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1 Simulating the effects of spatial configurations of agricultural ditch drainage 2 networks on surface runoff from agricultural catchments

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8 9 Abstract

10 The study of runoff is a crucial issue because it is closely related to flooding, water quality
11 and erosion. In cultivated catchments, agricultural ditch drainage networks are known to
12 influence runoff. As anthropogenic elements, agricultural ditch drainage networks can
13 therefore be altered to better manage surface runoff in cultivated catchments. However, the
14 relationship between the spatial configuration, i.e., the density and the topology, of
15 agricultural ditch drainage networks and surface runoff in cultivated catchments is not
16 understood. We studied this relationship by using a random network simulator that was
17 coupled to a distributed hydrological model. The simulations explored a large variety of
18 spatial configurations corresponding to a thousand stochastic agricultural ditch drainage
19 networks on a 6.4 km² Mediterranean cultivated catchment. Next, several distributed
20 hydrological functions were used to compute water flow-paths and runoff for each simulation.
21 The results showed that (i) denser networks increased the drained volume and the peak
22 discharge and decreased hillslopes runoff, (ii) greater network density did not affect the
23 surface runoff any further above a given network density, (iii) the correlation between
24 network density and runoff was weaker for small subcatchments (< 2 km²) where the
25 variability in the drained area that resulted from changes in agricultural ditch drainage

26 networks increased the variability of runoff and (iv) the actual agricultural ditch drainage
27 network appeared to be well optimized for managing runoff as compared with the simulated
28 networks. Finally, our results highlighted the role of agricultural ditch drainage networks in
29 intercepting and decreasing overland flow on hillslopes and increasing runoff in drainage
30 networks.

31

32 **Keywords**

33 Agricultural ditch drainage network, cultivated catchments, stochastic simulations,
34 hydrological modeling, runoff.

35 **1 Introduction**

36 Hedges, ditches, terrace fronts, embankments, grass strips and roads are common linear
37 features of cultivated landscapes (Figure 1).

38 Figure 1

39 The functional importance of these features has been emphasized in various contexts and
40 biophysical processes. In ecology, they provide valuable habitats, enhance connectivity within
41 landscapes and can serve as habitats for rare species (Forman & Baudry, 1984; Herzon &
42 Helenius, 2008; Watson & Ormerod, 2004; Pita et al., 2006). Linear features affect soil
43 redistribution as well, especially terraces that attenuate slopes, facilitate agriculture and limit
44 long-term soil loss (Bevan & Conolly, 2011; Paroissien et al., 2010). By favoring water
45 infiltration, they play a role in groundwater hydrology (Dages et al., 2009). Linear features
46 also alter overland flow paths (Duke et al., 2006; Gascuel-Oudoux et al., 2011). They can force
47 water to not follow the steepest slope, but they can also concentrate runoff along the steepest
48 slope.

49 When focusing on the impacts of agricultural ditch drainage networks, four roles are
50 commonly considered: the interception of overland flow on hillslopes, the drainage of
51 groundwater and exfiltration to ditch networks by lowering the water table, infiltration from
52 the ditch towards the groundwater and conveyance of water towards downstream areas
53 (Adamiade, 2004; Carluer & Marsily, 2004; Dunn & Mackay, 1996). A role will be
54 predominant or will not, depending on various factors, including climate, soil, direction to the
55 steepest slope and the location of the network within a catchment.

56 In Mediterranean catchments, where short but intense storms predominate, Hortonian runoff
57 is much more important than subsurface flow (Moussa et al., 2002). Hence, considering
58 surface runoff is crucial because it is closely related to flooding, water quality and erosion
59 (Fiener et al., 2011).

60 To control runoff in agricultural catchments, we can work with many anthropogenic elements,
61 such as land use and the tillage practices (Colin et al., 2011 a; Souchère et al., 2005; Takken
62 et al., 2001) or the use of grassed waterways (Fiener et al., 2003). Agricultural ditch drainage
63 networks are also one of the few structural landscape elements that control runoff and that can
64 be changed without consuming or drastically modifying the agricultural area. Therefore, the
65 relationship between agricultural ditch drainage networks and runoff is a crucial landscape
66 structure-function question that is worth investigating. In addition to this relationship, the
67 optimization of agricultural ditch drainage networks is of interest to agricultural landscape
68 managers, for example, in minimizing floods or the fate of pesticides (DGFAR, 2008).

69 Consequently, such an investigation of the relationship between agricultural ditch drainage
70 network spatial configurations and runoff will permit an assessment of the hydrological
71 benefits that we could expect through modifying these networks.

72 Because of the emphasized role of ditches in cultivated landscape hydrology, an increasing
73 number of spatially distributed models have explicitly considered ditch networks and their

74 spatial configurations in landscapes, which have always been considered to be directed tree
75 structures (Al-Khudhairy, 1999; Branger, 2007; Carluer & Marsily, 2004; Dunn et al., 1996;
76 Moussa et al., 2002). Consequently, these models allow for the assessment of the hydrological
77 impact of agricultural ditch drainage networks. These models can also be used to test certain
78 scenarios concerning possible evolutions of these networks. For example, Krause et al. (2007)
79 modeled the effect of removing part of an agricultural ditch drainage network on the
80 hydrology of a lowland floodplain in northeast Germany and showed that groundwater
81 recharge was altered. In the Mediterranean area, Moussa et al. (2002) found that the
82 substitution of a ditch network by a hypothetical natural drainage network that followed the
83 steepest slopes could affect runoff by decreasing peak discharge and increasing lag time.
84 However, these latter studies only considered a few scenarios, such as the suppression of the
85 agricultural parts of the drainage network.

86 Because these studies only considered a limited variability of the ditch network, they could
87 not determine, even for a given catchment, the relationship between the agricultural ditch
88 drainage network spatial configuration, i.e., network density and topology, a landscape
89 structural property, and surface runoff, a landscape functioning property. To explore the
90 relationship between the structure and the function of a landscape, the usual way to proceed in
91 environmental sciences is to couple stochastic landscape structure simulations to a landscape
92 functioning model (Colin et al., 2011 b; Gumiere, 2009; Le Ber et al., 2009; Van
93 Nieuwenhuysse et al., 2011; Viaud et al., 2005). To date, there has not been an equivalent
94 study of the impacts of agricultural ditch drainage networks on runoff.

95 In this study, the objective was to analyze the extent to which the spatial configuration and
96 especially the density of an agricultural ditch drainage network could control the surface
97 runoff of a given cultivated catchment. The investigated case study was the 6.4 km² Bourdic
98 catchment, which is located in the Languedoc vineyards in southern France, where previous

99 hydrological modeling studies could be used as source of data for the hydrological
100 parameterization. We performed this investigation by coupling a ditch network simulator
101 (Bailly et al., 2011) to the surface runoff functions of the MHYDAS model. We focused on
102 the hydrological response both at the catchment and subcatchment outlets and over hillslopes
103 to investigate the influence of the agricultural ditch drainage network spatial configuration,
104 i.e., density and topology, on surface runoff at various spatial scales.

