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.

Drainage location	Inlets Count	Fraction	Maintenance manholes Count	Fraction	Other manholes Count	Fraction	Unknown type 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

391 maintenance manholes belonging to a certain landscape element for each study area can be found in

392 Figure S 18 in the supporting information.

393 **Table 4: Percentage of manholes found on a certain type of landscape element. The category "other areas" integrates**
394 **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 %

395

396 We correlated the densities of inlets and maintenance manholes per study area with possible

397 explanatory variables. Only the density of paved roads was significantly correlated to the density of

398 inlets ($R^2 = 0.33$, $p = 0.008$) and maintenance manholes ($R^2 = 0.37$, $p = 0.005$) (see Table S 6 and

399 Table S 7).

400 **Channel drains and ditches**

401 In addition to manholes, we also mapped channel drains and ditches. With the exception of the study

402 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

403 Figure S 16). In Meyrin and Buchs, most channel drains and ditches (98 % of the total length) drain to

404 surface waters, and only few of them to infiltration areas (2 %).

405 **Mapping accuracy**

406 The results above were generated using three different mapping methods (*field survey*, *UAV images*,

407 and *drainage plans*). These methods differ in their ability to identify and classify a potential shortcut

408 structure correctly and in the study area they cover. We determined the accuracy of the mapping

409 methods aerial images and drainage plans using the field survey method as a ground truth (see Table

410 5) for those parts of the study areas where all three methods were applied. Since channel drains and

411 ditches were rare, this assessment was only performed for manholes.

412 The recall (i.e. the probability that a potential shortcut is found by a mapping method) was limited for

413 the aerial images method (53 % for inlets, and 62 % for maintenance manholes), and even lower for

414 the drainage plans method (32 % for inlets, and 21 % for maintenance manholes). However, identified

415   shortcuts were in most of the cases classified correctly (accuracy: 93 % to 94 % for aerial images,

416   88 % to 89 % for drainage plans).

417   For the entire study areas, Figure 4 shows the number of potential shortcuts identified by the three

418   mapping methods. Despite a low recall, aerial images identified the largest number of potential

419   shortcuts. This is due to the large spatial coverage by the aerial images method. Since the overlap

420   between the three methods is small (only 32 % of the inlets and 15 % of the maintenance manholes

421   were found by more than one method), each of the methods was important to determine the total

422   number of potential shortcuts in the study areas. Because the aerial images and drainage plans have a

423   low recall, but cover large parts of the study areas that were not assessed by the field survey, the

424   numbers reported above are a lower boundary estimate.

425   **Table 5: Recall and classification accuracies of the mapping methods aerial images and drainage plans. The recall**
426   **corresponds to the probability that a potential shortcut is found by the mapping method. Percentages indicate the**
427   **recall of each individual mapping method. In brackets, the recall of the combination of both methods is given. The**
428   **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 %

429
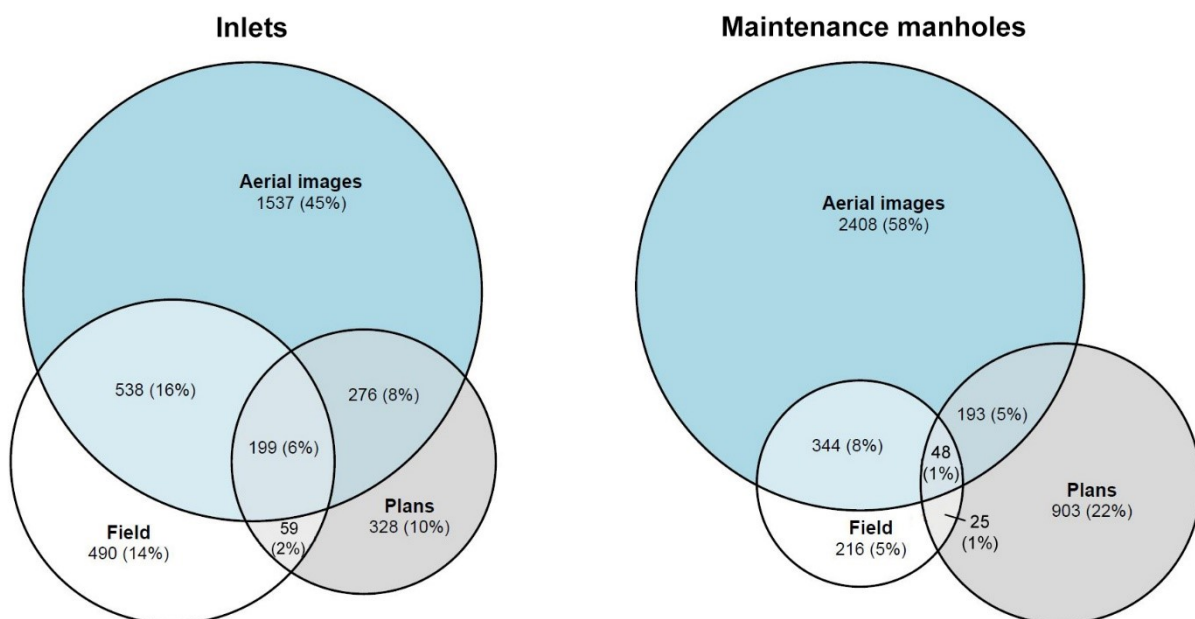
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432

## 3.2. Surface runoff connectivity

3.2.1. Study areas

435 From the Monte Carlo analysis of the surface runoff connectivity model, we obtained an estimate for

436 the fractions of agricultural areas that are connected directly, indirectly, or not at all to surface waters.

