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1 Title: A surface runoff mapping method for optimizing risk assessment on railways

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12 Abstract:

13 Railways are critical infrastructures for the transportation of people and goods and network failures  
14 must be controlled in order to maintain safety and to limit economic losses. The railway network is  
15 exposed to natural hazards and particularly to intense pluvial runoff. Due to the complexity of the  
16 phenomenon, management of risks induced by pluvial runoff raises technical and scientific issues. An  
17 innovative method for runoff susceptibility mapping, called IRIP for “Indicator of Intense Pluvial  
18 Runoff”, has been created and adapted to the railway context. The objective of this paper is to  
19 evaluate the relevance of the mapping method and to provide application advice. The mapping  
20 method is evaluated by comparison with the results of a hydraulic diagnosis, on a 20 km railway line,  
21 using quantitative and qualitative comparisons. On the basis of contingency tables, probabilities of  
22 detection (POD, railway sections exposed and detected by IRIP) and false alarm ratios (FAR, railway  
23 sections detected by IRIP whereas they are not exposed) are computed. POD range from 94 to 100%  
24 and FAR range from 20 to 26%. Then spatial information provided by the maps is compared with field  
25 observations and recommendations. It is shown that the mapping method can bring substantial  
26 contribution to risk identification and that the IRIP method can allow pushing forward the current  
27 risk reduction methods. Thus, the surface runoff maps open up new opportunities to manage surface  
28 runoff, such as targeting mitigation actions at the origin of the hazard in partnership with the other  
29 territory stakeholders.

30

31 Highlights:

- 32 • The IRIP method “Indicator of Intense Pluvial Runoff” maps the surface runoff susceptibility.
- 33 • The method performance and reliability are evaluated in the railway context
- 34 • The IRIP method makes a substantial contribution to risk assessment
- 35 • Surface runoff maps open up new opportunities to push forward the current processes

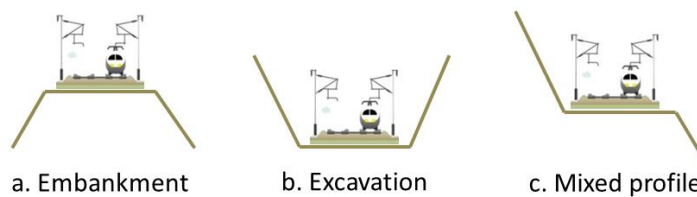
36 Keywords: Railway infrastructure; natural hazards; water surface runoff; risk assessment;

37 mapping method; evaluation

38 1. Introduction

39 1.1. Context

40 Railways are critical infrastructures for the transportation of people and goods (Maurer et al., 2012).  
41 The French railway network operates about 30,000 km of railways and about 15,000 trains run daily  
42 for freight and passengers. Railway network failures must be imperatively controlled in order to  
43 maintain user and employee safety and to limit economic losses for the company, either direct cost  
44 (reconstruction works after an incident, delay compensations) or indirect cost (foregone revenues  
45 due to network unavailability, possible brand-image deterioration). Railway infrastructure is  
46 composed of multiple interacting elements such as the fixed installations for electric traction, the  
47 telecommunication installations, the traffic control installations, the tracks, the civil engineering  
48 structures, and the earthworks. Earthworks are built to get a steady longitudinal profile of the tracks  
49 and avoid the natural terrain fluctuations. Different transversal profiles can be created:  
50 embankments, when the tracks are above compacted material layers; excavations, when the tracks  
51 are below the natural terrain; mixed profiles, with an embankment on one side and an excavation on  
52 the other, and flat profiles when no particular earthwork is undertaken (Figure 1).



54 Figure 1: Three types of transversal profiles of the railway infrastructure

55 Railways are exposed to water-related hazards since they cross natural water-flow paths (Chazelle et  
56 al., 2014). Water-related hazards can be classified into different types: fluvial flooding when rivers  
57 flow over their banks, coastal flooding when normally dry lands are flooded by sea water, ground  
58 water flooding when the ground water table level rises above the natural terrain, and pluvial flooding  
59 when rainfall generates floods on hillslopes outside the river network. This study focuses on pluvial  
60 flooding. When rainfall intensity exceeds soil infiltration capacity, water can flow over the ground  
61 surface (Beven, 2011; Dehotin et al., 2015a) and generate damage. Water surface runoff can reach  
62 high velocities and densities by carrying materials. This phenomenon is influenced by multiple factors  
63 (Le Bissonnais et al., 2005; Sivapalan et al., 1987): rainfall characteristics (intensity, duration, and  
64 frequency), soil surface characteristics such as topography, land use (agricultural and urban areas)  
65 and soil physical properties (type, permeability, erodibility, thickness). Once water is generated on  
66 the surface, it can flow downstream and generate various hazards such as floods, mudflows, shallow  
67 landslides, and erosion.

68 Railway infrastructure is particularly vulnerable to surface runoff given its characteristics. Electric  
69 installations may experience failure when impacted by water. The tracks are composed of ballast  
70 between the rails and the platform, which provide good mechanical properties but which can easily  
71 be swept away by water flows (Amblard et al., 2015). Earthworks are also vulnerable to surface  
72 runoff depending on their profile, length, slope or construction materials. They may experience  
73 erosion, landslides or destruction (Figure 2). In order to protect the infrastructure, railways are  
74 equipped with hydraulic structures. Their function is to ensure the natural water flows from  
75 upstream to downstream and to manage water generated within the railway right-of-way. Hydraulic  
76 structures can be transversal (aqueduct, nozzle, bridge) to make the water cross the railway. They  
77 can be longitudinal (ditches, drains, dikes) to pipe water towards an outlet. Retention basins can also  
78 be installed to dampen incoming and outgoing water volumes.



79  
80 Figure 2: Illustration of surface runoff impacts on railways: from left to right, flood, landslide, and  
81 breach in the embankment

82 From an operational point of view, the risks for the railway network are disrupting train circulation  
83 and jeopardizing safety. Thus, risks induced by surface runoff are 1/ railway unavailability due to the  
84 presence of obstacles (water, materials), 2/ railway unavailability due to the absence of an element  
85 or of the whole railway (breach, destruction) and 3/ accelerated degradation of railway elements or  
86 railway stability. To manage these risks, actions must be undertaken at every railway life-stage:  
87 during new railway or new structure design, during maintenance, during operation by monitoring,  
88 during crisis phases, and after a crisis for recovery and feedback. However, surface runoff risk  
89 management generates technical issues as well as scientific issues.

## 90 1.2. Technical issues

91 Current issues in managing risks induced by surface runoff on railways lie in quantifying and  
92 qualifying surface runoff. Quantifying refers to a flow rate estimate at a catchment outlet and  
93 qualifying refers to a spatial assessment of areas where surface runoff is susceptible to occur. Flow  
94 rates are computed in order to dimension hydraulic structures or to verify they have a sufficient  
95 capacity. Surface runoff flow rate can be estimated for a catchment, thanks to historical discharge

96 data, by applying statistical methods on rainfall and runoff data. In nearly all cases, however,  
97 catchments intercepted by railways are ungauged. In this case, pseudo-empirical formula can be  
98 applied, such as the rational method (Thompson, 2007). The rational method allows computing the  
99 flow rate by multiplying the catchment area, the rainfall intensity, and a surface runoff coefficient.  
100 Uncertainties arise, amongst others, with the estimation of the surface runoff coefficient, which  
101 varies from 0 (totally permeable) to 1 (totally impervious), and which relies on expert opinion.  
102 Pseudo-empirical formulas are difficult to reproduce and not automated. So, they are difficult to  
103 apply for long railway sections. Moreover, peak flow rate is not the only representative variable for  
104 characterizing surface runoff since it can also carry mud and materials. This can clog hydraulic  
105 structures and significantly reduce their capacity. Moreover, the environment surrounding the  
106 railway is permanently evolving: land use can change (cultivation, urbanization), it can increase or  
107 deflect the incoming water volumes and existing hydraulic structures can become insufficient.

108 The surface runoff phenomenon itself is difficult to study and there is no hazard reference map  
109 available. There are different approaches in the scientific literature for surface runoff mapping. The  
110 approaches based on topography analysis only (Pons et al., 2010) are rather simple but they do not  
111 take into account the other parameters that influence surface runoff occurrence and intensity, such  
112 as land use or soil types. The approaches based on indicator combinations (Cerdan et al., 2006; Le  
113 Gouee et al., 2010) are more complex, but mainly focus on the erosion process and require accurate  
114 soil data, which are not available on a large scale. The approaches based on physical modelling  
115 (Dabney et al., 2011; Smith et al., 1995) are interesting since they can model the spatial and temporal  
116 dynamics at catchment scale, but they also require numerous input and calibration data and are  
117 hardly applicable on a large scale. Difficulties lie in the complexity of the surface runoff phenomenon.  
118 Surface runoff is generated by rainfall whose location and intensity are still difficult to forecast with  
119 current meteorological models. It is influenced by multiple factors and can occur in various forms  
120 (flood, erosion, mud). Thus, data from observations and measurements remain scarce, although they  
121 are essential to better understand the phenomenon and to calibrate and evaluate models. For these  
122 reasons, there is generally no mapping of the surface runoff hazard available on a national scale.

### 123 1.3. Scientific issues

124 A method called IRIP (for “Indicator of Intense Pluvial Runoff”, French acronym) for surface runoff  
125 susceptibility mapping was developed by Dehotin and Breil (2011) from IRSTEA (French National  
126 Research Institute of Science and Technology for Environment and Agriculture). The IRIP method  
127 proposes an innovative approach for considering surface runoff. The method allows the creation of  
128 three maps representing three different phases of the surface runoff phenomenon: generation,  
129 transfer, and accumulation. The territory understanding is thus simplified by a spatial segmentation

130 of the dominant processes, and the risk management can be optimized by adapting the mitigation  
131 techniques depending on the areas. The mapping method has been designed to be simple enough in  
132 order to be widely applicable, in particular in an operational context. It requires only three input  
133 data: a digital elevation model, a land use map, and a soil map. The IRIP method provides an  
134 operational method for surface runoff hazard mapping that can be used by regional organizations for  
135 land planning objectives. By sharing these issues in part with the railway infrastructure manager, the  
136 IRIP method has been adapted to the railway context in collaboration with SNCF Réseau. The maps  
137 created by the IRIP method are intended for use as a tool for decision-making. However, decisions  
138 can generate changes and induce costs in terms of planning or works, or affect safety aspects. Thus,  
139 decision-makers must be aware of the map interpretation rules, their range of application, and their  
140 uncertainties. For these reasons, the IRIP maps must be evaluated.