105 **2 Material and Methods**

106 **2.1 Study area**

107 The study area was the 6.4 km² Mediterranean Bourdic catchment (Figure 2). It is located 50
108 km west of Montpellier in southern France. The altitude varies between 45 m at the outlet to
109 128 m westwards. The southern part of the catchment is compounded by rather well
110 delineated small subcatchments with gentle hillslopes whereas the northern part is relatively
111 flat. The land cover consists of mainly vineyards, with a small amount of cereal fields and
112 shrubs. The actual agricultural ditch drainage network is 72 km long and covers all of the
113 catchment except for the limestone uplands (cuesta) located in the center of the catchment. In
114 addition to the drainage networks that are mapped in hydrographic databases (BD TOPO ®,
115 BD CARTHAGE ®), the ditches highly extend past the drainage network (72 km by 10.8
116 km). The actual ditch drainage network was surveyed during the summer 2010 at an average
117 rate of 1.5 to 3 km² per day per person, depending on the difficulty of the terrain. Fifty-
118 centimeter resolution aerial photographs from IGN (Insitut Géographique National) were used
119 to locate the ditches. Agricultural ditch drainage networks are rarely represented in
120 hydrographic databases. An exhaustive survey of the ditch sizes in a sub-catchment of 1 km²
121 revealed that 75 % of the ditches had an upper width between 50 and 120 cm and a depth
122 between 30 and 80 cm.

123 The Bourdic catchment contains the Roujan subcatchment (approximately 1 km²), where
124 numerous studies have been conducted for twenty years on soil and water resources. Because
125 it is in the Mediterranean area, high-intensity and short-duration storms are frequent and
126 Hortonian overland flow dominates subsurface flow (Moussa et al., 2002). This latter fact
127 motivated the choice of this catchment for studying the impact of agricultural ditch drainage
128 networks on runoff.

129  Figure 2

130 **2.2 Summary of the methods**

131 The general methodology of the paper relied on the coupling of a landscape simulator with a
132 distributed hydrological model (Figure 3).

133  Figure 3

134 **2.2.1 Stochastic simulations of ditch drainage networks**

135 The ditch network simulator has previously been described in detail in Bailly et al. (2011),
136 and only the main principles are described below. It uses as its inputs the lattice of the field
137 units' boundaries and a Digital Terrain Model (DTM). Each segment of this lattice determines
138 a potential location for a ditch. The role of the algorithm is to select whether each potential
139 location is a ditch or not according to a stochastic drainage process and DTM uncertainties.
140 Start and end nodes of each segment of the lattice have an elevation value that is extracted
141 from the DTM. This lattice is partially directed by providing a unique direction to the lattice
142 segments that have start node and end nodes with significant differences in elevation, i.e., that
143 exceed a parameter of elevation uncertainty. For these segments, the slope is calculated as the
144 difference between the start node and the end node altitudes, divided by the length of the
145 segment. If the difference in the nodes' altitudes does not exceed the elevation uncertainty, the
146 direction of the segment is not fixed and may be different for different simulations. The

147 segments of the lattice that correspond to the main downstream parts of the network are
148 considered invariant and are simulated as ditches for all of the ditch network simulations.
149 They define the invariant main downstream network.

150 The method of network generation consists of a stochastic drainage-like algorithm. It
151 generates directed tree network structures corresponding to connected sub-graphs of the
152 directed lattice of the agricultural field units' boundaries. The method is based on (i) directed
153 random walks throughout the directed lattice of the field units that connect randomly selected
154 segments to the invariant main downstream segments and (ii) a random branching/pruning
155 process enabling the convergence to a targeted network length. The only parameters of this
156 algorithm include the target network length, the tolerance parameter and the elevation
157 uncertainty parameter. Once the simulation process leads to a simulated network with a
158 network length that is equal to the target network length greater than or less than the tolerance
159 parameter, the simulation process stops and the simulated network is saved. With this
160 stochastic simulation process, each field unit boundary can be a ditch in a given simulation.

161 Numerous networks can thus be simulated to represent a wide variability of spatial
162 configurations, i.e., density and topology.

163 In our case study, the invariant main downstream segments came from the French national
164 databases on hydrography (BD TOPO ®, BD CARTHAGE ®), representing in total 10.8 km
165 of segments (Figure 2). In fact, these segments mainly corresponded to actual channelized
166 streams and not to ditches. However, for purposes of simplification, we called agricultural
167 ditch drainage networks (or ditch networks) our simulated networks even if they contained
168 these streams. A 5 m resolution photogrammetric DTM¹ was used for the network simulation
169 process. The elevation uncertainty parameter was fixed to 1 m according to the accuracy of
170 the DTM. In contrast to the study of Bailly et al. (2011), the total network length that

1 Source: Conseil Général de l'Hérault

171 governed the simulation process was not fixed. A thousand networks were simulated, and for
172 each one, the targeted total network length was selected randomly and uniformly between a
173 minimal value that corresponded to the total length of the invariant main downstream
174 network, i.e., 10.8 km, and a maximal value that corresponded to the total cumulative length
175 of the field units' boundaries, i.e. 220 km.

176 **2.2.2 Hydrological modelling**

177 The catchment hydrological behavior was simulated at the rainfall event scale using the
178 physically based rainfall runoff MHYDAS model (Modélisation Hydrologique Distribuée des
179 Agro-systèmes—Distributed Hydrological Modeling of Agrosystems). This is a distributed
180 model that considers the catchment as a series of interconnected geographical units by which
181 infiltration/runoff partition and runoff routing are performed. Full details of the MHYDAS
182 model description are available in Moussa et al. (2000) and Moussa et al. (2002). The
183 MHYDAS model has mainly been used in the context of farming (Chahinian, 2004; Charlier,
184 2007; Gumiere et al., 2011; Hallema et al., submitted; Moussa et al., 2002; Tiemeyer et al.,
185 2007) and is available within the modeling platform Openfluid ® (Fabre et al., 2010).

186 **2.2.2.1 Landscape representation**

187 We used the landscape representation of the MHYDAS hydrological model. The
188 interconnected geographical units considered here were the field units (surface units) and the
189 ditch network (linear unit), which was located on the boundaries of field units. The Geo-
190 MHYDAS algorithm, running under GRASS GIS, was used to build a deterministic oriented
191 tree topology between these irregularly shaped surface units and linear units, which allows the
192 routing of simulated water flows across the landscape (Lagacherie et al., 2010). The Geo-
193 MHYDAS algorithm uses as its inputs a DTM and the GIS layers of the ditch network and the
194 field units. For each unit, the neighbor with the steepest slope is defined as its downstream
195 unit.

196 In our case study, we used Geo-MHYDAS with the same 5 m DTM as the one used for
197 network simulation. Geo-MHYDAS was thus used to define water flow paths of the surface
198 units for each simulated network and for the actual network. The topological relationship
199 between the field units and between the field units and the agricultural ditch drainage network
200 were then computed for each simulated network and resulted in different topological
201 configurations. In this process, water flow paths over the catchment (hillslopes and channels)
202 were only modified by the ditch network spatial configuration.