437 To illustrate the variability resulting from these Monte Carlo (MC) runs, Figure 5 shows the output of

438 three MC simulations (MC28, MC41, and MC40) for Molondin. These simulations correspond to the

439 5 %, 50 %, and 95 % quantile of the median fraction of indirectly connected per total connected

440 agricultural area over all study catchments. The classification of certain catchment parts is changing

441 depending on the model parametrisation (e.g. letters A to C). However, for other parts, the results are

442 consistent across the different MC simulations (e.g. letters D to F). Overall, the results show that not

443 only agricultural areas close to surface waters (e.g. letter D) are connected to surface waters. Hydraulic

444 shortcuts also create surface runoff connectivity for areas far away from surface waters (e.g. letter E).
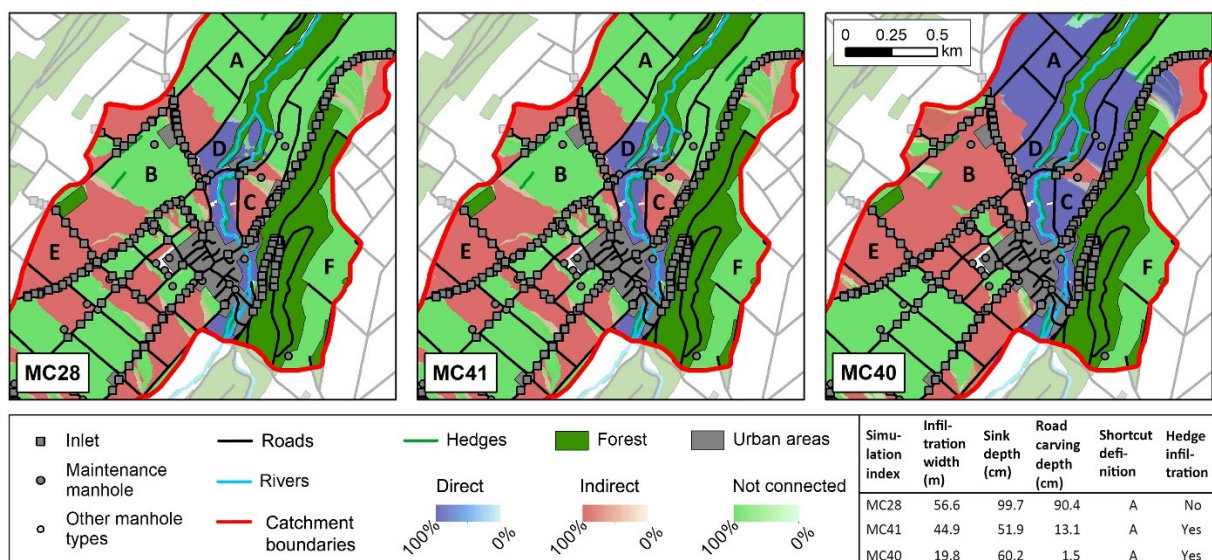
446 Figure 5: Results of three example Monte Carlo (MC) simulations for a part of the study area Molondin. The color
447 ramps show the probability of agricultural areas to be directly connected (blue), indirectly connected (red) and not
448 connected (green). The simulations represent approximately the 5 % (MC28), 50 % (MC41), and 95 % (MC40)
449 quantiles with respect to the resulting median fractions of indirectly connected per total connected area over all study
450 catchments. The parameters of the example MC simulations are shown on the bottom right. Source of background
451 map: Swisstopo (2010)

452 In order to assess the importance of hydraulic shortcuts, we calculated the fraction of indirectly

453 connected area to the total connected area. Across all Monte Carlo simulations, the median of this

454 fraction over all study catchments ranges between 43 % and 74 % (mean: 57 %, median: 58 %; Figure

455 5). Despite considerable uncertainty, the results demonstrate that a large fraction of the surface runoff