141 The scientific issue lies in the fact that, because of the surface runoff phenomenon complexity, there  
142 is no database of surface runoff observation or measurement available on a large scale to evaluate  
143 the surface runoff maps. So proxy data must be used for the evaluation. Proxy data are data which  
144 are not directly related to the physical phenomenon but which inform on the phenomenon  
145 occurrence, for example, data of surface runoff impacts. However, difficulties arise when comparing  
146 model outputs with proxy data because of the indirect relationship. Some studies used data of  
147 surface runoff impacts to evaluate or calibrate hydrologic models. Naulin et al. (2013) and Versini et  
148 al. (2010) used impact data on roads to evaluate and calibrate their flash-flood warning model.  
149 Defrance et al. (2014) and Javelle et al. (2014) used impact data to evaluate the performance of their  
150 flash-flood warnings. The IRIP method has also been evaluated by comparison with impact data on  
151 roads (Lagadec et al., 2016b) and on railways (Dehotin et al., 2015b; Lagadec et al., 2016a). During  
152 these evaluation tests, good probabilities of detection were obtained but also high false-alarm ratios  
153 because numerous areas were identified as susceptible to surface runoff but no impact has been  
154 recorded. For these studies, the major issue lies in characterizing the structural vulnerability of the  
155 transportation network, a key component when comparing hazards with effective impacts. For the  
156 same hazard intensity, the effective impact can be reduced by a low structural vulnerability or  
157 aggravated by a high structural vulnerability of the impacted network section. Use of proxy data also  
158 brings further uncertainties due to biases in the data exhaustiveness, representativeness, and  
159 location inaccuracy. So evaluation tests must go further in order to fully assess the IRIP method  
160 performance.

161

## 162 1.4. Objectives

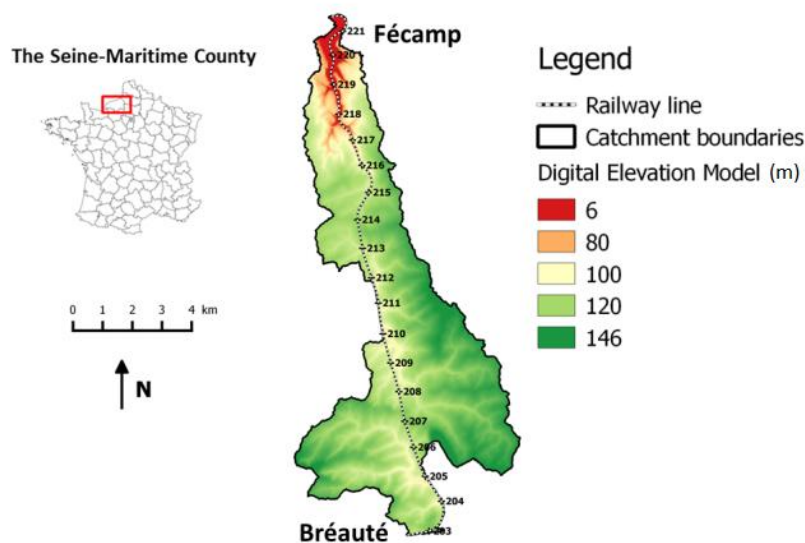
163 This paper has two objectives. The first one is to evaluate the surface runoff susceptibility maps  
164 created with the IRIP method by comparison with the results of a hydraulic diagnosis performed on a  
165 20-km stretch of railway. The evaluation focuses both on the performance of the IRIP method to  
166 detect railway sections exposed to surface runoff and on the relevance of the spatial information  
167 provided by the maps compared to the field reality. For this evaluation, the correspondence between  
168 the IRIP maps and the results of the hydraulic diagnosis is analyzed, taking into account the structural  
169 vulnerability of the railway infrastructure. The second objective is to provide practical solutions for  
170 integrating the IRIP method into the current risk assessment process in order to improve the  
171 management of surface runoff-related risks. Results of the IRIP method evaluation allow identifying  
172 specific tasks of the risk assessment process to which the IRIP method can make a direct  
173 contribution. Moreover, opportunities to improve risk reduction methods are discussed in the light of  
174 the new information brought by the IRIP method. The IRIP method development benefits from an  
175 industry-research partnership that makes it possible to go beyond a simple knowledge-to-application  
176 transfer, and enables the co-generation of new knowledge and new concepts for the two parts  
177 (Hatchuel et al., 2001; Klasing-Chen et al., 2017). Indeed, using data of the railway infrastructure  
178 manager allows evaluating the IRIP method and learning about the surface runoff physical  
179 phenomenon. Applying the IRIP method in an operational context makes it possible to identify  
180 possible new developments of the method to answer operational needs. Moreover, using an  
181 innovative mapping method opens up new possibilities for the management of surface runoff-related  
182 risks for the infrastructure manager.

## 183 2. Materials and methods

### 184 2.1. The hydraulic diagnosis of the Bréauté to Fécamp railway line

185 The Bréauté to Fécamp railway, located in the Normandy region, is line 359000 of the French railway  
186 network. The Bréauté to Fécamp railway is 20 km long. It is a single track line, non-electrified with a  
187 maximum speed limit of 80 km/h. The railway connects the city of Bréauté, on the Paris-to-Le Havre  
188 railway axis, to the port city of Fécamp. The railway was put into operation in 1856. Regarding the  
189 hydrological context, the railway intercepts several catchments with a total area of about 55 km<sup>2</sup>, an  
190 altitude ranging from 6 to 146 m ASL (Above Sea Level). The area is composed of large plateaus  
191 (south and start of the line) and a narrow valley (north and end of the line) (Figure 3). The catchment  
192 soil is mainly composed of silt and clay on the plateaus, with colluvial deposit in the valley and the  
193 bedrock is composed of chalk and flint stones. There is no perennial river in the catchment but  
194 intermittently, during rainfall, small streams can be activated within the main valleys. The land use is

195 dominated by agriculture with rural households and the small city of Fécamp in the north has about  
196 20,000 inhabitants. Due to its age, its location, and a low traffic level, this railway has been suffering  
197 from an advanced level of deterioration. To ensure safety aspects, the railway traffic was slowed,  
198 from 80 to 60 km/h, then to 40 km/h, and then was stopped. In the context of an Infrastructure and  
199 Transport Regional Plan adopted by the Normandy region in 2009, the Bréauté to Fécamp railway  
200 has been identified as a substantial means of transportation for regional development. Since then,  
201 several analyses have been undertaken to optimize regeneration works.



202

203 Figure 3: The study area which includes the railway from Bréauté to Fécamp and all the catchments  
204 intercepted by the railway

205 In this context of line regeneration, a railway line diagnosis was carried out in order to decide and  
206 prioritize works. All the infrastructure elements were considered, from the platform, the rails, to the  
207 earthworks and to the hydraulic structures. For the present paper, to evaluate the IRIP method, we  
208 focus on the hydraulic studies. Due to the important constraints in terms of budget and time during  
209 the diagnosis, the study only focused on drainage regeneration works. Hydraulic structures crossing  
210 under the railway or retention basins were not studied. The diagnosis consists of assessing the level  
211 of hazard exposure, and of assessing the capacity of the existing drainage structures, regarding their  
212 level of deterioration. In a second step, recommendations were provided in terms of drainage design  
213 and monitoring strategies. To this purpose, the Bréauté-Fécamp railway line was divided into 61  
214 sections depending on their transversal profile type (embankment, excavation, mixed profile). This  
215 division choice is consistent from a hydraulic point of view. The interaction type between the natural

216 surface runoff and the infrastructure strongly depends on the type of transversal profile. Among  
217 these 61 sections, 17 have been selected for drainage regeneration works.

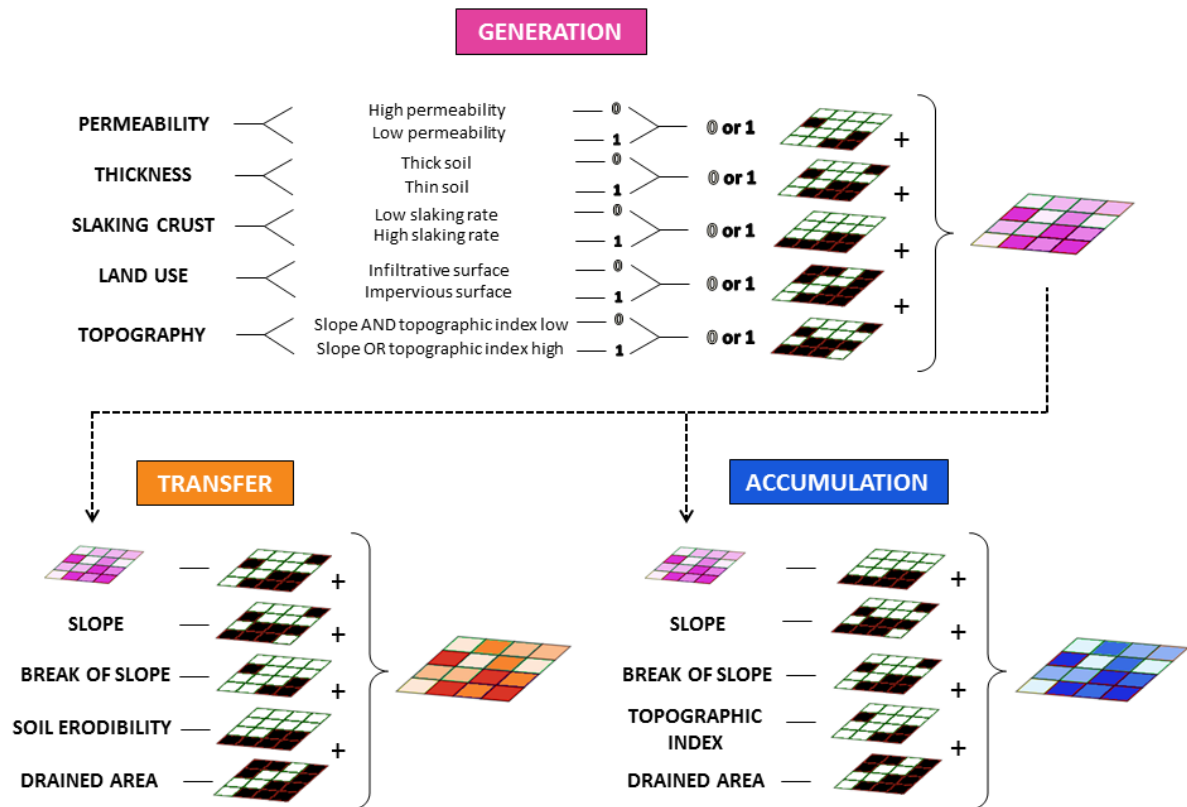
218 The results of the study performed on the Bréauté-Fécamp railway line do not only reflect the level  
219 of surface runoff hazard exposure along the line, but is a combination of the risk assessment and the  
220 budget, time and feasibility constraints. Recommendations for hydraulic works were required by the  
221 infrastructure manager to respect certain constraints such as a lack of space for implementing the  
222 sufficient drainage structures regarding the estimated flow rates and the mud inflows; time  
223 constraints of the work period, which hindered feasibility studies for works outside the railway right-  
224 of-way and made it impossible to establish special procedures for water legislation which would have  
225 taken too much time; and budget constraints, which obliged the study to focus only on the drainage  
226 structures and not on the hydraulic structure crossing under the railway or other structures such as  
227 retention basins. The study results however provide meaningful information about potential storm  
228 runoff coming from the surrounding environment, and a fair source of comparison for the IRIP maps.