203 **2.2.2.2 Modeled hydrological processes**

204 Over each surface (areal) unit, MHYDAS simulated the infiltration-runoff partition as a
205 Hortonian process, while saturated runoff was neglected. The determination of the infiltration
206 rate was based on equations from Green and Ampt (1911) and Mein and Larson (1973) that
207 were adapted by Morel-Seytoux (1982) and allowed the calculation of the rainfall excess
208 under variable rain conditions. It depended on the saturated hydraulic conductivity, which was
209 a function of soil surface features that could vary in space and time. It also depended on the
210 mean initial water content at the soil surface. The other parameters were the hydraulic
211 properties of the hydrological units, such as the water content at saturation and the residual
212 water content.

213 The rainfall excess function for each unit was converted to a surface runoff hydrograph by
214 routing it to the proper outlet of the unit. The operation of converting excess rainfall into
215 surface outflow was performed by a numerical convolution involving a unit hydrograph that
216 was derived as a Hayami response function (Hayami, 1951; Moussa, 1996). This procedure
217 was a function of the mean distances between the centers of gravity of adjacent hydrological
218 units or between centers of gravity and the ditch network, the mean slope of the units and the

219 roughness. If runoff was routed downstream via other surface units, it could be reinfiltrated to
220 these surface units.

221 Once in the network that was considered as a set of linear reaches, water was routed to the
222 catchment outlet using a diffusive wave equation. Over each reach, the parameters of the
223 diffusive wave model were calculated using the length of the reach, its slope, the coefficient
224 of roughness and the cross-sectional shape.

225 Groundwater was considered a compartment that received water that was infiltrated from
226 surface units. Water could also be exchanged between the ditch network and groundwater
227 according to the differences in water levels that were computed inside these compartments.

228 **2.2.2.3 Parameterization strategy and simulation plan**

229 Because our focus was the hydrological impact of the spatial configuration of the agricultural
230 ditch drainage network, we considered a scenario in which the other sources of hydrological
231 variability were deliberately removed. For this scenario, the corresponding parameters for the
232 surface units (saturated hydraulic conductivity, water content at saturation, residual water
233 content and roughness) and for the linear units (coefficient of roughness and cross-sectional
234 size) were made invariant in the catchment. However, the values given to these parameters
235 were selected so as to be coherent with the values that were calibrated in the previously
236 mentioned studies of the same study area. They were also selected to simulate a coherent
237 flood at the catchment outlet in comparison to the available outlet discharge data.

238 Rainfall was taken to be spatially homogeneous and was represented by a simple triangular
239 rainfall of 50 mm in 4 hours to symbolize high and frequent rain events. Two other rainfall
240 events, 30 mm in 2 hours and 60 mm in 4 hours, were used to test the sensitivity of the
241 simulations to the rain. This set of three rain events represented events with a return period
242 from one to two years in the area.

243 No interaction between surface and groundwater was introduced in the modeling because we
244 focused on surface runoff and on the fast hydrological response of the catchment and
245 interaction between the ditches and groundwater was a slower process. Moreover, during
246 heavy rain events such as the one studied here, surface runoff was assumed to be the major
247 component of runoff.

248 These simplified landscape and meteorological conditions allowed us to solely test the
249 hydrological impact of the variability in the partitioning between diffuse and channelized flow
250 paths and in the associated topographic parameters. Moreover, even if we did not aim to
251 provide a validated case study, we used the model with a range of parameters and for a type of
252 rain events in which the model has been calibrated and validated several times.

253 **2.3 Evaluation of ditch network effects on hydrology**

254 **2.3.1 Classical indices**

255 To compare simulated networks with the real network and to relate network runoff variability
256 with network variability, we evaluated runoff indices (lag time, peak discharge and runoff
257 volume) at three invariant locations within the catchment (points A-C, Figure 5). At the same
258 three invariant locations, the total cumulative network length and the drained area were
259 computed.

260 **2.3.2 Need for new indices**

261 To evaluate the variability in the runoff on the hillslopes (the overland flow), we defined an
262 adequate geographical support at which the runoff could be computed. A 500 m × 500 m
263 square grid was applied over the study area. Each cell of this grid was sufficiently large to
264 include a piece of the landscape (individual fields were not) and could be also held invariant
265 across simulations (subcatchments could not).

266 Inside a cell of this 500 m × 500 m grid, different hillslopes that were compounded of several
267 field units were delineated during hydrological simulations. A hillslope was defined as a
268 succession of field units whose overland flow exited the cell or entered the ditch network
269 (Figure 4). The overland flow indicator of the cell was calculated as the mean of the
270 maximum field unit (j) overland flow of all of the n hillslopes (i) inside the cell (Equations 1
271 and 2). For each cell, the cumulative network length was also computed.

272 Figure 4

$$\text{Equation 1} \quad Q_{max_{hillslope\ i}} = \max_{\substack{j \in [1, \text{number of fields inside hillslope } i] \\ i \in [1, \text{number of hillslopes inside the cell } k]}} (Q_{max_{field\ j}}) \quad field\ j \in hillslope\ i$$

$$\text{Equation 2} \quad \text{Overland . flow . indicator}_{cell\ k} = \frac{1}{n} \times \sum_{i=1 \text{ to } n} Q_{max_{hillslope\ i}} \quad hillslope\ i \in cell\ k \\ k \in [1, \text{number of cells inside the catchment}]$$

275 3 Results

276 3.1 Agricultural ditch drainage network and water flow path variability

277 We simulated a thousand networks, which allowed us to explore the full range of potential
278 cumulative network lengths (Figure 5). The invariant main downstream segments were
279 conserved in both the actual network and simulated networks. Because of the simulation
280 process, the mean length over the set of simulated networks was higher than the actual
281 network, which was approximately half of the cumulative field boundary length. Some very
282 different networks were obtained, including some that were very dense (Figure 5, IV) and
283 others that were not very dense (Figure 5, II).

284 Figure 5

285 The modification of water flow paths by ditch networks implied modifications in
286 subcatchment delineation and consequently the drained area (see the Roujan subcatchment

287 defined at point B in Figure 5). To investigate this effect, we took as an example the evolution
288 of the variability in the simulated drained area along the northern main invariant segment of
289 the network (Figure 5, from point A to point C). At the start of the northern main invariant
290 segment, the coefficient of variation of the simulated drained area was higher than 100 %
291 (Figure 6). The coefficient of variation decreased rapidly with an increase in the mean
292 simulated drained area. However, it was still high at point B (Roujan subcatchment) (20 %).
293 The coefficient of variation rapidly decreased to 5 % for a mean simulated drained area of 1.7
294 km². This high variability of the drained area emphasized the role of the ditch drainage
295 network in modifying water flow paths. After the confluence with the southern main invariant
296 segment, the coefficient of variation was low (decreasing to 2 %). The decreasing variability
297 of the drained area along the main invariant segment could be explained by (i) the simulated
298 drained area that became increasingly constrained by the catchment morphology and the
299 invariant main segments near the outlet and (ii) the whole catchment boundary that was fixed
300 for all of the simulations.

