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).

a. Embankment   b. Excavation   c. Mixed profile

53
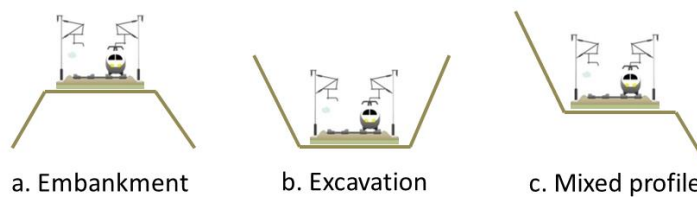
54   Figure 1: Three types of transversal profiles of the railway infrastructure

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 where 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 km², 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.
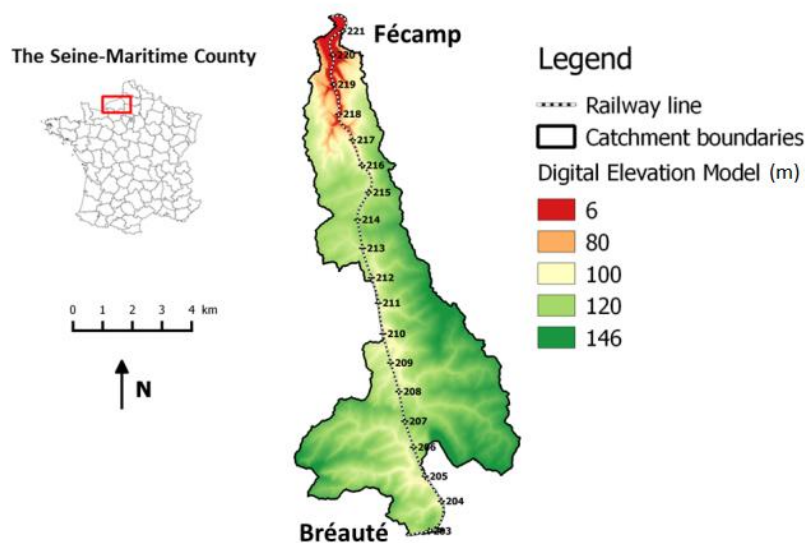
202

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.
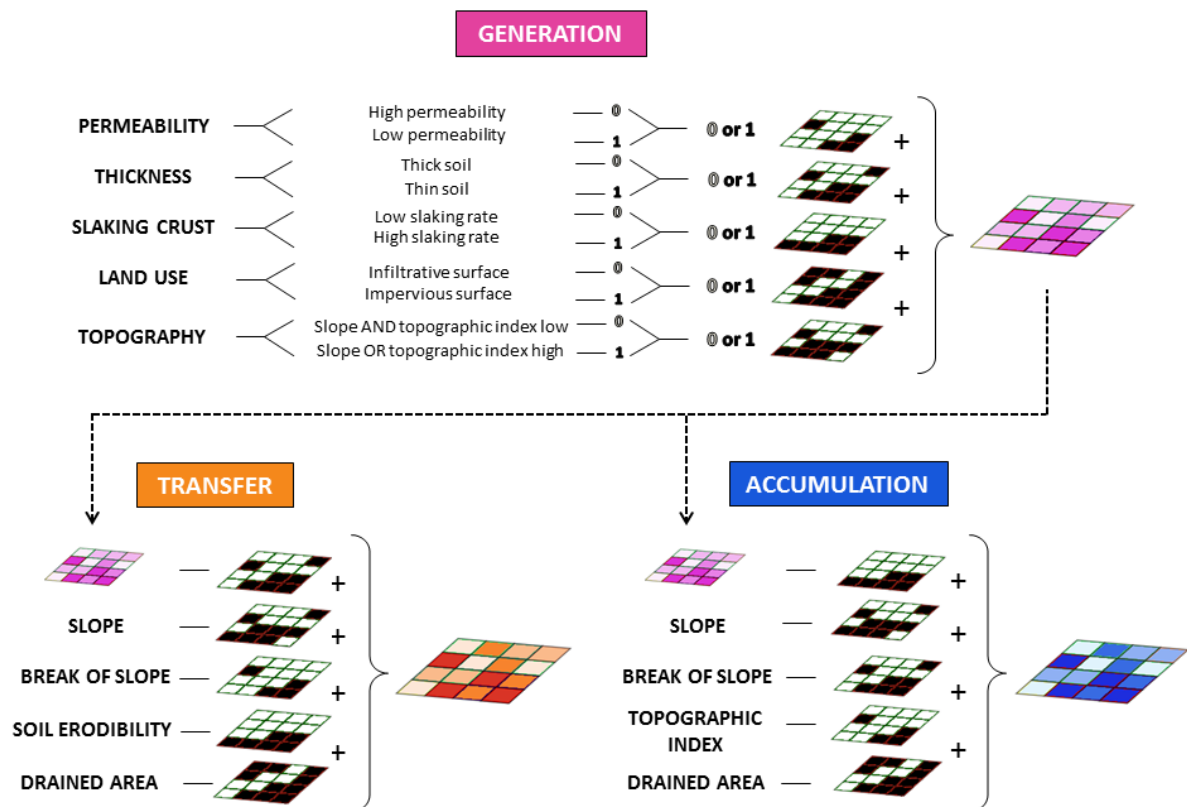
260