456 connectivity to surface waters is established by hydraulic shortcuts.
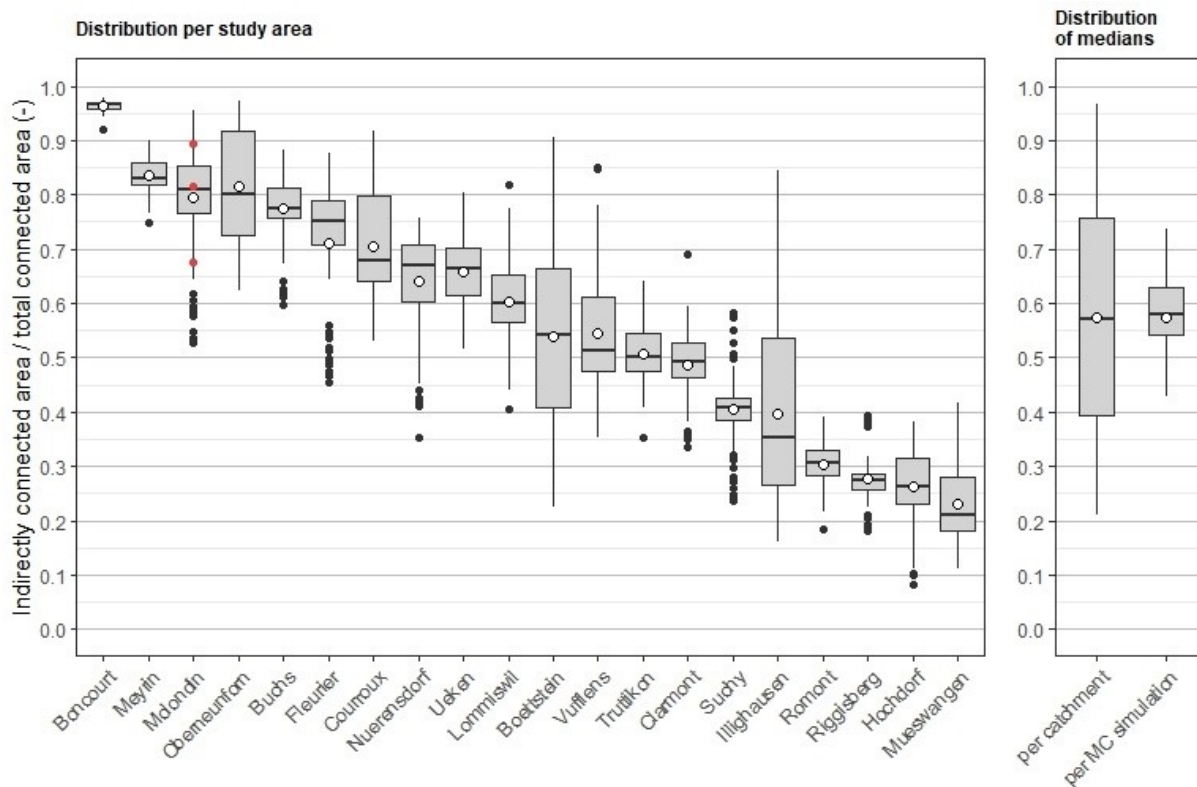
457

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

463 For different flow distances, the fraction of indirectly connected area to the total connected area

464 underlies only minor variations (see Figure S 24). However, this fraction varies strongly between the

465 study areas, with median fractions ranging from 21 % in Müswangen to 97 % in Boncourt. Although

466 the occurrence of hydraulic shortcuts is a prerequisite of indirect connectivity, high manholes densities

467 are not necessarily leading to high fractions of indirect connectivity in a catchment. The densities of

468 inlets and maintenance manholes show only a weak positive correlation to the catchment medians of

469 the fraction of indirectly connected areas (inlets: $R^2 = 0.11$, p = 0.15; maintenance manholes: $R^2 =$

470 0.08, p = 0.23; see Table S 8). By contrast, the two study areas with high channel drain and ditch

471   densities (Meyrin and Buchs) show high fractions of indirect connectivity. Similarly, the density of

472   surface waters is strongly negatively correlated to the fraction of indirect connectivity ($R^2 = 0.51$, $p <$

473   0.001). This suggests that line elements like channel drains, ditches and surface waters usually have

474   an influence on connectivity if they occur in a catchment. By contrast, the influence of point elements

475   seems to depend a lot on the surrounding landscape structure.

476   As a further consequence of the structural differences between the study areas, not all of them reacted

477   the same way to changes in model parameters of the Monte Carlo analysis. For example, the fraction

478   of indirectly to total connected areas in the study area Boncourt was quite insensitive to changes in

479   model parameters. Since Boncourt has a very low water body density, only small areas are connected

480   directly, independent of the model parametrization. The study area Illighausen, on the other hand,

481   reacted very sensitively (range of results = 68 %). Since Illighausen is a very flat catchment, changes

482   in the sink depth parameter had a large influence on the estimated fractions of direct and indirect

483   connectivity.

484   So far, we only reported on the fraction of indirectly connected per total connected area. In Table 6,

485   we additionally report the fractions of total agricultural area connected directly, indirectly, and not at

486   all to surface waters. On average, we estimate between 5.5 % and 38 % (mean: 28 %) of the

487   agricultural area to be connected directly, 13 % to 51 % (mean: 35 %) to be connected indirectly, and

488   12 % to 77 % (mean: 37 %) not to be connected to surface waters. However, the variation between the

489   catchments is much larger than the variation of the Monte Carlo analysis.

490   **Table 6: Fractions of directly, indirectly, and not connected agricultural areas in our study catchments. The first row**
491   **represent the mean fraction over all catchments and Monte Carlo simulations. The second row represents the median**
492   **of the median over all catchments per MC simulation. The third row represents the median of the median over all MC**
493   **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 %)

494

495   **Sensitivity analysis**

496 To analyse which model parameters have the largest influence on our model results, we tested the

497 local model parameter sensitivity on our benchmark model. The fraction of indirectly to total

498 connected area reacts most sensitive to changes in the road carving depth parameter. The difference

499 between the minimal and maximal fraction reported was 17 %. Results were also sensitive to the

500 parameters shortcut definition (14 %) and sink depth (13 %). Infiltration width (4.3 %) and hedge

501 infiltration (2.5 %) had only a minor influence on the fraction reported (see Figure S 22 and Figure S

502 23)..

503 **Hydrological activity**

504 Systematic differences in hydrological activity between directly and indirectly connected areas would

505 have a major influence on the interpretation of our connectivity analysis. We therefore tested for such

506 differences by calculating the distributions of slope and topographic wetness index on these areas.