301  Figure 6

302 **3.2 Discharge variability and scaling**

303 We computed the hydrographs at three points along the northern main downstream segment
304 of the network (Figure 7), including the starting point of the invariant main downstream
305 network (Figure 5, point A), at 1000 m downstream (Figure 5, point B, corresponding to the
306 Roujan subcatchment) and at the outlet, 5000 m downstream (Figure 5, point C,
307 corresponding to the Bourdic catchment). The hydrographs exhibited a high variability in
308 amplitude, but the shapes of the actual hydrographs were preserved across the simulated
309 networks. For point A, the high variability that was observed was mainly related to the very
310 high variability in the area that was drained at this point (Figure 6). In some cases, this point

311 corresponded to a source, as no ditch was present upstream and it did not drain any field unit.
312 On the contrary, an upstream ditch network that drained several field units, could be branched
313 upstream of this point for other simulations. For the two other points, the Roujan
314 subcatchment and the Bourdic catchment, the variability in hydrographs remained high
315 despite the smaller variability in the drained area. We hypothesized this property to be related
316 to other network characteristics, especially network density.

317 Figure 7

318 We calculated lag times, peak discharges and total volumes from the 1,001 hydrographs. We
319 focused on the sensitivity of these runoff indices to the variation in network lengths at two
320 specific locations (Figure 8): at the outlet of a small upstream watershed, the Roujan
321 subcatchment (the second hydrograph on Figure 6, point B on Figure 5) and at the outlet of
322 the whole Bourdic catchment (the third hydrograph on Figure 6, point C on Figure 5). At the
323 Bourdic catchment outlet, the range in peak discharge was -50 to +24 % compared with the
324 value that was simulated for the actual network. The range in total volume was -55 to +14 %.
325 Furthermore, the peak discharge and total volume quickly increased with the network length
326 and then reached a plateau. This plateau corresponded to a situation in which all of the fields
327 units were connected to a ditch. Indeed, the denser the network, the greater the connectivity
328 between the field units and the ditch network, which limited the re-infiltration to the fields.
329 The lag time exhibited a more complicated trend and less relative variability (-15 to +12 % in
330 comparison with the value simulated for the actual network). First, there was a quick increase
331 and then a slow decrease as the network length increased. We hypothesized that for short
332 networks, only the runoff of the closest area to the outlet contributed to the flood and that the
333 runoff of the more distant areas was re-infiltrated before reaching the network. For dense
334 networks, distant areas contributed to the flood and thus the lag time was higher because of
335 longer average flow paths. Then, when all areas contributed runoff and the network grew

336 again, flow paths were increasingly channelized in the networks, which decreased the lag time
337 because the mean celerity was higher in the network than in the field (Moussa et al., 2002).
338 Even if the catchment area was constant at the outlet, there was a variability in runoff for a
339 given network length. This variability may have been caused by variability in the topographic
340 parameters or the topology of the ditch networks.

341 The variability was more significant for the Roujan subcatchment scale. The lag time, peak
342 discharge and total volume ranged from -18 to +90 %, -96 to +19 % and -71 to +29 %, respectively,
343 in comparison with the simulated value for the actual network. An obvious
344 reason was the fact that the drained area varied for the Roujan subcatchment outlet, but not at
345 the Bourdic catchment outlet (Figure 6). However, there was also a clear trend for the peak
346 discharge and total volume at the Roujan outlet: these variables increased as the network
347 length increased. A trend was more difficult to identify for the lag time, but we observed a
348 decrease with increasing network length.

349  Figure 8

350 Finally, we also investigated whether the relationship between the runoff metrics and the
351 length of the ditch drainage network was dependent on the rain event. With two other
352 triangular rain events, i.e., 30 mm in 2 hours and 60 mm in 4 hours, the type of relationship
353 was not changed. An example of the peak discharge as a function of the ditch network length
354 is shown in Figure 9.

355  Figure 9

356 **3.3 Hillslope overland flow variability**

357 Using the squared grid and the method described above (Figure 4), we observed how the
358 overland flow indicator varied inside every cell grid on the catchment. Figure 10 shows an
359 example of a cell that was located in the western part of the catchment, mainly in a zone with

360 slopes greater than 10 %. The overland flow indicator decreased exponentially as the
361 cumulative ditch network length increased and trended toward an asymptote across the
362 highest drainage densities. Approximately 25 % of the maximum drainage density
363 (approximately 2150 m in this cell) corresponded to a third of the maximum overland flow
364 (6.9 l.s^{-1} against 21 l.s^{-1}). For a given network length within a cell, a small amount of
365 variability remained, which corresponded to the efficiency of the network to intercept
366 overland flow. For example, if 2000 m of ditches were grouped into a small part of a cell or
367 were parallel to the highest slope, they intercepted less overland flow than if they were well
368 distributed throughout the cell and were perpendicular to the highest slope. We also noticed
369 the position of the actual network, in that simulated networks with similar lengths produced
370 more overland flow in the cell than the actual network.

371 As for the example cell in Figure 10, a trend line could be fitted for each cell. To represent the
372 exponential decrease of the overland flow indicator as a function of network length, a model
373 in the form of $\text{overland.flow} = a + b \times \exp(-c \times \text{network.length})$ was fitted. We used a non-linear
374 least-squares algorithm for the estimation of the a, b and c parameters. The median coefficient
375 of determination (R^2) between the fitted and actual values of the overland flow indicator was
376 equal to 0.96, which indicated a very good fit and an overland flow indicator that was closely
377 dependent on the drainage density. The exponential decrease revealed that few ditches were
378 efficient in greatly limiting overland flow and that more and more ditches were needed to
379 further reduce the overland flow.

380 Figure 10

381 **4 Discussion**

382 **4.1 Importance of the agricultural ditch drainage network on the** 383 **hydrology of a small, cultivated catchment**

384 Agricultural ditch drainage networks are known to influence the runoff of small, cultivated
385 catchments (Carlier & Marsily, 2004; Moussa et al., 2002). However, the nature of this
386 statement is dependent on the studied area and its actual network and is generally made
387 through a comparison with a hypothetical natural network that is extracted from a DTM. In
388 this study, the importance of ditch networks was confirmed in a more general context, even
389 though it was still dependent on the catchment morphology and field geometry. Among the
390 set of simulated networks, the variability in the area drained was very high, which reinforced
391 the evidence that linear features alter overland flow-paths (Duke et al., 2006; Gascuel-Oudou
392 et al., 2011). Therefore, our study revealed how agricultural ditch drainage networks can
393 modify delivery pathways, which is a major component of the hydrological connectivity of a
394 catchment (Bracken & Croke, 2007).

395 The runoff variability was very high, both on the scale of the whole Bourdic catchment and
396 the Roujan subcatchment. The peak discharge and total volume clearly increased with
397 network density, but they also depended on other induced changes (e.g. topology and slope of
398 the networks), which should be better quantified in the future. These results agreed with the
399 study of Moussa et al. (2002), which concluded that agricultural ditch drainage networks
400 accelerated runoff. However, we showed that this statement clearly depended on the drainage
401 density. Concerning runoff on the hillslopes, we showed that the ditches that were present on
402 hillslopes intercepted the diffuse water flow paths and rapidly decreased the overland flow.
403 However, above a certain network density, adding new ditches became less and less efficient
404 for decreasing overland flow.