## 229 2.2. The IRIP method

### 230 2.2.1. Description

231 The IRIP method is described briefly here, but further information can be found in the literature  
232 (Dehotin and Breil, 2011a; Lagadec et al., 2016b). The IRIP method combines indicators from  
233 geographic information layers and produces three maps representing three processes of storm  
234 runoff (Figure 4, Table 1): generation, representing areas with low infiltration capacity and which are  
235 susceptible to generate water at ground surface; transfer, representing areas where surface water  
236 can move downward, accelerate, and erode soils; and accumulation, representing areas where  
237 surface runoff can concentrate following topography, where it can slow down and generate floods  
238 out of rivers and deposits. Each map is created by combining five indicators. Each indicator is  
239 classified into two categories: favorable, where 1 is attributed to the pixel, or not favorable, where 0  
240 is attributed. This yields 5 binary maps. The maps are added to create a susceptibility map with 6  
241 levels, from 0 (not susceptible) to 5 (very susceptible). For each of the three susceptibility maps, the  
242 5 indicators are different. The generation map is created thanks to three indicators derived from a  
243 soil map, one indicator derived from a land use map, and one derived from the topography. The  
244 latter is a combination of the slope and the topographic index (Beven and Kirkby, 1979): 1 if both are  
245 favorable, 0 if one is not favorable. The generation map is then considered as an input indicator for  
246 the two other maps of transfer and accumulation in order to represent the necessity for the surface  
247 water to be generated before being transferred and/or accumulated. Maps of transfer and  
248 accumulation are created mainly by associating indicators based on topography, but with opposed  
249 favorability conditions, in order to represent the opposed movement of acceleration and slowdown.

250 For example, the slope indicator is favorable for transfer in the case of steep slopes, and for  
 251 accumulation in the case of low slopes. The break of slope indicator is favorable for transfer in the  
 252 case of convex break of slopes and for accumulation in the case of concave break of slopes.  
 253 Topographic indicators are computed for each pixel relatively to the upstream sub-catchment in  
 254 order to follow the hydrological logic from upstream to downstream. The resolution of the  
 255 susceptibility maps retains the resolution of the Digital Elevation Model (rasterized topography map)  
 256 used as input data. To determine the favorability thresholds for topographic indicators, a  
 257 classification method is used (Rubin, 1967), in order to compute a relative threshold depending on  
 258 the study area. Thus, the method can be applied on various territories without a priori local  
 259 knowledge.



260

261 Figure 4: The indicator combination scheme of the IRIP method

262

263 Table 1: List of the indicators used in the IRIP method along with their conditions of favorability to  
 264 surface runoff

IRIP maps	Indicators	Conditional values
Generation	Soil permeability	0: Saturated hydraulic conductivity ( $K_s$ ) $\geq 1e-6$ m/s
		1: $K_s < 1e-6$ m/s
	Soil thickness	0: Thickness $\geq 50$ cm
		1: Thickness $< 50$ cm
	Soil crustability	0: Crustability $< 3$ (Cerdan et al., 2006)
		1: Crustability $\geq 3$
Topography	0: Slope $\leq 0.5\%$ AND topographic index $\leq$ (mean + standard deviation)	
	1: Slope $> 0.5\%$ OR topographic index $>$ (mean + standard deviation)	
Land use	0: Pastures, grasslands, and forests	
	1: Urban areas and agricultural lands	
Transfer	Upstream generation susceptibility	0: Modal value of the upstream sub-catchment $< 3/5$
		1: Modal value of the upstream sub-catchment $\geq 3/5$
	Slope	0: Slope $\leq 5\%$
		1: Slope $> 5\%$
	Break of slope	0: Concave break of slope
		1: Convex break of slope
Drained area	0: Drained area $\leq$ (mean + standard deviation)	
	1: Drained area $>$ (mean + standard deviation)	
Soil erodibility	0: Erodibility $< 3$	
	1: Erodibility $\geq 3$	
Accumulation	Upstream generation susceptibility	0: Modal value of the upstream sub-catchment $< 3/5$
		1: Modal value of the upstream sub-catchment $\geq 3/5$
	Slope	0: Slope $> 5\%$
		1: Slope $\leq 5\%$
	Break of slope	0: Convex break of slope
		1: Concave break of slope
Topographic index	0: Topographic index $\leq$ (mean + standard deviation)	
	1: Topographic index $>$ (mean + standard deviation)	
Drained area	0: Drained area $\leq$ (mean + standard deviation)	
	1: Drained area $>$ (mean + standard deviation)	

265

266 2.2.2. Input data and parameterization for the study

267 Input data used for the study area are: a 5m resolution Lidar DEM from IGN (French National  
 268 Geographic Institute<sup>1</sup>), the European Soil Database at 500 meters resolution created from the LUCAS

<sup>1</sup> IGN Website : <http://professionnels.ign.fr/>

269 database (Ballabio et al., 2016), and the regional land use map<sup>2</sup> at a scale of 1/5000 in rural areas and  
270 1/2000 in urban areas. Because high resolution input data were available and previous works had  
271 been conducted in the Seine-Maritime County with the IRIP method (Lagadec et al., 2016b), a specific  
272 parameterization of the method was proposed for this study. Two indicators were adapted along  
273 with some favorability thresholds, which are the condition for a pixel to be set at 1 or 0. Concerning  
274 the indicators, because of a strong disposition of the soil to slaking crust in this region (Cerdan et al.,  
275 2002), a slaking indicator was used in the generation map, instead of the erodibility indicator. The  
276 erodibility indicator was used in the transfer map to highlight the erosion mechanism, which is  
277 important in this territory. The erodibility indicator replaces the ground linear axes in the transfer  
278 map. The ground linear axis indicator is used in the case of coarse resolution DEM, in order to  
279 represent the effect of interception and redirection of surface runoff by roads, agricultural drainage  
280 or even railways (1 for presence of a linear axis, otherwise 0). For this study, the use of a Lidar DEM  
281 allows the detection of this kind of ground axes, so their effects of interception and redirection are  
282 directly taken into account within the topographic indicators.

283 Concerning the favorability thresholds, they are summarized in Table 1. A soil is considered as having  
284 low infiltration capacity for saturated hydraulic conductivity lower than  $10^{-6}$  m/s. A soil is considered  
285 as thin, and thus with a low storage capacity, for a thickness lower than 50 cm. The thresholds for soil  
286 slaking ability and erodibility are set at 3 with respect to the pedo-transfer rules (Cerdan et al., 2006).  
287 These thresholds are set by default in the IRIP method and are based on a literature review in the  
288 pedology field (Dehotin and Breil, 2011a, 2011b). For this study, the thresholds that are adjusted for  
289 the study area are those for the slope, the topographic index, and the drained area indicators. The  
290 threshold of 5% was chosen thanks to discussions with local actors (SMBV Pointe de Caux<sup>3</sup>), who  
291 generally observe intense surface runoff on about 5% slopes. A threshold of 0.5% is chosen for the  
292 generation map, because below 0.5% the area is considered flat and surface runoff can infiltrate into  
293 the soil. The thresholds of topographic index and drained areas are set at the mean plus the standard  
294 deviation of the range of values over the study area, instead of using the classification method. The  
295 classification method provides good results for coarser resolution DEM, but for this study using a  
296 very high resolution DEM modifies the range of values, and the threshold must be more restrictive to  
297 display less information and to simplify the interpretation of the maps. Note that the hydraulic  
298 structures are not taken into account in the IRIP method, in particular those under the railway that  
299 do not appear in the DTM.

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<sup>2</sup> Website to download the regional land use map and further information about its creation:

<http://mos.hautenormandie.fr/>

<sup>3</sup> SMBV Pointe de Caux: Mixed association of the Pointe de Caux Region

300       2.3. Comparison method of the IRIP maps and the hydraulic diagnosis results  
301 The objective of the comparison is to evaluate the performance of the IRIP method to retrieve  
302 railway sections exposed to surface runoff. Two types of comparisons are performed: a quantitative  
303 comparison over the whole line, using statistical methods; and a qualitative comparison on three  
304 railway sections to assess the relevance of the spatial information over the catchment.

#### 305       2.3.1. Quantitative comparison

306 In this part, the question we want to address is: are the highest susceptibility levels of the IRIP maps  
307 located on the railway sections selected for regeneration works? In other words, what is the  
308 Correspondence rate between the IRIP maps and the hydraulic diagnosis results, over the whole  
309 railway line? To answer this question, the railway was divided into 3 types of transversal profile  
310 (embankment, excavation, and mixed profile) following the division performed during the hydraulic  
311 diagnosis. For each profile type, the following information was summarized: its length (in meters),  
312 the presence of an aperture under the railway (bridge or hydraulic structure), and whether or not the  
313 section was selected for regeneration works. Concerning the IRIP information, the following  
314 information was computed for each profile type: the number of pixels greater than or equal to 4/5  
315 for the maps of transfer and accumulation that are located within a buffer area of 5 meters both  
316 sides of the railway. This 10-meter width of analysis was chosen in order to take into account the  
317 track, which is a single track, the sidetracks, and a part of the earthworks. As it is difficult to state  
318 from which level of exposure a railway is susceptible to suffer damage, two hypotheses were tested  
319 to consider a railway section detected by IRIP as exposed to surface runoff or not: condition no. 1, at  
320 least 1 pixel of the transfer or the accumulation map greater than or equal to 4/5 located within the  
321 10-m buffer area; and condition no. 2, at least 10% of the linear of the railway section is covered by  
322 pixels transfer or accumulation greater than or equal to 4/5. This ratio was computed by the sum of  
323 the pixel numbers of accumulation and transfer, multiplied by 5 (the length of a pixel), divided by the  
324 section linear, and multiplied by 100 to get a percentage. This allowed having a rather permissive  
325 condition (the first), and a more binding condition (the second).