507 The distributions of both, slope and topographic wetness index were very similar for directly,

508 indirectly, and not connected areas (see Figure S 25 and Figure S 26). Only the slope of not connected

509 areas was found to be slightly smaller than the slope of connected areas. Hence, we could not identify

510 any systematic differences in the factors affecting hydrological activity between directly and indirectly

511 connected areas.

512 Consequently, given the current knowledge, the proportions of direct and indirect surface runoff

513 entering surface waters are expected to be equal to the proportions of directly and indirectly connected

514 agricultural areas. Analogously, the proportion of directly and indirectly transported pesticide loads

515 are expected to be equal to the proportions of directly and indirectly connected crop areas.

516 **3.2.2. Extrapolation to the national level**

517 We created a model for extrapolating the results of our study areas to the national level, using area

518 fractions of the national erosion connectivity model (NECM) (Alder et al., 2015) aggregated to the

519 catchment scale as explanatory variables. The area fractions of the NECM were transformed such that

520 they fit the area fractions of the local surface runoff connectivity model (LSCM) resulting from the

521 Monte Carlo analysis in our study areas. The resulting dataset is called the national surface runoff

522   connectivity model (NSCM). The NSCM provides a separate model for each of the 100 Monte Carlo

523   runs of the LSCM. It is aggregated to the catchment scale and covers all catchments of the valley

524   zones, hill zones and lower elevation mountain zones. The differences between the fitted NSCM and

525   the LSCM were strongly reduced compared to the original NECM (see Figure 7). The root-mean-

526   square error (RSME) on average reduced from 17 % to 9.5 % for directly connected fractions, from

527   12 % to 7.6 % for indirectly connected fractions, and from 18 % to 7.6 % for not connected fractions.
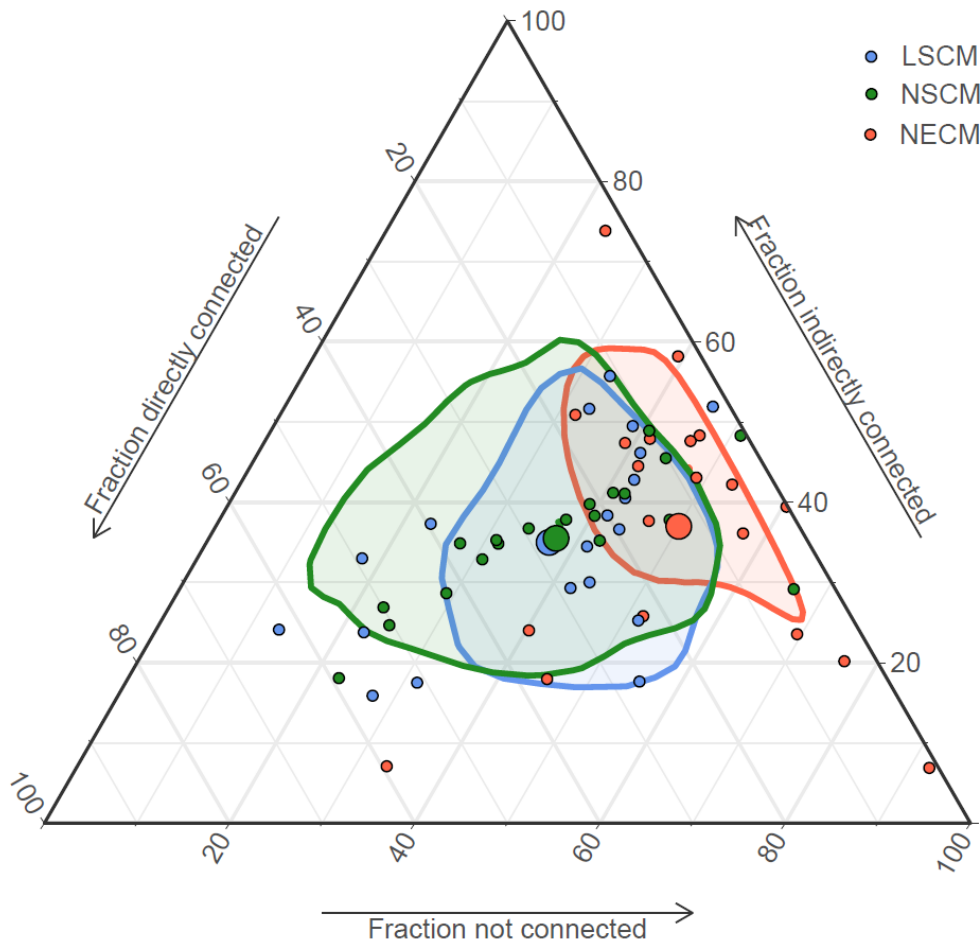
528

529

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

537   By combining the NSCM with land use data, we came up with an estimate of connected crop areas on

538   the national scale. Half of the Swiss agricultural areas in the model region are crop areas (i.e. arable

26

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

566   valleys, and the valleys of Ticino) and in the region of Lake Constance (see Figure S 40). However,

567   when looking at the difference in average predicted connectivity fractions of *crop* areas (Δf_{crop} =

568   (($f_{NSCM,crop,dir}$ - $f_{NECM,crop,dir}$) + ($f_{NSCM,crop,indir}$ - $f_{NECM,crop,indir}$) + ($f_{NSCM,crop,nc}$ - $f_{NECM,crop,nc}$))/3), large

569   differences almost exclusively are found in a band of catchments with high crop densities spreading