405 Our study also confirmed the predominant role of ditches in intercepting overland flow on the
406 hillslopes in Mediterranean areas (Martínez-Casasnovas et al., 2002) and enabled the better
407 quantification of the relationship between the density of the ditch network and the overland
408 flow. This interception of overland flow thus explained the statistical effects of ditches in
409 reducing erosion that was observed in the study by Paroissien et al. (2010).

410 Finally, these results showed the effects of removing or adding ditches to a drainage network
411 when no other field borders were considered when removing ditches. Conversely, in
412 Verstraeten et al. (2002), replacing the ditches with grassed waterways was considered and
413 was shown to reduce sediment delivery. Such an investigation was not considered here, and
414 no obstacle to the runoff were considered between two given field units after removing a
415 ditch.

416 **4.2 Catchment extent effect**


417 All of these findings were dependent on the extent of catchments. At any point of the
418 catchment, a high variability in the network induced a high variability in runoff, but the
419 variability in runoff was higher at the Roujan subcatchment scale than at the whole Bourdic
420 catchment scale at any given network density. This fact was explained by the high variability
421 in the area that was drained in the upstream part of the network, whereas the low variability in
422 the area that was drained, the morphology of the catchment and the invariant main
423 downstream network constrained the routing of the runoff and all served to limit the
424 downstream variability (from approximately 2 km²).

425 Concerning the hillslope overland flow, the effect of scale was not investigated in this study.
426 However, the extent effect was considered to become significant with a decreasing cell size
427 that would increase the overland flow indicator variability. A 500 m × 500 m square grid
428 seemed to be appropriate because, in contrast to individual field units, it was sufficiently large

429 to include a piece of the landscape (which individual field units were not) and was sufficiently
430 fine to enable the spatialization of overland flow in a small cultivated catchment with
431 sufficient detail.

432 **4.3 Hydrological efficiency**

433 The actual ditch network seemed to be quite efficient in comparison with the simulated
434 networks for draining floods (Figure 8) and limiting overland flow on the hillslopes (Figure
435 10). For instance, when looking at the peak discharge and the total volume of all of the points
436 of the main invariant segments of the networks, the drainage that was provided by the actual
437 network was almost always greater than the fitted value for the simulations, and the lag time
438 was shorter (Figure 11). The actual network drained more water and accomplished that more
439 rapidly. For the overland flow on the hillslopes, the overland flow indicator was almost
440 always lower than that of the simulated networks; therefore, for a given length, the actual
441 network intercepted more overland flow than the simulated networks. However, an optimum
442 network should be not only more efficient than a network of similar length, but also a
443 compromise between the network length and the hydrological efficiency because the
444 maintenance of the ditch network requires a tremendous amount of work from farmers. To
445 define such an optimum network, we must take into account the local conditions that
446 influence the overland flow, such as land cover and soil properties. Therefore, we could not
447 accomplish this task here. Finally, we question whether the actual agricultural ditch drainage
448 network is optimal in all agricultural catchments or if this was the case in the Bourdic
449 catchment only.

450  Figure 11

451 Current agricultural ditch drainage networks are the results of a sum of individual ditch
452 digging efforts of hundreds of farmers over the last two thousand years (Berger et al., 2000),

453 and they continue to evolve. Therefore, we may wonder how this optimum can emerge from a
454 sum of individual decisions. A survey of farmers would be useful to understand this finding
455 and would perhaps highlight some guidelines for the creation of ditch drainage networks and
456 cooperation between farmers, which could be further implemented in the simulation
457 algorithm.

458 **4.4 Limitations and uncertainties in results**

459 This modeling study revealed the effects of modifications in the spatial configurations of
460 ditch networks in an agricultural catchment, which can not be tested in the real world.
461 However, even if the model was previously used and validated in this area, we used this
462 model in virtual conditions and outside its tested bounds (concerning drainage density).
463 Therefore, like in all studies testing scenarios, we must carefully interpret the results
464 (Silberstein, 2006).

465 The results of this study should thus not be taken as universal, but the trends deserve
466 consideration. In addition to these first limitations, the simplified hydrological case studied
467 here does not allow for confidence in absolute values. Thus, this type of study should be
468 extended to more complicated cases with various actual rain events and a realistically
469 distributed land cover. Indeed, in our case study, each field unit generated the same amount of
470 runoff, which would obviously be inaccurate in a real landscape. The consideration of
471 patterns of runoff generation would probably modify the effect of the ditch networks. This
472 effect would most likely be reinforced in areas with a high production of runoff and lessened
473 in other areas. Ditch networks could thus modify the delimitation of active areas (Ambroise,
474 2004), for example, by avoiding the runoff that is produced in a low-permeability area to be
475 reinfiltred to a permeable area that is located downslope.

476 Another limitation concerns the parameterization of the ditch. First, neither infiltration into
477 the ditch network nor ex-filtration were considered in this study, whereas groundwater
478 recharge by channel infiltration may be important in Mediterranean and semi-arid areas
479 (Dages et al. 2009; Ponce et al., 1999). If such an interaction was modeled, the network
480 hydrology would probably have been much more complex, with patterns of infiltration and
481 ex-filtration along the network, and the relation between network density and runoff may have
482 been modified. Accordingly, we decided to focus on surface runoff in this study. Moreover,
483 the calibration of the exchange function between a ditch network and groundwater is very
484 delicate, especially with a variable network. Therefore, the interactions between surface and
485 ground water in the ditches should be considered in future works, especially when studying
486 rain events with lower intensities. The second limitation concerning the parameterization of
487 the ditches involved their cross-sectional size and roughness which were considered invariant
488 in our study. These parameters greatly affect surface runoff (Nédélec et al., 2004) and are
489 known to be highly spatially variable, both in natural streams (O'Hare et al., 2010) and in
490 small agricultural ditches (Bouldin et al., 2004; Crabit et al., 2011). These limitations should
491 therefore be addressed in future works, with the use of spatial models of these ditch
492 parameters, as it exists for ditch cross-sectional sizes (Bailly et al., 2006).

493 To summarize, the results concerning the hydrological response of the network should thus be
494 carefully interpreted. The results on overland flow in the fields seemed more robust because
495 they were not affected by the simplification of the parameterization of the ditches.

496 Finally, the high variability that was observed here was predominantly a result of the high
497 variability in the drainage density. However, some of this variability was improbable,
498 especially the variability that resulted from including the very high drainage densities.

499 However, their inclusion provided the advantage of defining what was possible. Compared
500 with the large survey that was realized in the Hérault French département (Levassasseur et al.,

501 submitted), the drainage density observed in the Bourdic catchment was one of the highest
502 densities that has been observed. Therefore, the most interesting part of this study concerned
503 low drainage densities for which hydrological sensitivity appeared to be the highest.
504 The coupling of a ditch network simulator with a hydrological model provided several
505 interesting results and offered new prospects. Here, we used this method to investigate the
506 impact of the spatial configuration of agricultural ditch drainage networks on the hydrology of
507 a small catchment. We could imagine that this type of method could also be used to test
508 certain scenarios of landscape arrangements or to optimize an existing network, as it has been
509 done with land use patterns (Newbold, 2005; Seppelt & Voinov, 2002). For example, the
510 minimization of the peak discharge at the outlet combined with the minimization of overland
511 flow on hillslopes could be accomplished by branching or pruning the existing network. The
512 optimization of the network could also concern reductions in erosion or pesticides impacts by
513 coupling with appropriate models (Gumiere et al., 2011).