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 (Ks) ≥ 1e-6 m/s
		1: Ks < 1e-6 m/s
	Soil thickness	0: Thickness ≥ 50 cm
		1: Thickness < 50 cm
	Soil crustability	0: Crustability < 3 (Cerdan et al., 2006)
		1: Crustability ≥ 3
	Topography	0: Slope ≤ 0.5% AND topographic index ≤ (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 ≥ 3/5
	Slope	0: Slope ≤ 5%
		1: Slope > 5%
	Break of slope	0: Concave break of slope
		1: Convex break of slope
	Drained area	0: Drained area ≤ (mean + standard deviation)
		1: Drained area > (mean + standard deviation)
	Soil erodibility	0: Erodibility < 3
		1: Erodibility ≥ 3
Accumulation	Upstream generation susceptibility	0: Modal value of the upstream sub-catchment < 3/5
		1: Modal value of the upstream sub-catchment ≥ 3/5
	Slope	0: Slope > 5%
		1: Slope ≤ 5%
	Break of slope	0: Convex break of slope
		1: Concave break of slope
	Topographic index	0: Topographic index ≤ (mean + standard deviation)
		1: Topographic index > (mean + standard deviation)
	Drained area	0: Drained area ≤ (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[1]), the European Soil Database at 500 meters resolution created from the LUCAS

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[1] IGN Website : http://professionnels.ign.fr/

269   database (Ballabio et al., 2016), and the regional land use map[2] 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[3]), 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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[2] Website to download the regional land use map and further information about its creation:
http://mos.hautenormandie.fr/
[3] 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	$\dfrac{(T+)}{(T+)+(F-)}$	Range: $0-1$ Best score: 1
FAR	$\dfrac{(F+)}{(F+)+(T+)}$	Range: $0-1$ Best score: 0
Chi-Square	$\sum \dfrac{(O-E)^2}{E}$ O = Observed headcounts E = Expected headcounts	For 1 degree of freedom: $P(X_2>6.63)=0.01$ $P(X_2>7.88)=0.005$ $P(X_2>10.83)=0.001$

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.

15

No.	Type	Linear (m)	Selected for works	Σ Acc 4&5	Σ 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

16

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.