570   through the Swiss midland (see Figure 8).
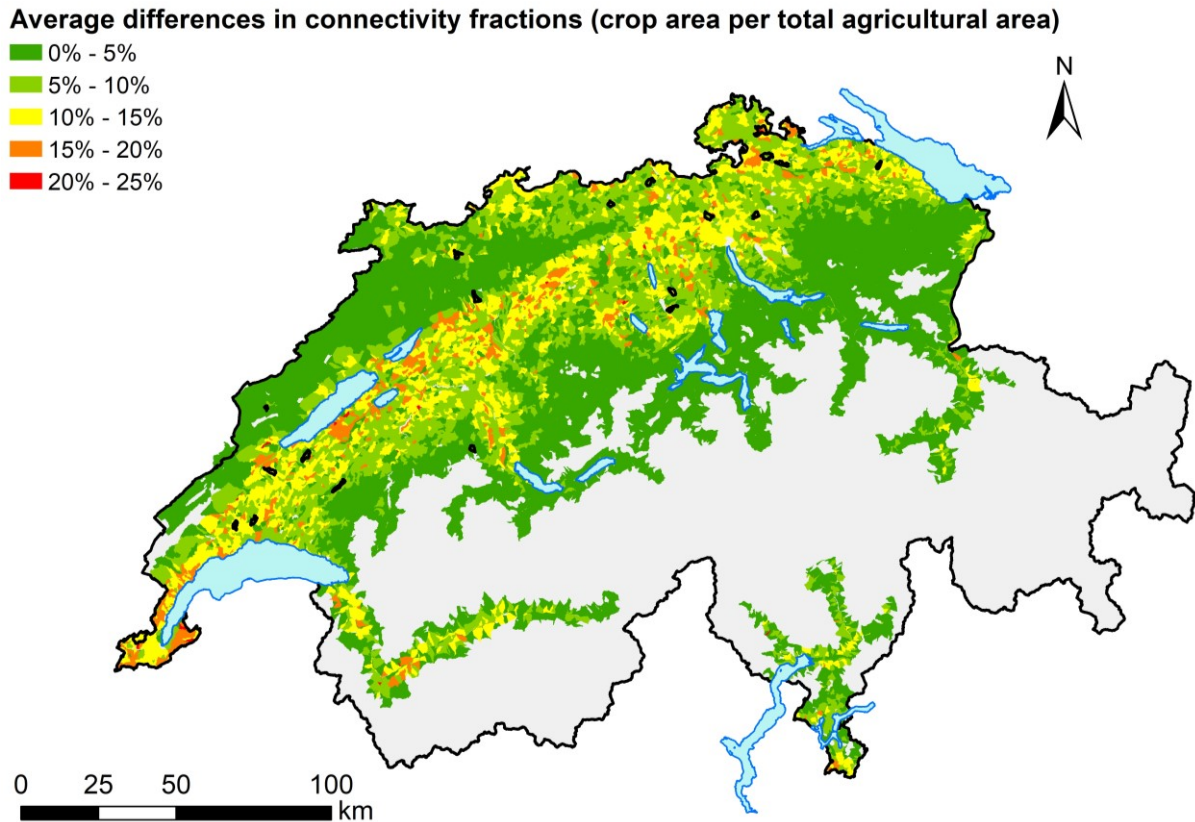
571
572   **Figure 8: Average differences in connectivity fractions of crop areas between the NSCM and the NECM: Δf_{crop} =**
573   **(($f_{NSCM,crop,dir}$ - $f_{NECM,crop,dir}$) + ($f_{NSCM,crop,indir}$ - $f_{NECM,crop,indir}$) + ($f_{NSCM,crop,nc}$ - $f_{NECM,crop,nc}$))/3. The map shows data for all**
574   **Swiss catchments in the valley zones, hill zones and lower elevation mountain zones. Grey areas represent higher**
575   **elevation mountain zones that were excluded from the analysis. Study areas are marked with black lines. Details on**
576   **directly, indirectly, and not connected agricultural areas and crop areas are given in Figure S 37 to Figure S 43. For**
577   **comparison, a map of crop densities is given in Figure S 29. Source of background map: Swisstopo (2010)**

578

579   ## 4. Discussion

580   **Occurrence of hydraulic shortcuts**

581   Our study shows that storm drainage inlets and maintenance manholes are common structures found in

582   Swiss agricultural areas. While in neighbouring countries roads are often drained by ditches, Swiss

583   roads are usually drained by storm drainage inlets (Alder et al., 2015). It is therefore not surprising that

584   most of the inlets found in the study areas are located on roads. These findings are in accordance with

585   the only other study in Switzerland reporting numbers on storm drainage inlets (Prasuhn and Grünig,

586   2001).

587   The vast majority of mapped storm drainage inlets were found to discharge to surface waters directly

588   or via wastewater treatment plants (WWTPs). Thus, the occurrence of an inlet is in most cases directly

589   related to a risk for pesticide transport to surface waters. The following three processes generate this

590   risk: Firstly, pesticide loaded surface runoff produced on crop areas can enter the inlet. Secondly,

591   spray drift deposited on roads can be washed off and enter the inlet. Thirdly, inlets can be oversprayed

592   during pesticide application, which is mainly considered probable for inlets located in the fields.