514 **5 Conclusions**

515 A ditch network simulator coupled with a distributed hydrological model allowed for a study
516 of how runoff is related to the densities of an agricultural ditch drainage network in cultivated
517 landscapes. New hydrological and network parameters were defined to deal with the
518 variations in hillslope and subcatchment delineations that were induced by variations in the
519 ditch drainage networks.

520 The importance of spatial configurations of agricultural ditch drainage networks in the
521 alteration of water flow paths and in the control of runoff was highlighted, both in
522 channelized flow-paths and on hillslopes. From our case study, we observed that variability of
523 the spatial configuration and especially an increase of the ditch network density strongly
524 influenced the subcatchment delineation and area, increased the drained volume and the peak

525 discharge and decreased overland flow on hillslopes. However, these hydrological behaviors
526 were only sensitive to network density for drainage networks with densities that did not
527 exceed a certain threshold. This study also highlighted the efficiency of the actual network in
528 comparison with the networks that were simulated by the ditch network simulator, which
529 suggest an anthropogenic optimization process that should be further explored.

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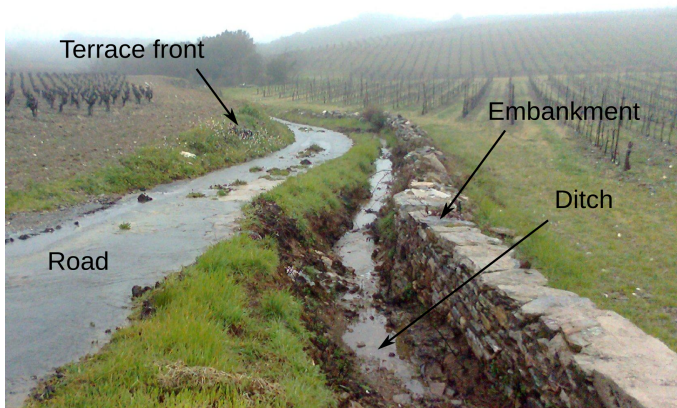


Figure 1: Linear features in cultivated landscapes. Ditches and roads channel water, whereas embankments act as barriers to water flow.

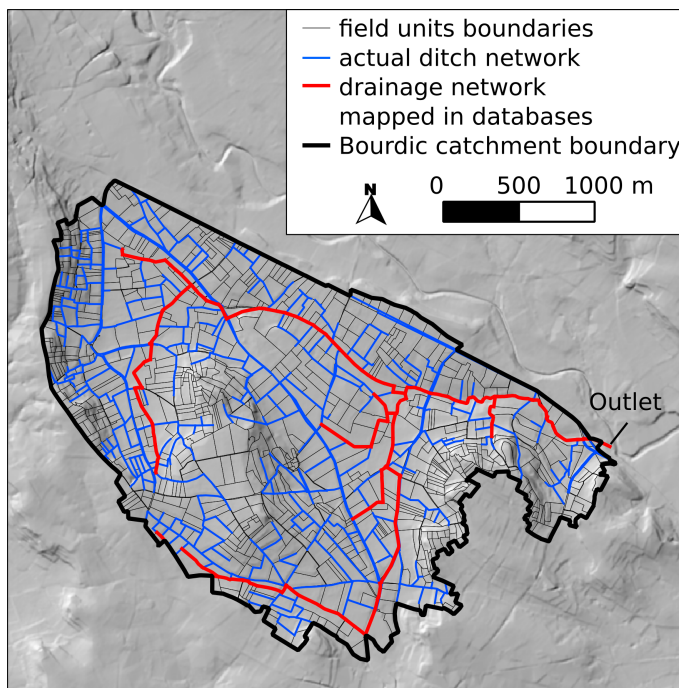


Figure 2: Study area. Drainage network of the Bourdic catchment is represented in a hillshade view, with an azimuth to the light equal to 315° . The inclusion of the agricultural ditch drainage network greatly expanded the drainage network that was mapped in hydrographic databases.

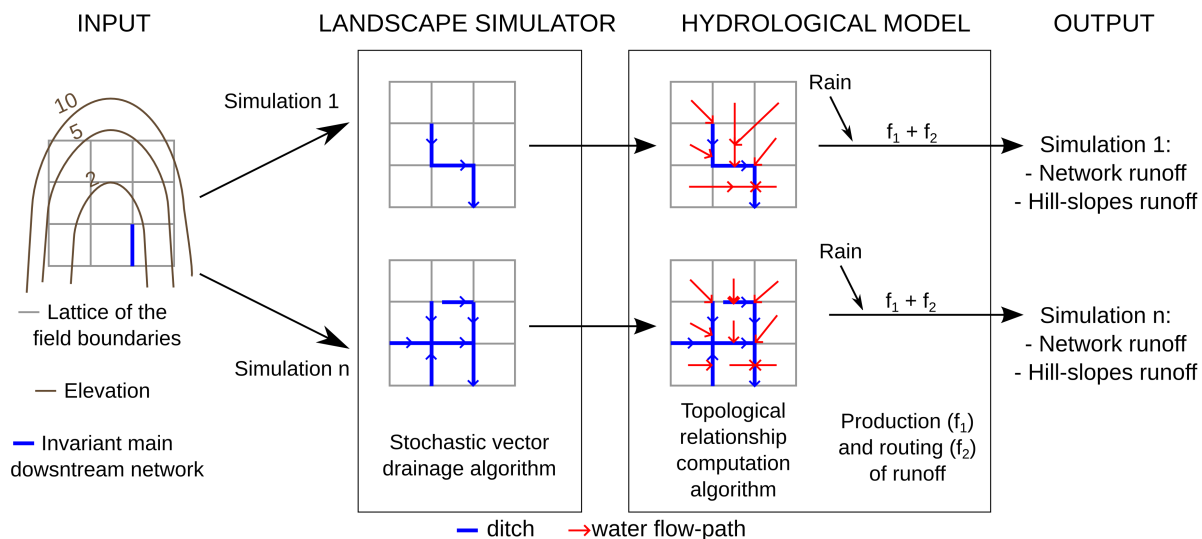


Figure 3: Conceptual diagram of the methodology: coupling of a stochastic vector drainage algorithm with distributed hydrological modelling to study the impact of the network structure of agricultural ditch drainage on surface runoff.