434
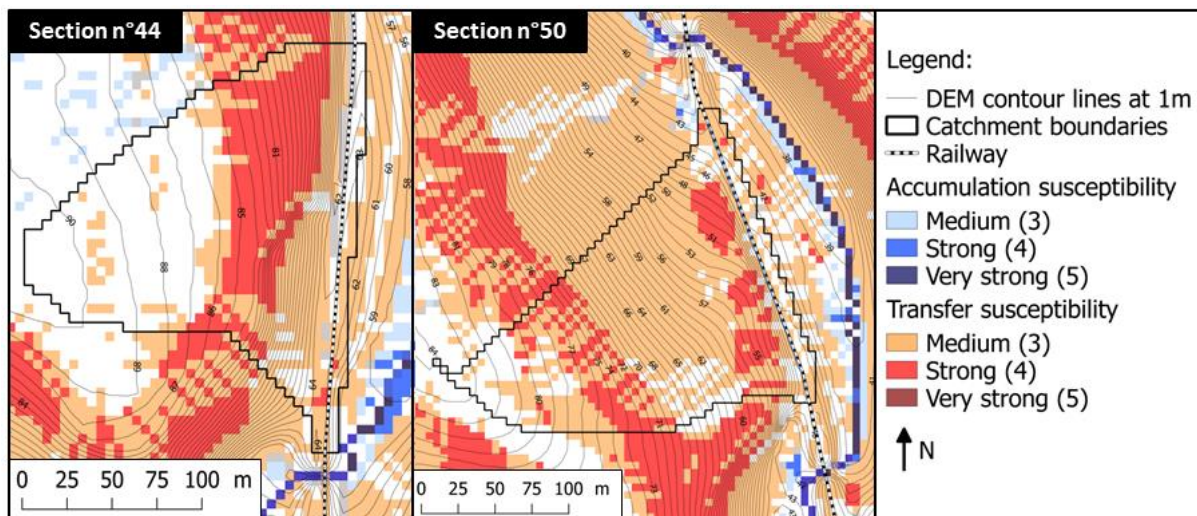
435 Figure 5: The two false negatives correspondences, where the conditions to consider a railway