593   Although maintenance manholes were also found to discharge to surface waters directly or via

594   WWTPs, their occurrence does not directly translate into a risk for pesticide transport to surface

595   waters. In contrast to storm drainage inlets, maintenance manholes are not designed to collect surface

596   runoff. Their lids are usually closed or only have a small opening, significantly decreasing the risk of

597   surface runoff entering the manhole or of overspraying. In addition, lids of maintenance manholes in

598   fields are often elevated compared to the soil surface. Maintenance manholes on roads are (in contrast

599   to inlets) usually positioned such that concentrated surface runoff is bypassing them. However, as also

600   shown by Doppler et al. (2012), maintenance manholes can collect surface runoff from fields if they

601   are located in a sink or a thalweg and water is ponding above them during rain events. During our field

602   mapping campaign, we additionally found several damaged maintenance manholes that could easily

603   act as a shortcut.

604   Channel drains and ditches discharging into surface waters were rare in most study areas with two

605   exceptions. In Meyrin, the large length of these structures can be explained by the existence of a large

606   vineyard. Additionally, the density of manholes in this vineyard was higher than on the surrounding

607   arable land. This indicates that vineyards could generally have higher shortcut densities than arable

608   land. In Buchs, around 60 % of the channel drain and ditch length consists of ditches that cannot be

609   clearly distinguished from small streams. They are not appearing in the national topographic landscape

610   model (Swisstopo, 2010) that was used for the definition of rivers and streams and did not appear to be

611   streams during field mapping or when analysing aerial images.

612 The number of mapped shortcuts represents a lower boundary estimate of the shortcuts present (see

613 results) and therefore leads to an underestimation of indirect connectivity. Probabilities for missing

614 shortcuts during our mapping campaign depend on their location. While aerial images were at almost

615 full coverage of the study areas, field mapping was performed mainly along roads. Drainage plans

616 were available more often along roads than on fields. Therefore, we expect that detection probability

617 of shortcuts is generally higher along roads than on fields. Besides coverage, various other factors

618 influence the detection probabilities of the mapping methods. Field mapping and aerial image

619 detection performance is reduced if shortcuts are covered. Along roads, this is mainly caused by

620 leaves, soil, and for aerial images also by trees and vehicles. On the fields, this is mainly caused by

621 soil or by crops. Detection performance of the aerial images method is additionally influenced by

622 image quality and ground resolution. Image quality is mainly influenced by wind and light conditions

623 during the UAV flights. In order to ensure high image quality, we planned UAV flights such that

624 weather conditions were favourable (low wind, slightly overcast). However, differences in image

625 quality between the study areas could not be completely avoided. Higher ground resolution could

626 further improve the data produced. Although detection performance is not expected to be limited by

627 the ground resolution used, higher resolution could improve the correct classification of shortcut types.

628 **Surface runoff connectivity**

629 Our study shows that around half of the surface runoff connectivity in our study areas, but also on the

630 national scale, is generated by hydraulic shortcuts. Surface runoff is considered one of the most

631 important processes for pesticide transport to surface waters. Consequently, a large amount of the

632 pesticide loads found in surface waters during rain events is expected to be transported by hydraulic

633 shortcuts. These findings are in accordance to the results of other studies investigating the influence of

634 hydraulic shortcuts on surface runoff connectivity (Alder et al., 2015;Prasuhn and Grünig, 2001;Bug

635 and Mosimann, 2011) and on pesticide transport (Doppler et al., 2012).

636 The fraction of indirect connectivity was found to be very different between study areas. The

637 variability introduced by the different properties of the study areas was larger than the variability

638 introduced by the different model parameters of the Monte Carlo analysis, indicating that our results

639　are robust against changes of our model parameters. Our model was most sensitive to changes of the

640　parameters *road carving depth*, *shortcut definition*, and *sink depth*. These parameters are discussed in

641　the following.

642　The parameter *road carving depth* accounts for the property of roads of collecting and concentrating

643　surface runoff. This effect is strongly dependent on microtopography, extremely variable in space, and

644　can therefore not be properly accounted for by a space-independent parameter. Usage of a higher

645　resoluted digital elevation model could however reduce the uncertainty on the effect of roads on

646　connectivity. Higher resolved digital elevation models could also help in capturing the influence of

647　other microtopographical features better. For example, small ditches or small elevations on the ground

648　can easily channel surface runoff. This can either direct surface runoff into a shortcut from areas not

649　modelled to drain to a shortcut, or vice versa. In Switzerland, a new digital elevation model with a

650　raster resolution of 0.5 m (Swisstopo, 2019) recently became available and could be used for this

651　purpose. This elevation model was not used within this study, since the study already had progressed

652　further by the time the dataset was published.

653　The model parameters *shortcut definition* (i.e. are maintenance manholes in a sink considered as a

654　shortcut) and *sink depth* are both related to the fate of surface runoff ponding in a sink. This indicates

655　that maintenance manholes in sinks could have an important influence on surface runoff connectivity

656　of agricultural areas. During our field mapping campaign, only few maintenance manholes in sinks

657　were investigated. It is therefore unclear if most maintenance manholes in sinks are capturing ponding

658　surface runoff, if surface runoff is usually infiltrating into the soil, or if it continues to flow on the

659　surface. Sensitivity of our model to the parameter *sink depth* additionally indicates that sinks might

660　play an important role for connectivity. Therefore, they should not be filled completely during GIS

661　analyses, as this is done by default by some flow routing algorithms.