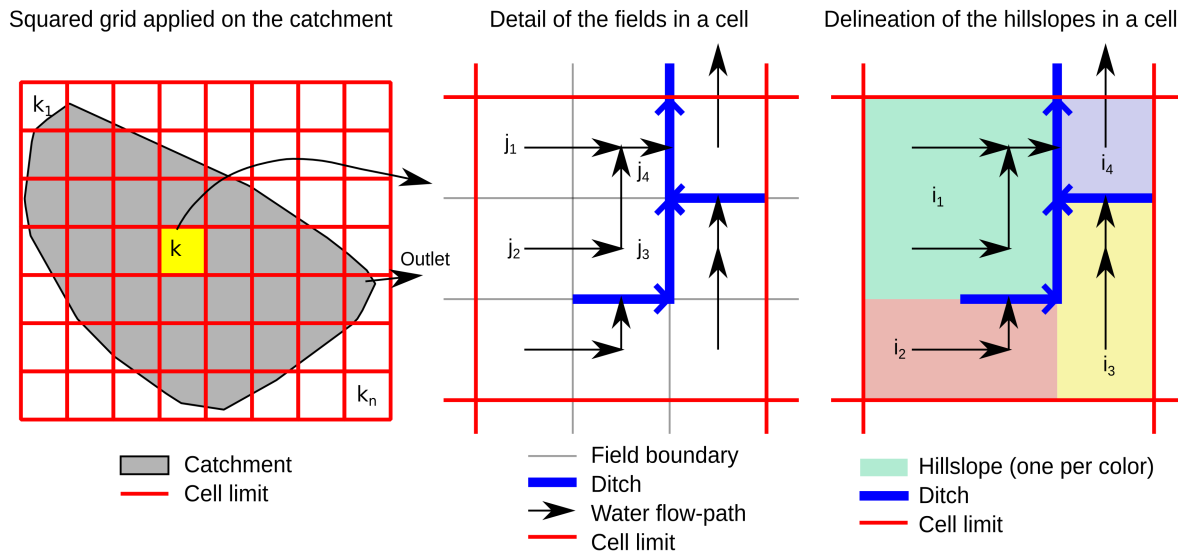


Figure 4: Space discretization used to compute an overland flow indicator value. Hillslopes were delineated in each cell of the grid applied on the catchment. Then, the overland flow indicator of a cell was calculated as the mean of the maximum field unit (j) overland flow of all the hillslopes (i) inside the cell (Equations 1 and 2).

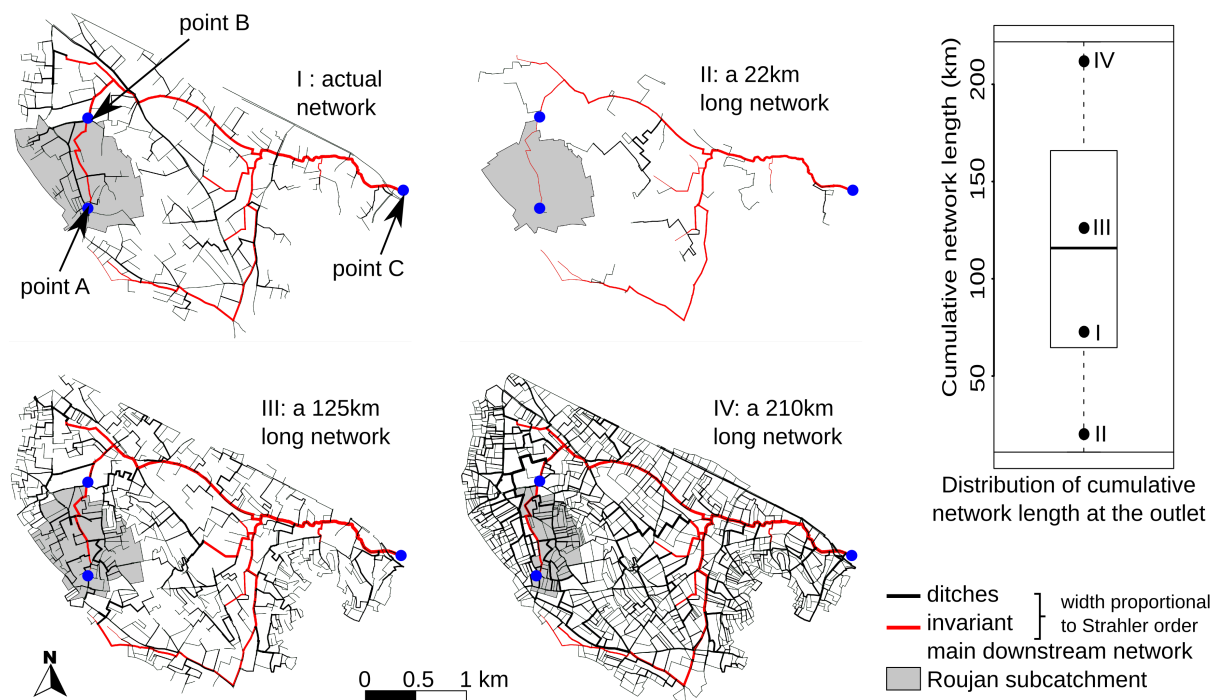


Figure 5: Variability of the spatial configuration and length of the drainage networks. Both small and very dense networks were simulated. We also observed variability in the delineation of subcatchments.

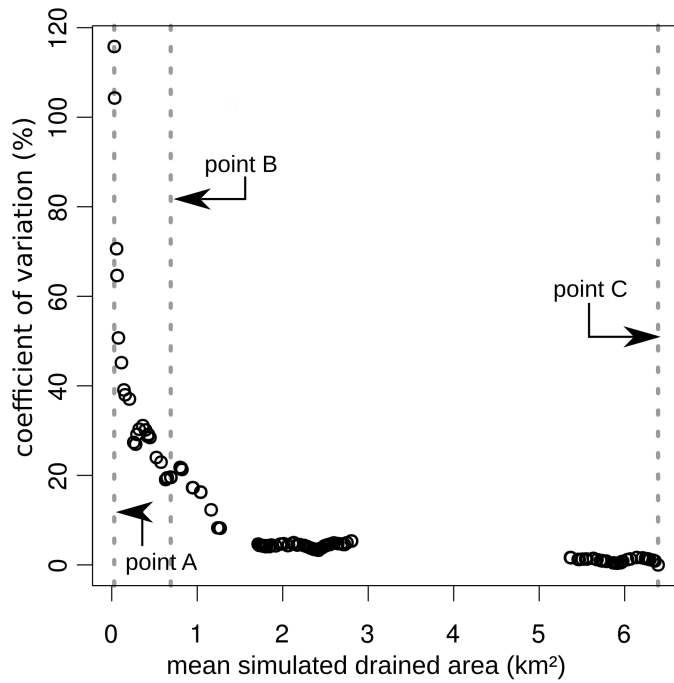


Figure 6: Coefficient of variation (CV) for the drainage area along the northern main invariant segment of the network (Fig. 5). The CV was calculated based on 1001 realizations of the ditch network. The dotted lines indicate the main drainage area at points A, B and C.