326 To analyze the performance of the IRIP method, contingency tables were created and verification  
327 indicators were computed. A contingency table is a matrix that represents the interrelation between  
328 two variables (Hogan and Mason, 2012; Stanski et al., 1989). For this study, contingency tables were  
329 computed between the number of sections that are detected by IRIP or not (lines) and the number of  
330 sections that are selected for works or not (columns) (Table 2). The true positives (T+) are sections  
331 which are detected by IRIP and selected for regeneration works. The false positives (F+) are sections  
332 which are detected by IRIP but not selected for works. The false negatives (F-) are sections which are  
333 not detected by IRIP but are selected for works. And the true negatives (T-) are sections which are

334 not detected by IRIP and not selected for works. Table 3 presents the indicators used for evaluating  
 335 the IRIP method performance. The probability of detection (POD) and the false alarm ratio (FAR) are  
 336 computed from the contingency tables. The best score is for a greatest POD combined with a lowest  
 337 FAR. In addition to this, Chi-Square tests are performed for each contingency table in order to assess  
 338 the statistical significance of the contingency tables. A Chi-Square test allows the assessment of the  
 339 statistical dependence between the IRIP maps and the diagnosis results, by comparing the observed  
 340 headcount of the contingency table to headcount got with a hypothesis of total independence. For  
 341 example, according to the tabulated Chi-Square values, if the computed Chi-Square is above 6.63, it  
 342 means that the probability of independence between the IRIP maps and the diagnosis results is less  
 343 than 1%. Finally, the false negatives and the false positives were explained through a brief  
 344 assessment of the vulnerability.

345 Table 2: The theoretical contingency table representing the interrelation between the number of  
 346 sections detected by IRIP and the number of sections selected for work

		Selected for work	
		Yes	No
Detected by IRIP	Yes	T+	F+
	No	F-	T-

347

348 Table 3: Summary of the indicators used to evaluate the IRIP method performance along with their  
 349 equation and interpretation.

Indicators	Equations	Interpretation
POD	$\frac{(T+)}{(T+) + (F-)}$	Range: 0 – 1 Best score: 1
FAR	$\frac{(F+)}{(F+) + (T+)}$	Range: 0 – 1 Best score: 0
Chi-Square	$\sum \frac{(O - E)^2}{E}$ O = Observed headcounts E = Expected headcounts	For 1 degree of freedom: P(X <sub>2</sub> >6.63)=0.01 P(X <sub>2</sub> >7.88)=0.005 P(X <sub>2</sub> >10.83)=0.001

350

### 351 2.3.2. Qualitative comparison

352 In this part, the question we want to answer is: do the field observations and the recommendations  
 353 fit with the spatial information of the IRIP maps of transfer and accumulation? In other words, on  
 354 which map and in which forms is the information from the field retrieved? The relevancy of the IRIP  
 355 maps is assessed in terms of location of the preferential water flow paths, of areas susceptible to  
 356 surface water accumulation and susceptible to erosion, and in terms of IRIP susceptibility levels.

357 Schemes from the hydraulic diagnosis are used to perform the comparisons. For each section  
358 selected for works, the schemes represent the recommended measures along with the field  
359 observations. The comparison is visual and qualitative because it displays the two maps, IRIP and the  
360 diagnosis, of the same area side by side. Photos from the field allow supporting identification of  
361 matching areas. Although all railway sections analyzed in the diagnosis were compared to IRIP maps,  
362 this paper presents four sections. Two of them illustrate mainly the contribution of the accumulation  
363 susceptibility map and the other two illustrate mainly the contribution of the transfer susceptibility  
364 map. Finally, some patterns of storm runoff spatial dynamics and railway infrastructure configuration  
365 can be identified from this comparison as being a configuration at risk. So interpretation guidelines of  
366 the IRIP maps are provided in order to support forthcoming risk assessment of railway lines.

### 367 3. Results

#### 368 3.1. Quantitative comparison

369 Table 4: List of the 61 railway sections along with their type of transversal profile (Emb:  
370 Embankment, Exc: Excavation, MP: Mixte Profile), their length, whether or not they have been  
371 selected for drainage regeneration works, the number of pixels with susceptibility levels greater than  
372 or equal to 4/5 in transfer and in accumulation, the ratio of the number of pixel and the length,  
373 whether or not the section has been detected by IRIP according to 2 conditions and whether or not  
374 there is an aperture under the railway.

No.	Type	Linear (m)	Selected for works	$\Sigma$ Acc 4&5	$\Sigma$ Trans 4&5	Ratio IRIP/linear (%)	Detected by IRIP Condition 1	Detected by IRIP Condition 2	Aperture under the railway
1	Emb	230	no	0	0	0	no	no	no
2	Emb	225	no	3	8	24	yes	yes	yes
3	Exc	1020	yes	70	0	34	yes	yes	no
4	Emb	30	no	1	0	17	yes	yes	yes
5	Exc	290	no	22	0	38	yes	yes	no
6	Emb	520	no	0	0	0	no	no	no
7	Exc	340	yes	29	0	43	yes	yes	no
8	Emb	470	no	0	0	0	no	no	no
9	Exc	1010	yes	129	0	64	yes	yes	no
10	Emb	520	no	1	1	2	yes	no	yes
11	Exc	1250	yes	91	1	37	yes	yes	no
12	Emb	650	no	2	2	3	yes	no	yes
13	Exc	200	no	0	0	0	no	no	no
14	Emb	250	no	1	2	6	yes	no	yes
15	Exc	100	no	0	0	0	no	no	no
16	Emb	50	no	2	0	20	yes	yes	yes
17	Exc	440	no	24	0	27	yes	yes	no
18	Emb	250	no	0	2	4	yes	no	yes
19	Exc	250	no	5	0	10	yes	yes	no
20	Emb	460	no	0	1	1	yes	no	yes
21	Exc	300	no	11	0	18	yes	yes	no
22	Emb	200	no	1	1	5	yes	no	yes
23	Exc	500	yes	28	0	28	yes	yes	no
24	Emb	570	no	0	0	0	no	no	no
25	Exc	500	no	25	0	25	yes	yes	no
26	Emb	150	no	0	0	0	no	no	no
27	Exc	300	no	4	0	7	yes	no	no
28	Emb	330	no	2	2	6	yes	no	yes
29	Exc	1200	yes	130	0	54	yes	yes	no
30	Emb	200	yes	32	2	85	yes	yes	no
31	Exc	200	yes	26	1	68	yes	yes	no
32	Emb	150	no	0	0	0	no	no	no
33	Exc	550	yes	54	24	71	yes	yes	no
34	Emb	100	no	1	1	10	yes	yes	yes
35	Exc	830	yes	46	0	28	yes	yes	no
36	MP	330	yes	3	38	62	yes	yes	no
37	Emb	120	no	2	1	13	yes	yes	yes
38	MP	260	no	0	0	0	no	no	no
39	Emb	110	no	0	0	0	no	no	no
40	Exc	410	yes	1	17	22	yes	yes	no
41	Emb	150	no	0	0	0	no	no	no
42	Exc	160	no	28	23	159	yes	yes	yes
43	Emb	110	no	1	2	14	yes	yes	yes
44	Exc	250	yes	0	4	8	yes	no	no

45	Emb	270	no	0	5	9	yes	no	no
46	MP	230	no	0	14	30	yes	yes	no
47	Emb	100	no	2	2	20	yes	yes	yes
48	MP	80	no	0	0	0	no	no	no
49	Emb	110	no	2	1	14	yes	yes	yes
50	Exc	190	yes	0	1	3	yes	no	no
51	Emb	70	no	2	1	21	yes	yes	yes
52	Exc	200	no	0	3	8	yes	no	no
53	Emb	150	no	2	2	13	yes	yes	yes
54	MP	100	no	0	0	0	no	no	no
55	Emb	90	no	2	0	11	yes	yes	yes
56	Exc	400	yes	24	0	30	yes	yes	no
57	Emb	60	yes	1	2	25	yes	yes	yes
58	Exc	1100	yes	16	21	17	yes	yes	no
59	Emb	150	no	0	0	0	no	no	no
60	Exc	320	no	1	0	2	yes	no	no
61	Emb	130	no	11	0	42	yes	yes	no

375

376 For this comparison, the railway is divided into 61 sections which represent the different profile  
377 types: embankment, excavation, and mixed profile. Sections range from 30 to 1250 m, with a mean  
378 length of about 350 m. Table 4 presents the information for each section. The number of sections per  
379 type of correspondence (T+, F+, F- and T-) is counted from this table. They are summarized in Table 5.  
380 The first column of Table 5 presents the correspondences between the column “detected by IRIP  
381 condition 1” and the column “selected for works” of Table 4. The second column presents the  
382 correspondences between “detected by IRIP condition 2” and “selected for works”. Then POD, FAR,  
383 and Chi-Square are computed for each column. For condition no. 1, the less binding, a score of 100%  
384 of POD is obtained, which means that all the sections detected by the IRIP method are indeed  
385 selected for drainage works. This POD is promising but must be analyzed with the associated FAR,  
386 which is here 65%. This means that 65% of all the sections detected by IRIP are not selected for  
387 works. Considering condition no. 2, which means a ratio IRIP/linear greater than or equal to 10, POD  
388 remains rather high at 88%, but FAR decreases to 56%. For both conditions, the Chi-Square test  
389 states that these headcounts are significant with probabilities of being due to chance of 1% and  
390 0.01% respectively. To continue analyzing the IRIP method performance, the FAR percentages, which  
391 are sections with a false positive correspondence, are further investigated.

392

393 Table 5: Number of railway sections among the 61 for each type of correspondence along with the  
 394 POD, FAR, and Chi-Square, for the 2 conditions for a section being detected by the IRIP method and  
 395 considering the infrastructure configuration or not.