662　Surface runoff is usually assumed to drain to the receiving water of its topographical catchment.

663　However, in various cases, the pipes draining hydraulic shortcuts were found to cross topographical

664　catchment boundaries. Consequently, surface runoff and related pesticide loads are transported to a

665　different receiving water than expected by the topographical catchment. This may be important to

666 consider when interpreting pesticide monitoring data from small catchments. Similar effects were

667 already reported for karstic aquifers or the storm drainage systems of urban areas (Jankowfsky et al.,

668 2013;Luo et al., 2016).

Hydrological activity

670 We did not find any indication on systematic differences between the factors controlling hydrological

671 activities of directly and indirectly connected agricultural areas by analysing slope and topographic

672 wetness index. Those variables are a proxy for surface runoff formation, soil moisture, groundwater

673 level, but also physical properties of the soil (Sorensen et al., 2006;Ayele et al., 2020). However, the

674 hydrological activity of an agricultural area also depends on other factors that were not quantitatively

675 analysed, such as *rainfall intensities, crop types, soil management practices*, or the presence of *tile*

676 *drainage systems*.

677 *Rainfall intensities:* Because of the small size of the study areas and the close proximity between

678 directly and indirectly connected areas, systematic differences in rainfall intensities within a catchment

679 can be excluded.

680 *Crop types and soil management* can have a strong impact on runoff formation. These practices are

681 chosen by the farmers and there could be systematic differences of these variables. For example,

682 farmers aware of the effect of surface runoff and erosion on the pollution of surface waters might use

683 different cultivation methods or crops (e.g. conservation tillage) on fields close to surface waters than

684 on fields far away. This would lead to a higher probability of surface runoff formation on indirectly

685 connected areas compared to directly connected areas. However, different cultivation methods require

686 different farm machinery. Therefore, cultivation methods are often constrained by the machinery

687 available and farmers use the same cultivation method per crop for all of their fields. Consequently,

688 systematic differences in crop types or soil management between directly and indirectly connected

689 areas of a catchment are unlikely.

690 *Tile drainage systems:* Maintenance manholes and inlets found in the field often belong to a tile

691 drainage system. Therefore, fields on which maintenance manholes or inlets are located, have a higher

692   probability to be drained by tile drainage systems than other fields. This could lead to higher

693   infiltration capacities and consequently to reduced surface runoff on indirectly connected areas

694   compared to directly connected areas. However, since most of the inlets and manholes are located

695   along roads (see results) such differences would only have a minor effect on the overall surface runoff

696   connectivity.

697   Although rainfall intensities, crop types, or soil management practices, are not expected to differ

698   systematically within a catchment, they do differ across catchments. As mentioned in the results, we

699   therefore expect the proportion of directly connected areas to indirectly connected areas in a catchment

700   to be a good indicator for the proportion of surface runoff formed on directly and indirectly connected

701   areas in this catchment. However, due to differences in hydrological activity, two catchments with

702   similar total connected areas may differ strongly in the total amount of surface runoff formed.

703   **Extrapolation to the national level**

704   A major source of uncertainty in the national erosion connectivity model (NECM) is the usage of

705   generalising assumptions due to lack of empirical data. Our results show that some of the estimated

706   connectivity fractions of crop areas change significantly, when the NECM is transformed based on

707   additional empirical data from our field study. However, the results of both models still are in the

708   same order of magnitude and lead to the same general conclusion: Also at the national level, more than

709   half of the connected crop area is connected to surface waters via hydraulic shortcuts, as we observed

710   for the 20 study catchments. As shown in the results, large differences between the NECM and the

711   NSCM in the predictions of crop area connectivity are almost exclusively found in one band of

712   catchments with high cropping densities in the Swiss midland. Potential further empirical

713   investigations or improvements of the NECM should therefore focus on a better representation of

714   these catchments.

715   From all tested variables, the NECM connectivity fractions showed the strongest correlations to the

716   connectivity fractions reported by the local connectivity model (LSCM) in our study areas. This

717   indicates that the NECM is a valid tool for assessing the pesticide connectivity to surface water across

718   catchments in relative terms (e.g. which catchments have high indirect connectivity compared to other

719   catchments). Therefore, we recommend continuing to use the NECM for decision-making in practice,

720   but suggest that effort is put into improving the models in regions where the NECM and NSCM

721   substantially differ.

722   It is, however, important to note, that within this study none of the models (NECM, LSCM, and

723   NSCM) has been tested and validated empirically regarding their actual capacity to quantify the

724   connectivity effects on surface runoff and related pesticide transport. This aspect is addressed in detail

725   in the "further research" section.

726   For creating the NSCM, all crop areas on which pesticides are commonly applied (arable land,

727   vineyards, orchards, horticulture) were assumed to contribute by the same amount to the pesticide

728   transport via surface runoff. However, these crop types are known to differ in the amounts of pesticide

729   applied (De Baan et al., 2015), in the amounts of surface runoff produced, and also with respect to

730   their connectivity to surface waters. This assumption could therefore be refined by considering

731   pesticide application data and by investigating surface runoff connectivity in vineyards, orchards and

732   horticulture in more detail.

733   **Relevance in a broader geographical context**

734   This study focussed on the relevance of hydraulic shortcuts in Switzerland. To our knowledge, no

735   studies have systematically analysed the occurrence of hydraulic shortcuts in other countries.