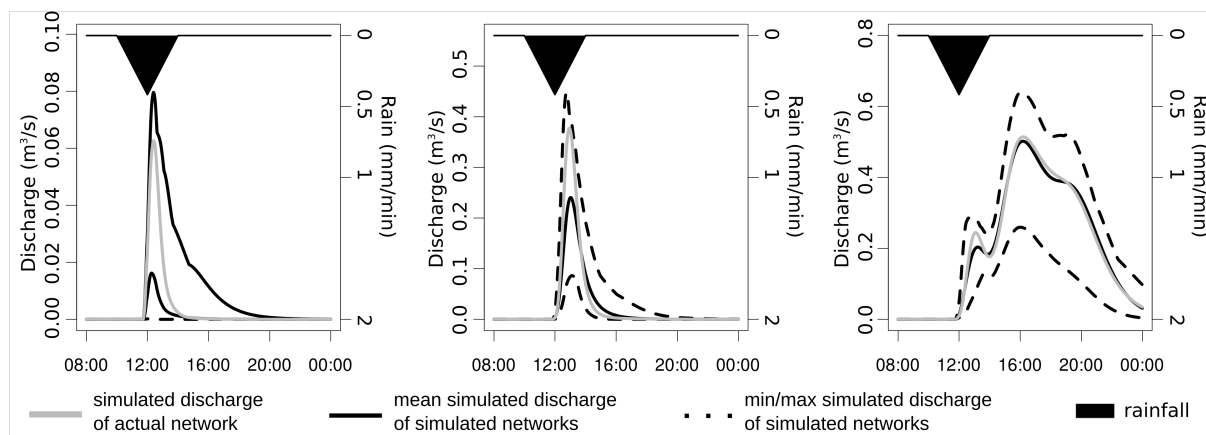


Figure 7: Hydrographs along the invariant main downstream network. The variability among hydrographs was high, although the shape of the actual hydrograph was well simulated.

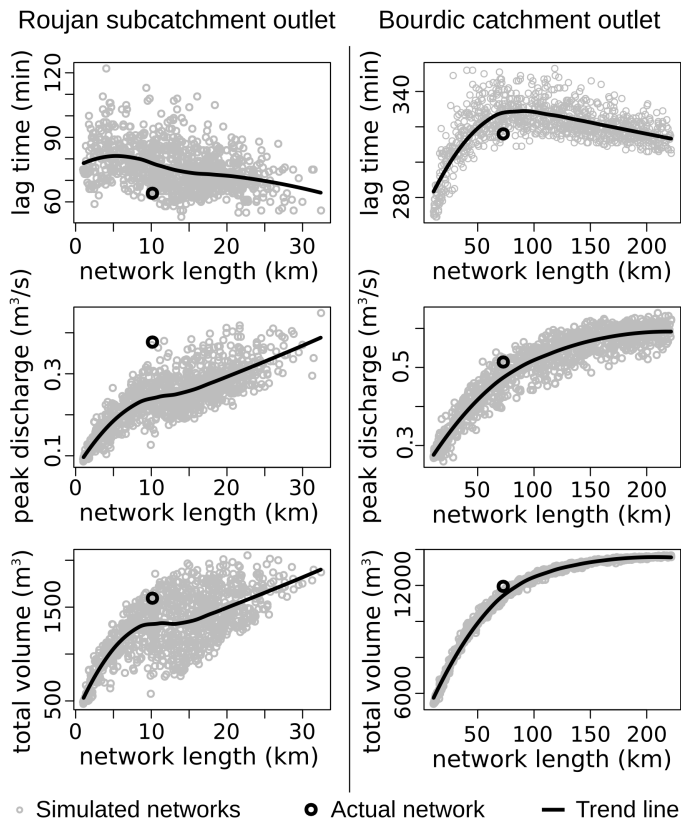


Figure 8: Relationship between runoff metrics and network lengths. The runoff metrics were correlated with the drainage network length at both the subcatchment and at the catchment scales. The variabilities in network metrics were higher at the subcatchment scale.

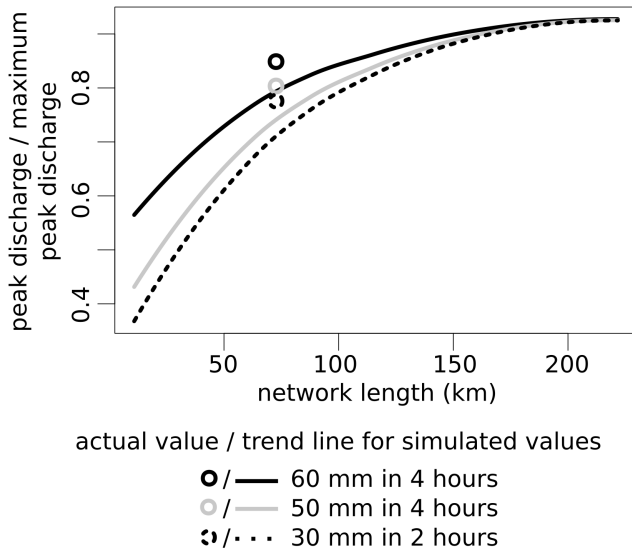


Figure 9: Relationship between peak discharge and network length for three different rain events.

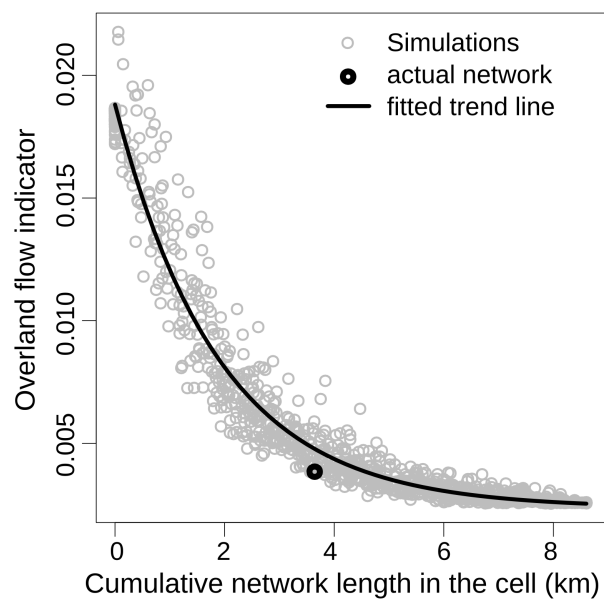


Figure 10: Relationship between the overland flow indicator value and the network length for a given cell.

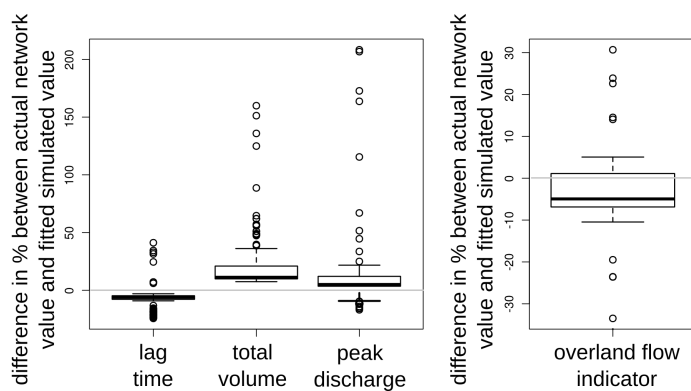


Figure 11: Efficiency of the actual network compared with simulated networks. The boxes represent the interquartile range. The whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the box. In comparison to the simulated networks, the lag time was lower and the total volume and peak discharge were higher for the actual network. The overland flow indicator was lower for the actual network.