	Without considering railway configuration		Considering railway configuration	
	Condition no. 1	Condition no. 2	Condition no. 1	Condition no. 2
T+	17	15	35	33
F+	30	19	12	8
F-	0	2	0	2
T-	14	25	14	18
POD	1	0.88	1	0.94
FAR	0.65	0.56	0.26	0.2
Chi-Square	7.02	10.09	24.46	27.31

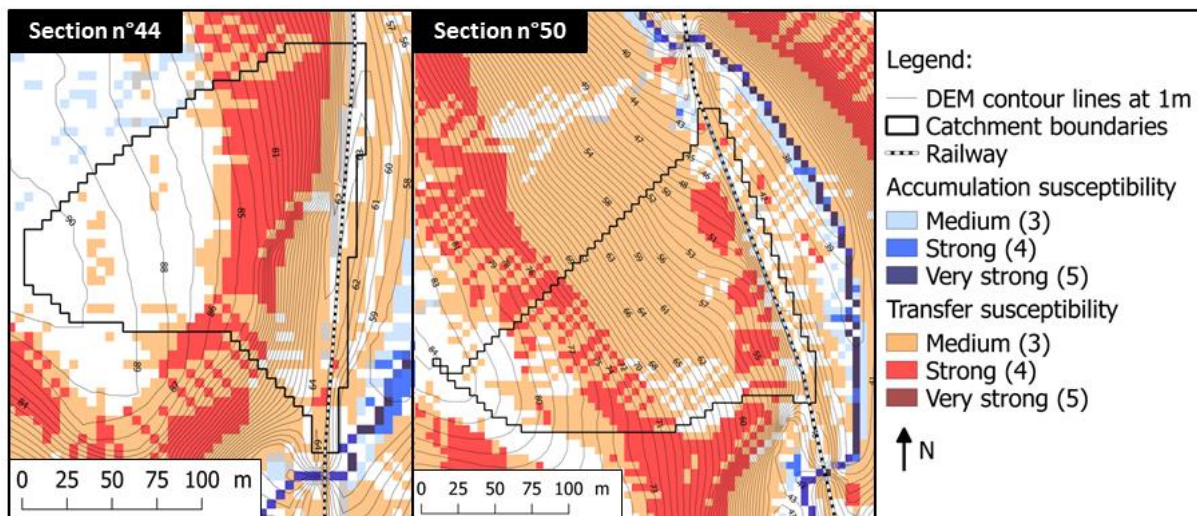
396

397 Among all the 61 railway sections, some sections are exposed to surface runoff according to the IRIP  
 398 maps but they were not selected for works after the hydraulic diagnosis. Their transversal profile is  
 399 an embankment equipped with an aperture under the railway (for example, railway sections no. 2,  
 400 12 or 28). It can be considered that these sections are not vulnerable. Moreover, it can be considered  
 401 that if there is an aperture under the railway, this is due to the necessity to allow surface runoff to  
 402 flow down, and that the exposure to surface runoff is effective. Railway sections with this type of  
 403 configuration, embankment and aperture, can thus be converted from false positive to true positive.  
 404 New correspondences are computed and are presented in the two last columns of Table 5 along with  
 405 their POD, FAR, and Chi-Square. The result is a decrease of the FAR, from 65 to 26% for condition no.  
 406 1, and from 56 to 20% for condition no. 2. It is also interesting to notice a very high POD of 94% for  
 407 condition no. 2, which is the most binding one. The Chi-Square tests state that these results are  
 408 statistically very significant (24.46 and 27.31). Explanations for the false negatives and the remaining  
 409 false positive are provided below.

### 410 3.1.1. Analysis of the false negatives and the false positives

411 First, we will focus on false negatives, which are railway sections no. 44 and 50 (Figure 5). Railway  
 412 section no. 44 is a deep excavation up to 15 meters high with woody vegetation. This earthwork is  
 413 considered to be fragile and is subject to particular attention since an important landslide occurred  
 414 on the left side. During a field visit, water stagnation was observed on the tracks, and the current  
 415 draining ditches were clogged by mud. These explanations actually fit with the IRIP map. Transfer  
 416 susceptibility levels of 4/5 are located all over the left side of the excavation, where the landslide  
 417 occurred, and accumulation susceptibility levels of 3/5 are located on the tracks where water

418 stagnation was observed. The other example, railway section no. 50, is an excavation up to 3 meters  
419 high and with an upstream surrounding of wood and grassland. This section was selected because a  
420 few shallow landslides have occurred on the left side. The hydraulic diagnosis stated that the  
421 landslides could have been influenced by rabbit holes. This can indeed aggravate consequences when  
422 surface runoff occurs but also can induce landslide by itself. It has been decided to create open  
423 ditches to help evacuate water. This earthwork has a transfer susceptibility level of 4/5 computed by  
424 the IRIP method. These examples show that, in some cases, high susceptibility levels of transfer must  
425 be taken into account not only when they are directly located on the tracks but also when they are  
426 on the earthwork sides. Moreover, in the case of railway section no. 44, accumulation susceptibility  
427 levels of 3 could also be considered for water stagnation issues. These two cases fit globally with the  
428 IRIP maps, but do not satisfy any of the two conditions stated for a railway section being considered  
429 as exposed to surface runoff according to the IRIP method. These cases illustrate how the IRIP pixel  
430 configuration along with their susceptibility levels could indicate an exposure to different types of  
431 surface runoff impacts (landslide, water stagnation, mudflow, flood...). For example, the quantity of  
432 stagnant water could be verified in the field to propose an eventual relationship with the IRIP  
433 susceptibility levels. Further tests should be performed to go further with this suggestion.



435 Figure 5: The two false negatives correspondences, where the conditions to consider a railway  
436 section as exposed to surface runoff, according to IRIP, are not satisfied but where regeneration  
437 works have been recommended.

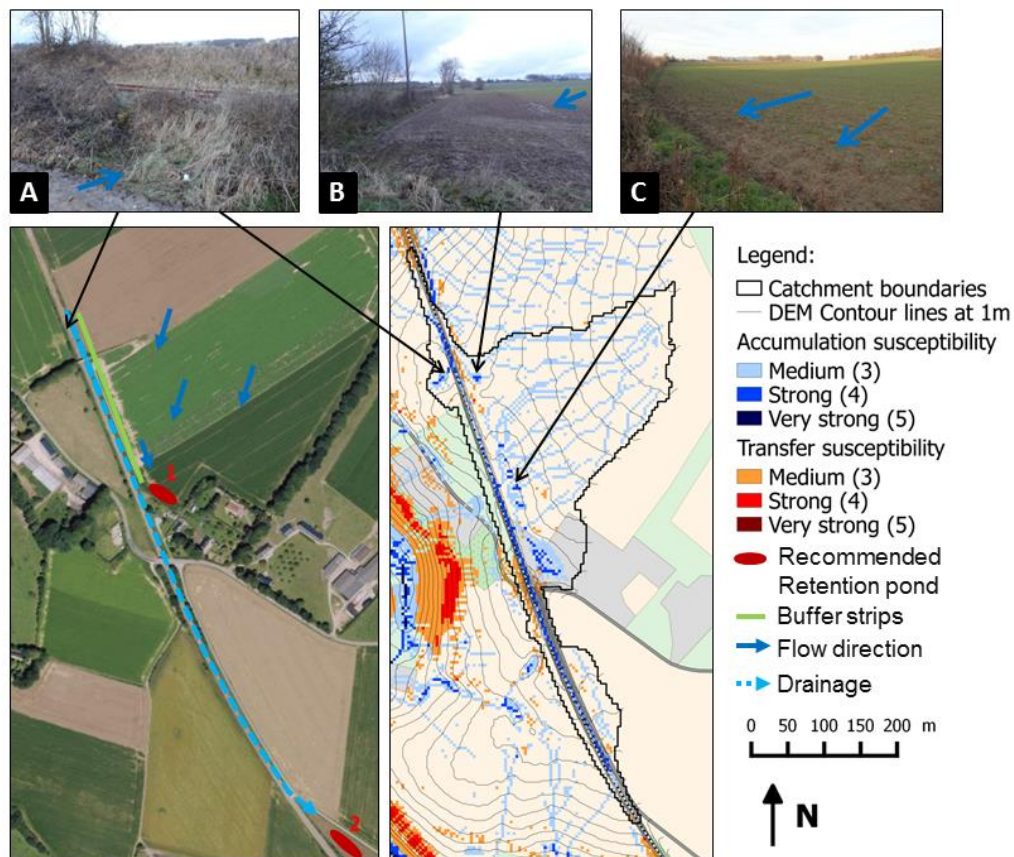
438 False positives represent 12 railway sections with condition no. 1 and 8 railway sections with  
439 condition no. 2. These false positives mean that the IRIP method detects an exposure of the railway  
440 to surface runoff but that no regeneration works were undertaken. Among the 8 remaining false  
441 positives with condition no. 2, two of these railway sections (no. 17 and 61) are train stations and

442 they present low vulnerability according to the hydraulic diagnosis. They have large areas able to  
443 store eventual water stagnation and are protected by large ditches. Railway sections no. 5, 19, and  
444 21 actually present very small catchment areas, of 8700, 5400 and 4900 m<sup>2</sup> respectively, and  
445 according to the diagnosis, railway tracksides would be large enough to store and evacuate the  
446 quantity of water that could be generated by these small catchments. Railway section no. 42  
447 presents a very high degree of exposure to surface runoff according to the IRIP method, but it has  
448 not been considered for works. This section has actually already been subject to particular  
449 modifications because of flooding problems. These modifications were undertaken in partnership  
450 with local regional organizations and the railway section has been equipped with a large aperture  
451 under the railway and a retention basin. So it can be considered that the section is effectively  
452 exposed to surface runoff but that it is sufficiently protected and thus less vulnerable. Railway  
453 section no. 25 was considered as less susceptible to landslide during the first field expertise, with  
454 observed traces of past shallow landslides maybe due to rabbit holes. But, this railway section has  
455 been retained for further analysis and thus was not selected for regeneration works. Finally, railway  
456 section no. 46 presents high susceptibility levels of surface runoff transfer according to IRIP but the  
457 hydraulic diagnosis does not mention particular exposure to surface runoff. It would be interesting to  
458 get more details thanks to a deeper field analysis.

459 This quantitative comparison between the IRIP maps and the diagnosis results makes it possible to  
460 show the global performance of the IRIP method to detect railway sections exposed to surface  
461 runoff. Results are promising but show there is a need to focus on specific sections to better  
462 understand the meaning of IRIP detection (or not) in view of local configuration, and to improve the  
463 correspondence between runoff hazard assessment and selection by experts of railway sections at  
464 risk. The analysis must be pursued with a qualitative comparison at the catchment scale in order to  
465 better assess the contribution of the IRIP maps to understanding the environment surrounding the  
466 railway.