736   Nevertheless, the available literature suggests that in some regions such man-made structures like

737   roads, pipes, or ditches are important for connecting fields with the stream network (Lefrancq et al.,

738   2013;Gassmann et al., 2012;Bug and Mosimann, 2011;Rübel, 1999). Based on our findings, we

739   hypothesise that shortcuts are mainly important in areas with small field sizes. This increases the

740   density of linear structures such as roads for access.

741   **Implications for practice**

742 In Swiss plant protection[1] legislation and authorisation, the effect of hydraulic shortcuts on pesticide

743 transport is currently not considered. Pesticide application is prohibited within a buffer of 3 m along

744 open water bodies and according to the Swiss proof of ecological performance (PEP) vegetated buffer

745 strip have to at least 6 m wide. In contrast, along roads, a buffer of only 0.5 m is required. Hence, the

746 current Swiss legislation is protecting surface waters against direct, but not against indirect transport.

747 This contrasts with the results of this study, showing that approximately half of the surface runoff

748 related pesticide transport is occurring indirectly. This gap between legislation on direct and indirect

749 transport was already pointed out by Alder et al. (2015) for soil erosion.

750 The most evident measure based on the current legislation are vegetated buffer strips along drained

751 roads and around hydraulic shortcuts, infiltrating surface runoff before it reaches a shortcut. Generally,

752 measures increasing infiltration capacity on the field would reduce pesticide transport. Other measures

753 could aim on the shortcut structures themselves (e.g. construction of shortcuts as small infiltration

754 basins, removal of shortcuts, or treatment of water in shortcuts) or on the pipe outlets (e.g. drainage of

755 shortcuts to infiltration basins, treatment of water at the pipe outlet).

756 Finally, pesticide transport via hydraulic shortcuts should be incorporated into the registration

757 procedure and be considered for the mandatory mitigation measures that go with a registration.

758 Models used in this context are currently only considering transport via direct surface runoff, erosion,

759 tile drainages, and spray drift (De Baan, 2020).

760 **Further research**

761 Our results suggest that the presence of hydraulic shortcuts as well as the fraction of indirectly

762 connected areas are higher in vineyards than on arable land. Since this study focused mainly on the

763 latter, the sample size was too small for a quantitative analysis of vineyards. The fact that Swiss

764 vineyards usually have high road densities points into the same direction. In Swiss vineyards,

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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.

765 pesticides are applied more often and in larger amounts than on arable land (De Baan et al., 2015).

766 Therefore, an assessment of hydraulic shortcut relevance in vineyards is needed.

767 Hydraulic shortcuts are not only collecting surface runoff from target areas, but also from non-target

768 areas such as roads. As shown by Lefrancq et al. (2013), large amounts of spray drift can be deposited

769 on roads. In Switzerland, these deposits are expected to be washed off during rain events and to be

770 transported to surface waters via hydraulic shortcuts. Further research should aim on quantifying the

771 amounts of spray drift deposited on roads and transported to surface waters via hydraulic shortcuts.

772 In our discussion on the hydrological activity (see above), we explained that systematic differences in

773 hydrological activity are unlikely within a catchment, but are expected across catchments. Further

774 research should aim on quantifying the differences in hydrological activity across catchments and their

775 influence on runoff formation. Some of the datasets that could serve such a comparison are available

776 on the national scale (e.g. map of tile drainage potential (Koch and Prasuhn, 2020), or rainfall statistics

777 (e.g. Frei et al. (2018)). Other datasets are currently being developed (e.g. a national plot-specific crop

778 type dataset) or have to be developed (e.g. national soil maps).

779 Although model estimations can give insight of pesticide transport via hydraulic shortcuts on a large

780 scale, they have not been tested and validated in the field with measurements on flow and pesticide

781 transport. Targeted measurements are needed to provide evidence on the quantitative relevance of this

782 flow path. A field study in one catchment in the Swiss plateau (Schönenberger et al., in preparation)

783 demonstrates that pesticide concentrations in shortcuts can be very high. However, more systematic

784 research is needed to quantify the relevance of shortcuts. Ideally, catchment-scale experiments – e.g.,

785 with controlled pesticide applications (see Leu et al. (2004a);Doppler et al. (2012)) – would be carried

786 out to quantify loss rates from directly and indirectly connected fields. Apart from the practical

787 problems of implementing such experiments in the context of farmers managing their land, this

788 approach will often face the problem that many fields are also tile drained. Consequently, any signal in

789 the stream is a superposition of different potential flow pathways. Given that the transport through

790 shortcuts has no unique characteristic in the receiving stream, it is difficult to disentangle and quantify

791 these pathways. This implies that one has to observe simultaneously flow and transport within a

792 catchment at locations where one can differentiate between the flow paths. Such a setup would allow

793 to determine the proportion of total catchment runoff and pesticide load that is transported via

794 hydraulic shortcuts. In addition, isotopic tracers and runoff separation techniques could be used to

795 determine the total amount of surface runoff contributing to catchment runoff. Knowing both, total and

796 indirect surface runoff, the amount of direct surface runoff could be calculated. These measurements

797 of direct and indirect surface runoff could then be compared to the data provided from our

798 connectivity maps. Since shortcuts are only active during rain-events, an event-based monitoring

799 approach would be essential.

800

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 that the national erosion connectivity model (NECM) is a valid tool for relatively comparing pesticide connectivity between catchments. However, the results also show that additional empirical data from the field significantly change the reported connectivity fractions and that the model 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 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 field measurements on actual water flow and pesticide transport in hydraulic shortcuts.

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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