467

468 3.2. Qualitative comparison  
469 3.2.1. Railway section no. 9



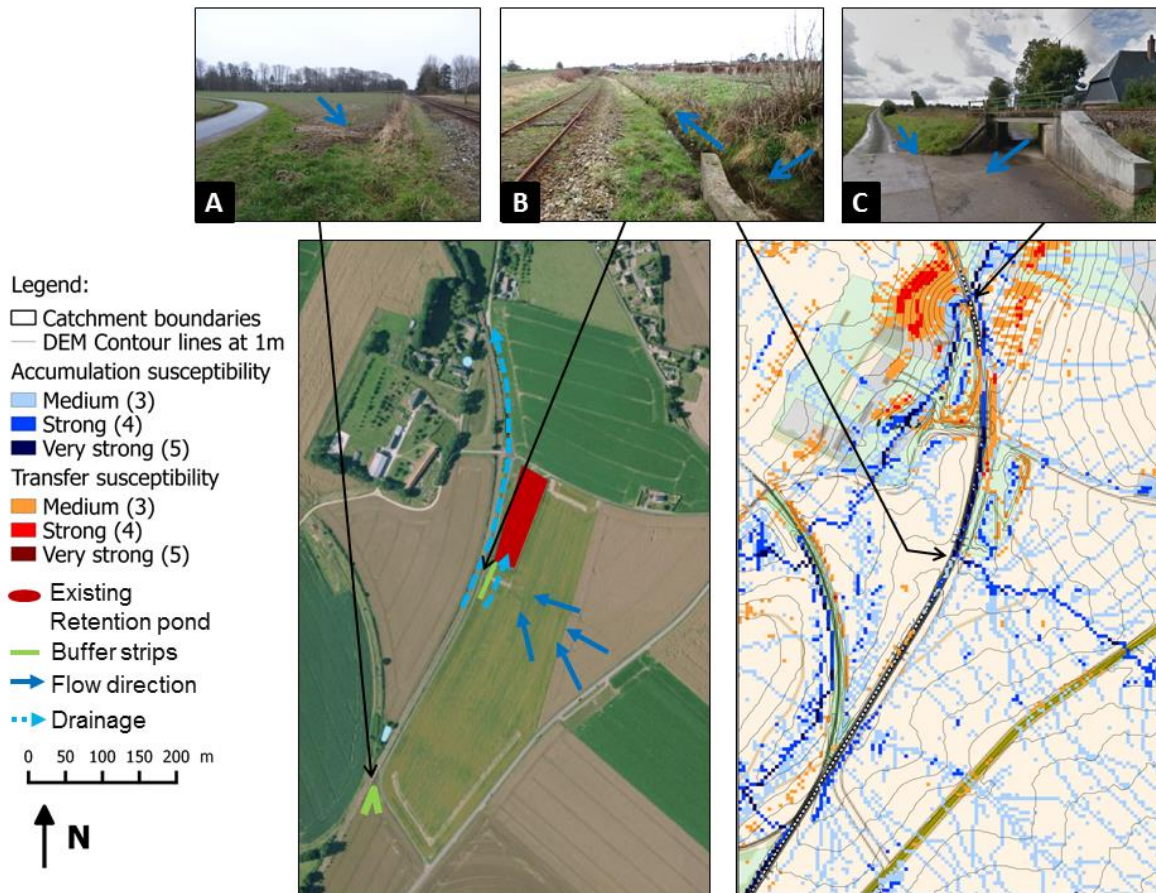
470  
471 Figure 6: Comparison of the IRIP susceptibility maps of surface runoff transfer of accumulation with  
472 the hydraulic diagnosis for railway section no. 9.

473 Figure 6 presents a 940 linear meter-long railway section, established in an excavation. The map on  
474 the left-hand side shows the measures recommended by hydraulic diagnosis. The dashed blue line  
475 represents the section which needs work, the dark blue arrows represents the directions of the  
476 preferential surface runoff paths observed in the field. The green line represents the location for the  
477 installation of a buffer strip, made with grass or hedges, to slow down surface runoff and to stop  
478 mud accumulating on the tracks. The two red spots show two solutions for installing a retention  
479 pond. The first location should retain surface runoff before reaching the tracks. The second location  
480 should receive surface runoff after having been drained along the track sides in order to avoid  
481 problems downstream. The map on the right-hand side shows the three highest levels of storm  
482 runoff transfer and accumulation susceptibility. The black line represents the catchment boundaries,  
483 that is, the area from which the railway section can potentially receive water from precipitation.  
484 First, the IRIP map shows a high susceptibility to storm runoff accumulation on the tracks, with the

485 dark blue pixels, which is consistent with the choice of the section selected for works. High  
486 accumulation susceptibility can also be retrieved at the edge of the excavation which is consistent  
487 with the recommendation of installing a buffer strip and with the photos from the field, which show  
488 signs of moisture and mud deposits (photos B and C). One can also see a wider area of storm runoff  
489 accumulation at the location of the first solution for the retention pond, which let us state that it  
490 could be a better solution for protecting infrastructure than no. 2, which was designed for improving  
491 the situation downstream of the railway. The directions of the preferential paths for surface water  
492 identified on the field are retrieved on the IRIP maps with levels of accumulation of 3 and with far  
493 more details. Moreover, in the northern part of the railway section, on the left-hand side of the  
494 railway, a very small catchment is detected (photo A) with a high susceptibility to storm runoff  
495 accumulation. This susceptibility is confirmed by the photo A and by the aerial photography which  
496 show mud deposits. At this point, the railway is established in a small embankment and is not  
497 equipped with any hydraulic system which makes the railway vulnerable to storm runoff. This point  
498 can be considered as at risk although the catchment is so small that significant water inflow is  
499 unlikely. Finally, the IRIP maps agree with the diagnosis and provide more information in the  
500 environment upstream of the railway.

501

502 3.2.2. Railway section no. 33



503

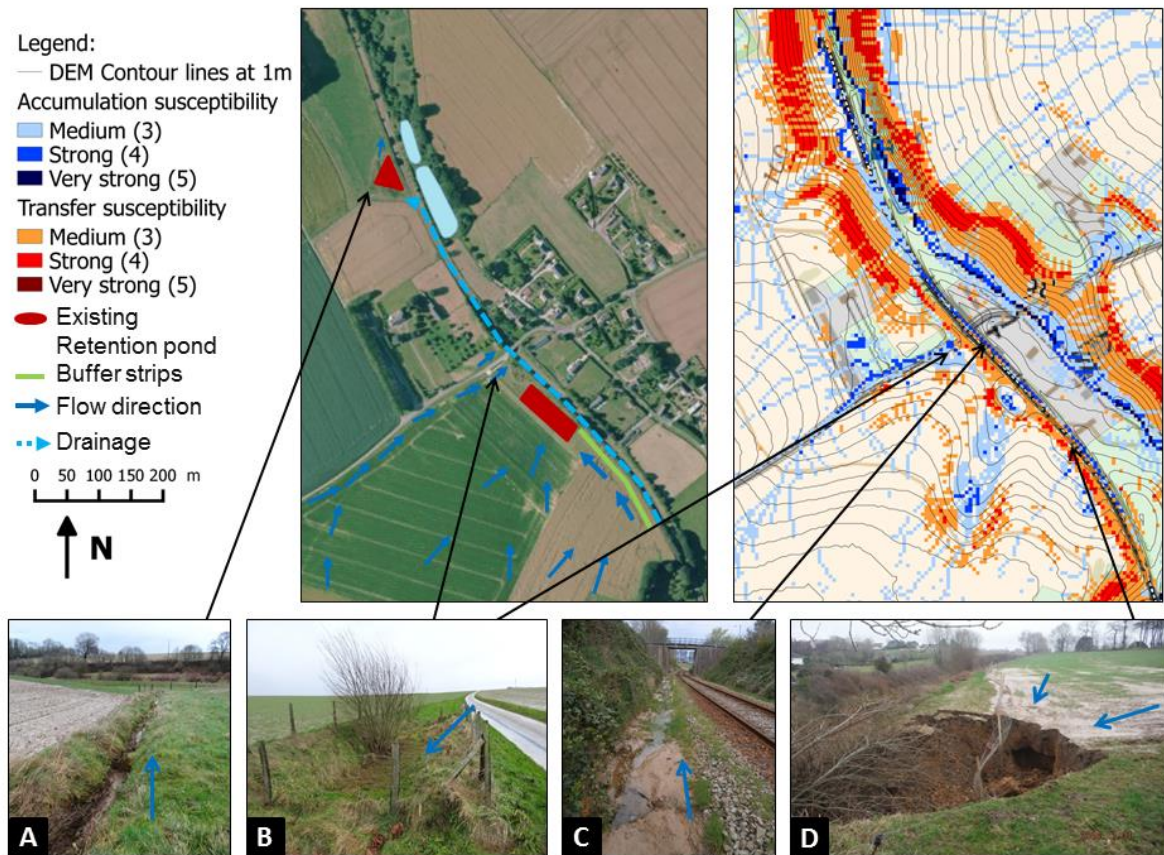
504 Figure 7: Comparison of the IRIP susceptibility maps of surface runoff transfer of accumulation with  
505 the hydraulic diagnosis for railway section no. 33.

506 Figure 7 presents another railway section of about 800 linear meters. The section is established at  
507 ground level in the southern part, in an excavation in the middle part, and on an embankment in the  
508 northern part. On the left-hand side map, two recommendations for installing buffer strips are  
509 indicated with the green lines and the red square indicates an already existing retention pond. On  
510 the right-hand side map, a main path of storm runoff arriving on the railway from the right hand side  
511 is detected by the IRIP map of accumulation susceptibility with levels of 4 and 5, a part is flowing in  
512 the retention pond and another part is flowing in the drainage system along the railway (photo B)  
513 which is consistent with the flow direction observed on the field and the selected railway section for  
514 regeneration works. Regarding the significant size of the catchment intercepted by the railway  
515 (about 1.2 km<sup>2</sup>, too large to be displayed but computed on the map), the drainage system capacity  
516 might not be sufficient considering the potential storm runoff inflow. The regeneration works only  
517 consider drainage works explaining why no solution for installing a hydraulic structure crossing the  
518 railway has been proposed. However, building a crossing structure at the intersection with the main

519 surface runoff path could be interesting. According to the IRIP maps, the natural surface runoff path  
520 is not to be intercepted by the railway and redirected toward the northern direction, but is to  
521 continue on the other side of the railway and to connect with the important water flow path  
522 downstream, indicated with high accumulation susceptibility levels. The question can be asked  
523 whether the railway infrastructure manager is responsible for the management of the entire volume  
524 of surface runoff coming from the upstream catchment or if it is responsible only for ensuring its  
525 natural flow from upstream to downstream. Here, a risk of drainage ditches overflowing can be  
526 expected. Such an incident could generate floods on tracks, erosion of the railway platform and  
527 erosion of the embankment at the exit of the longitudinal drainage, near the higher levels of storm  
528 runoff transfer (photo C). At another location, on the southern part of the railway section, an  
529 important surface water flow path is detected by the IRIP map: it corresponds to the  
530 recommendation for a buffer strip (photo A) but no particular flow direction has been indicated.  
531 Particular attention should be paid at this location which is exposed to surface runoff inflows. The  
532 IRIP maps reveal the storm runoff spatial organization in the surroundings of the railway. Such  
533 information can considerably support hydraulic experts in designing solutions to protect the railway  
534 from storm water inflows.

535

536 3.2.3. Railway section no. 35



537

538 Figure 8: Comparison of the IRIP susceptibility maps of surface runoff transfer of accumulation with  
539 the hydraulic diagnosis for railway section no. 35.

540 Figure 8 represents the third railway section. It is 1150 linear meters long and is established in an  
541 excavation. The catchment intercepted by this section is located in the left-hand side, with several  
542 storm runoff flow paths arriving perpendicularly to the railway. The important flow path, on the  
543 right-hand side, flows northward laterally to the railway but downstream. Anyway, the small town on  
544 the aerial photography and the downstream cities are frequently impacted by pluvial flooding. That is  
545 why two large retention ponds (light blue patches) can be seen on the northern part – they have  
546 been built by the agglomeration. Concerning the railway, the IRIP map presents strong accumulation  
547 susceptibility levels all along the section, meaning a high risk of track flooding (illustrated on photo  
548 C). Within the catchment, the flow directions indicated on the IRIP map agree with those observed in  
549 the field. Two already existing retention ponds belonging to the railway company protect the railway  
550 from storm runoff inflows. A small retention area has been set up to limit water coming from the  
551 road (photo B). However, on photo D, there were no protective structures and a landslide of the  
552 excavation occurred. This incident was due to a water stagnation area at the edge of the

553 embankment (mud deposits can be seen on the photo), which weakened the embankment, and a  
554 storm runoff inflow (small flow path upstream) on an area susceptible to runoff acceleration (orange  
555 and red pixels), which generated a landslide on the embankment slope. The deposit of materials on  
556 the tracks is a major risk of collision for a train, leading to a derailment risk. This location is  
557 recommended for installing a buffer strip which reflects this particular sensitivity. Along this railway  
558 section, this is the only location where the IRIP map indicates alternating patterns of high  
559 susceptibility to accumulation and transfer in the direct surrounding of the railway and where there  
560 is no protection. The other areas with high transfer susceptibility are farther away from the railway,  
561 or not directly linked with an important flow path. Finally, on this Figure, a lot of information is  
562 provided by the IRIP map, and an assessment of the local railway configuration is essential to identify  
563 locations at risk.

### 564 3.3. IRIP maps interpretation guidelines

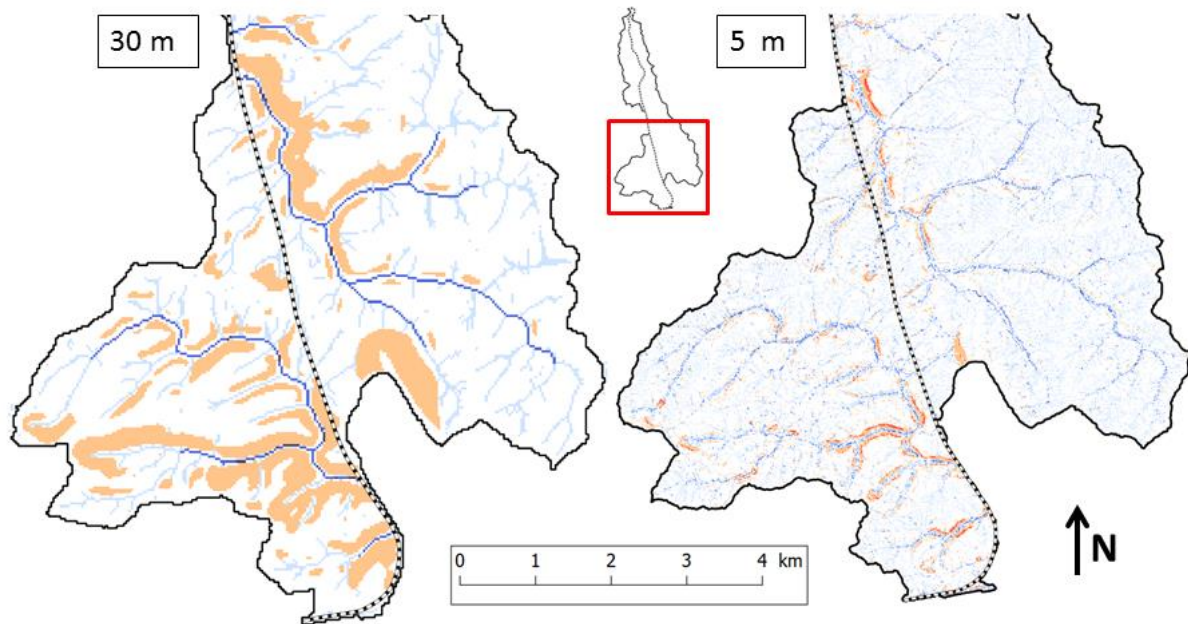
565 The comparison between the hydraulic diagnosis results and the IRIP maps shows a good agreement  
566 of areas exposed to surface runoff and areas with recommended works inside and outside the  
567 railway right-of-way. This allows the extrapolation of some patterns of surface runoff spatial  
568 connectivity with the railway infrastructure. Here are four examples of configurations of hazards and  
569 vulnerability which lead to considering a railway section as being at risk. First, high accumulation  
570 levels located on rail tracks could mean a risk of flooding if the railway is established in an excavation.  
571 Secondly, high accumulation levels at the ridge of an excavation are a sign for potential surface water  
572 stagnation and could generate a risk of a landslide of the excavation slope by material saturation of  
573 water. Thirdly, high transfer susceptibility levels on the slope of an excavation could indicate a risk of  
574 landslide if the transfer area is related to a surface water flow path indicated in the accumulation  
575 map. Fourth, a surface water preferential path crossing a railway embankment transversally is a risk  
576 for embankment backfilling and destruction, so at those locations experts must ensure that an  
577 aperture exists within the embankment (for example a rail bridge as illustrated in Figure 7, photo C).

### 578 3.4. Summary and limits of the comparison

579 This study presents two degrees of evaluation of the IRIP method: a statistical analysis and a spatial  
580 analysis. The spatial analysis shows the agreement between the IRIP spatial information and the field  
581 observations. The statistical analysis shows that the IRIP method is an efficient tool to detect railway  
582 sections exposed to surface runoff for relatively long linear distances. For the quantitative analysis,  
583 two conditions have been tested for considering a section as exposed to surface runoff or not, one  
584 permissive condition and one more binding. Moreover, we attempted to take the structural  
585 vulnerability of the railway into account, considering that embankments with apertures under the  
586 railway are configurations with low vulnerability. Considering that apertures are indicators of surface

587 runoff occurrence, these configurations are changed from false positives to true positives. Finally, it  
588 makes POD varying from 94 to 100% and FAR from 20 to 26%, along with extremely significant Chi-  
589 Square. However, we must recall some hypotheses that were made for this study and which must be  
590 taken into account in the interpretation of the results.

591 For this study, certain indicators and thresholds were adapted regarding the IRIP default  
592 parameterization, such as erodibility, slaking crust ability or the thresholds of slopes and topographic  
593 indexes. These changes are justified by a good knowledge of the local environment behavior  
594 acquired during previous studies and discussions with local actors. However, the hypotheses made as  
595 a result of IRIP method previous evaluations could be not applicable in the same way for other study  
596 areas. So additional tests must be performed to confirm the choices made for this study, or to find  
597 another parameterization which could better fit the comparison data, or else to analyze a possible  
598 change for other hydrological contexts. Concerning the repeatability of the results, input data are  
599 critical points. Indeed, good quality and high resolution data are important, but not available for all  
600 territories. Among the three input data required for the IRIP method, deciding which one is the most  
601 important in terms of quality depends on the objective of the study. For example, for territory  
602 planning or certain technical implementations regarding mitigation, the generation map will be  
603 relevant in order to know the poor infiltration capacity areas. Thus, quality of soil and land use data  
604 would be the most important. For an objective of impact assessment, the maps of transfer and  
605 accumulation would be the most relevant, so quality of the topographical data is the most important.  
606 Indeed, three indicators out of five are computed from topography for the map of transfer and four  
607 out of five for the map of accumulation. Figure 9 provides elements for discussing the required  
608 resolution of the topography. It shows two IRIP maps of the same part of the study area created with  
609 a 30-meter resolution DEM (left) and with a 5-meter resolution DEM (right). The map with the 30-  
610 meter resolution shows the mains surface runoff preferential paths (blue), which are the main  
611 talwegs along with transfer areas (orange), which are located mainly on the steepest talweg sides.  
612 The map with the 5-meter resolution is the one used for the current study and shows so many details  
613 that it is difficult to distinguish them at this scale. Further details can be observed on the hillslopes  
614 with the accumulation map, and information about surface runoff transfer susceptibility is more  
615 localized. Finally, the spatial information of the two maps overlaps globally, but provides different  
616 types of information that should be used regarding the objective of the analysis. For example, an IRIP  
617 map with a high resolution can be used for local analysis, and a coarser resolution IRIP map could be  
618 used for very long railway stretches (above about 100 km of railway) with very large catchments, or  
619 to have a global understanding of the environment behavior. In general terms, the input data  
620 resolution should not be larger than the resolution of the physical phenomenon.



621

622 Figure 9: Surface runoff susceptibility maps created with the IRIP method on the same area using two  
623 different resolutions of digital elevation model: 30 meters (left) and 5 meters (right). Although the  
624 two maps overlap globally, different information can be obtained using different input data.

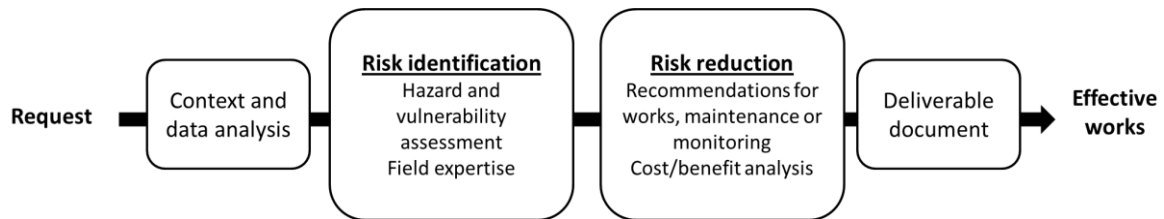
625 This study demonstrates the satisfying performance and the relevance of the IRIP method to perform  
626 hazard assessment. The IRIP maps can make a substantial contribution to identifying railway sections  
627 exposed to surface runoff and to better understanding the surrounding environment of the railway.

#### 628 4. Discussion

629 The previous part presents interesting results about the correspondence between the surface runoff  
630 maps created with the IRIP method and the results of the hydraulic diagnosis, both with the  
631 quantitative and the qualitative comparison. Here, we discuss how the IRIP method can practically  
632 contribute to the current hydraulic risk assessment process. First, the current process is described,  
633 and then steps are identified where the IRIP method can directly contribute and where there is an  
634 opportunity to push forward the current methods.

635

636 4.1. The current risk assessment process  
637



638  
639 Figure 10: General scheme of the risk assessment process to manage hydraulic risks on the railway  
640 infrastructure

641 Risk assessments are performed on railway sections or on railway network parts and aim at  
642 optimizing the maintenance strategy in terms of works, maintenance, and monitoring regarding  
643 specific risks. Figure 10 presents the general risk assessment process. It starts with a risk assessment  
644 request from the infrastructure manager to the engineering services. Experts then collect and gather  
645 all information about the study area. Information can be contextual about the current request, the  
646 stakeholders, and the final objectives. It can be about the infrastructure configuration and its  
647 elements, and it can be about past studies or past disorders on the study area, within the railway  
648 right-of-way and within the surrounding environment. Then it follows two main steps, the risk  
649 identification and the risk reduction. The risk identification step aims at assessing the hazard to  
650 which the railway is exposed, its intensity, and its probability of occurrence. It also aims at assessing  
651 the infrastructure structural vulnerability, in order to define railway sections at risk. Field  
652 assessments and discussions with local actors help the experts with the hazard and vulnerability  
653 assessment. Risk ranking can be made along the study area in order to prioritize sections at risk. Then  
654 the risk reduction step aims at making recommendations in terms of works, maintenance, and  
655 monitoring, providing technical solutions and also hierarchizing actions. For this step, compromises  
656 are found between costs, efficiency, and feasibility. Discussions with the infrastructure manager also  
657 allow analyzing the risk acceptability and the conditions of this acceptability. Finally, a deliverable  
658 document is provided to the infrastructure manager and effective works can start. This process  
659 remains general and each risk assessment has specific objectives and constraints that must be taken  
660 into account for each step of the process. Examples of contributions of the IRIP method are  
661 suggested for each step.

662 4.2. Contribution to context and data analysis

663 At the start of a risk assessment, experts must dedicate time to gathering data about the study area.  
664 Implicitly, a wealth of knowledge is provided by local actors and company employees that are used to  
665 working on the study area and that know areas susceptible to specific risks. Difficulties lie in the fact

666 that soft knowledge remains subjective and that can be lost or modified with long periods of time.  
667 Knowledge can also be lost when employees move or retire. Concerning more conventional data,  
668 archive data are generally difficult to use (Saint-Marc et al., 2016). Storage locations can be difficult  
669 to access, storage conditions are often not perennial, and the information is difficult to extract  
670 regarding the quantity of documents. Using numerical databases can also be difficult due to the large  
671 number of available databases, which have different operational objectives and which focus on  
672 different elements of the infrastructure. Regarding the quantity of data, information is often difficult  
673 to process. So information about a study area can be difficult to gather and especially when analyzing  
674 the surface runoff hazard, since there is no hazard mapping available on the railway network scale.  
675 For this step, the IRIP method can provide a reference map of surface runoff susceptibility along  
676 railways. The IRIP maps can be used as the basis when starting an assessment, to better assess the  
677 behavior of the environment surrounding the railway. Moreover, the IRIP method uses GIS  
678 (Geographical Information System) software, so the IRIP maps can be combined with all other  
679 information available on the study area (railway infrastructure, impact locations, surrounding  
680 structures) and information can be displayed on the same map. Although additional assessment is  
681 needed to interpret the data, gathering the data in a single visual tool can facilitate its processing  
682 (Saint-Marc et al., 2014). Further dialog between experts and project sponsors would also be useful  
683 in this step. Once the area characteristics have been analyzed, the needs can be detailed and  
684 objectives can be refined.

#### 685 4.3. Contribution to risk identification

686 This study shows that the surface runoff susceptibility maps created with the IRIP method can bring  
687 valuable information for hazard assessment. The IRIP method can bring direct contribution in terms  
688 of accuracy and time saving. The IRIP method brings accuracy on the qualification of surface runoff-  
689 related risks. Indeed, the three maps of generation, transfer, and accumulation bring information on  
690 the forms that surface runoff can get. Erosion or landslide can be expected for high transfer  
691 susceptibility areas. Floods or mud deposits can be expected for high accumulation susceptibility  
692 areas. Further assessment about the vulnerability of the railway infrastructure makes it possible to  
693 anticipate particular types of impact. More generally, the IRIP method is an additional tool to support  
694 decision-making. Experts can rely on the maps to confirm their analysis or to explain it. Moreover,  
695 the IRIP method can save time for the field assessment. The maps can help with the preparation of  
696 the field works and by supporting field observations. Indeed, the IRIP maps can help deciding which  
697 sites to visit by prioritizing the sites with the highest susceptibility levels. Moreover, the IRIP maps  
698 are a simple combination of landscape factors, so they help the expert to interpret landscape  
699 features such as the catchment boundaries, the surface water preferential path, areas with low

700 infiltration capacities, etc. Moreover, the three maps of storm runoff generation, transfer, and  
701 accumulation can orient the expert on the field by knowing what is expected to be seen and where.  
702 For example, areas susceptible to storm runoff transfer will present erosion traces and areas  
703 susceptible to storm runoff accumulation will present humidity, water stagnation or sediment mud  
704 deposits. More and more, experts have access to digital tools during their field assessments, so they  
705 can carry tools with GIS software which collate all the information about the study area. A potential  
706 evolution of the IRIP method could be the automatic detection of accumulation and transfer patterns  
707 near particular railway configurations, as identified in the map interpretation guidelines.

#### 708 4.4. Opportunity to push forward the risk reduction methods

709 Recommendations of solutions in terms of works, maintenance or monitoring can sometimes require  
710 creativity in order to optimize the effects, minimize costs, and provide sustainable solutions. In some  
711 cases, for surface runoff issues, standard hydraulic structures and drainage systems are not  
712 sufficient, since surface runoff not only carries water but also mud and debris that can clog structures  
713 and significantly reduce their capacity. Moreover, in some areas, surface runoff impacts are recent  
714 because of changes in the upstream environment (i.e. urbanization, forest turning into cultivated  
715 land). In some cases, there is no space available for adapting the railway with new structures. It is  
716 also worth considering who is responsible for the management of this new influx of pluvial water.  
717 These cases illustrate the fact that it is sometimes necessary to manage water issues outside the  
718 railway right-of-way, at the origin of the problem. These are not usual methods because it is complex  
719 to communicate with the other stakeholders. They can have the same surface runoff issues but not  
720 the same constraints and it can be difficult to work outside the railway right-of-way from a legal  
721 point of view. The current processes will have to evolve in this direction. The IRIP maps provide  
722 information about the spatial catchment characteristics and its surface runoff exposure. The maps  
723 can help adapting the mitigation techniques depending on the area. For high generation  
724 susceptibility areas, water infiltration capacity must be improved, for example with retention basins.  
725 The maps can help to choose the location of the basins. For areas with high transfer susceptibility  
726 (soil loss issues), it can be suggested to plant vegetation in order to stabilize earth and limit soil  
727 losses. For areas with high accumulation susceptibility, it can be suggested to implement wetlands  
728 (Fressignac et al., 2016) and to minimize vulnerability.

729 Moreover, the IRIP maps, being visual tools, can facilitate the communication between the project  
730 stakeholders. When convincing others about the importance of a recommendation, presenting  
731 model outputs which support this analysis and the conclusions can be helpful. There is a need for  
732 educational tools to support discussions with local actors and with project sponsors who are often  
733 not accustomed to implementing alternative techniques outside the railway right-of-way. The expert

734 must be able to explain the behavior of the catchment and the contribution of the different areas to  
735 prove the necessity of implementing such solutions for managing storm runoff-related risks.

## 736 5. Conclusion

737 This study presents interesting results when comparing the surface runoff maps created with the IRIP  
738 method and the result of a hydraulic diagnosis. The quantitative comparison shows high probabilities  
739 of detection along with low false alarm ratios. The qualitative comparison shows good  
740 correspondence between the IRIP maps and the field observations. This indicates a good  
741 performance and high level of reliability of the IRIP method to detect railway sections exposed to  
742 surface runoff. These results suggest that the IRIP method could help performing risk assessment  
743 studies. Similar results were obtained for another railway line, a 80 km railway stretch from Rouen to  
744 Le Havre (Normandie county) (Lagadec, 2017). The discussion part shows that the IRIP method can  
745 make a direct contribution to numerous tasks in the risk analysis process and suggests some  
746 examples for applications. Moreover, having a better understanding of the surface runoff hazard  
747 opens up new opportunities to push forward the risk reduction method, particularly by managing  
748 surface runoff issues at the origins of the problems, outside the railway right-of-way. Integrating the  
749 IRIP method into the current process and more generally, integrating a new tool into current working  
750 processes can be challenging. However, the innovation part, between the research and the  
751 development process, is essential for achieving a real improvement, which in our case would be a  
752 sustainable development of the railway network in its environment.

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755

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