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 m² 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
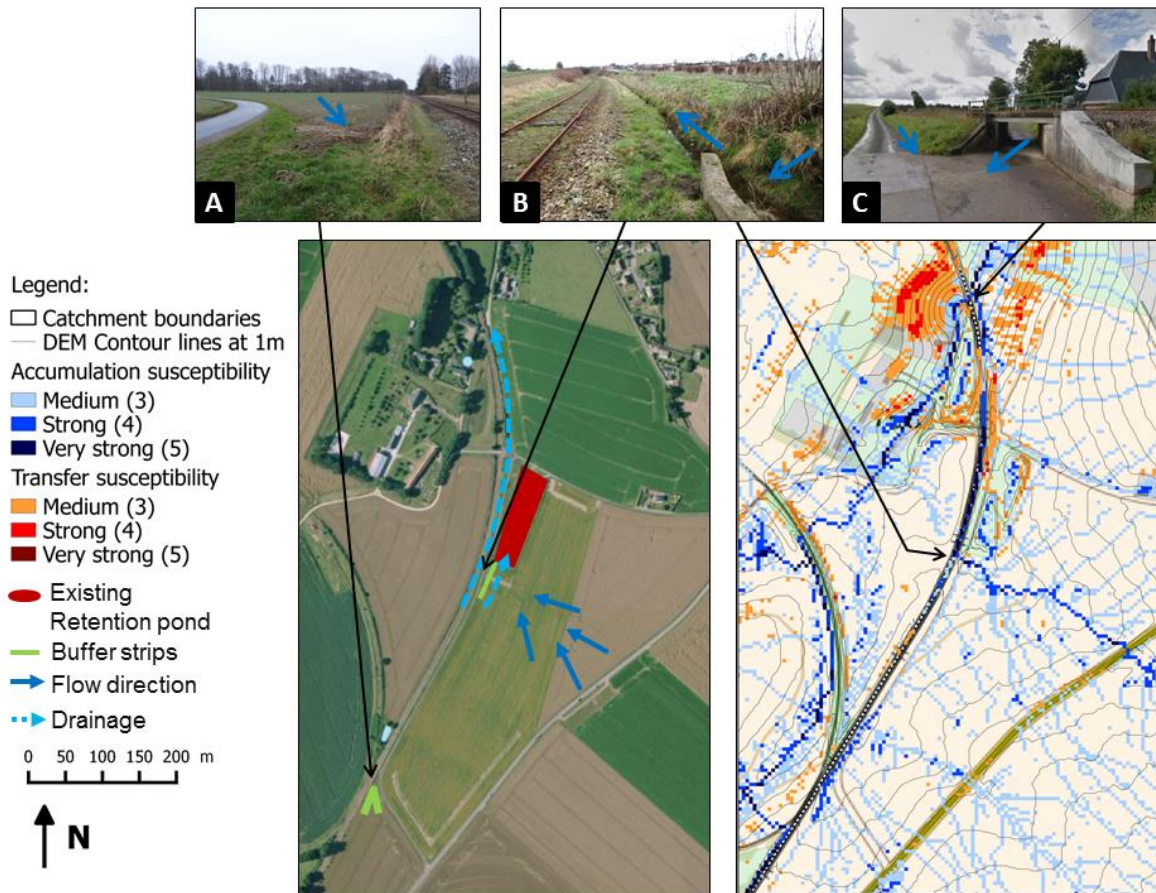469   3.2.1.   Railway section no. 9
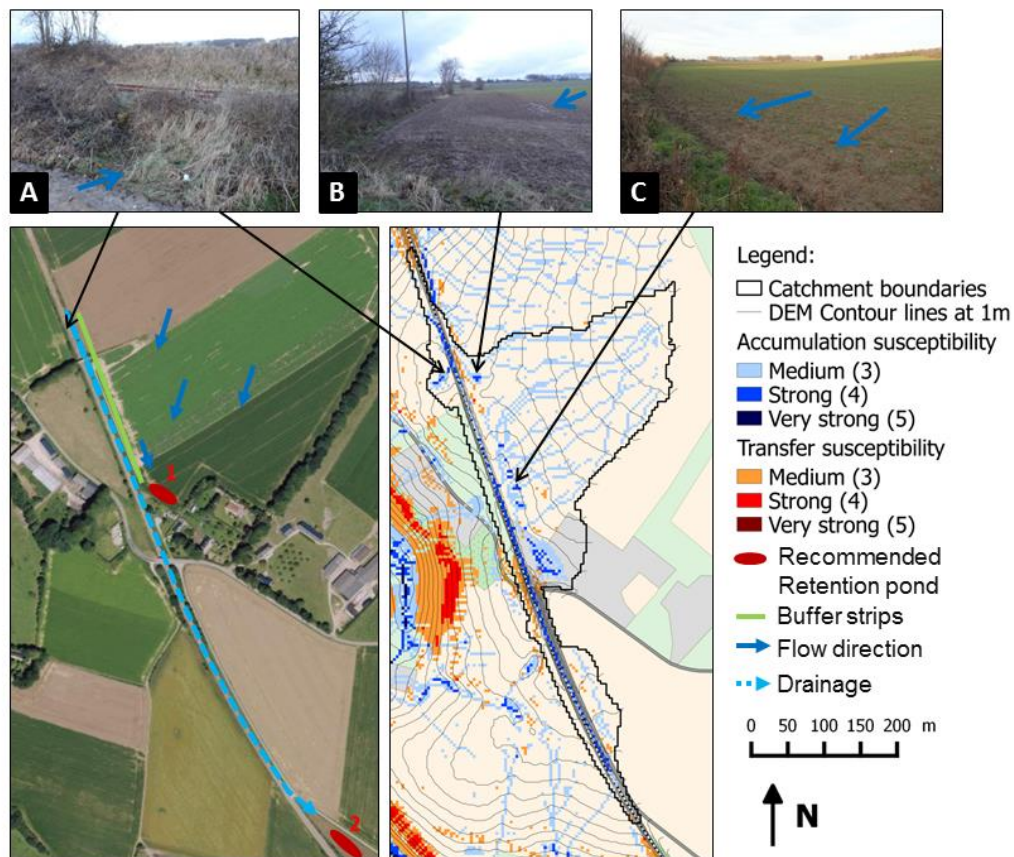
470

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
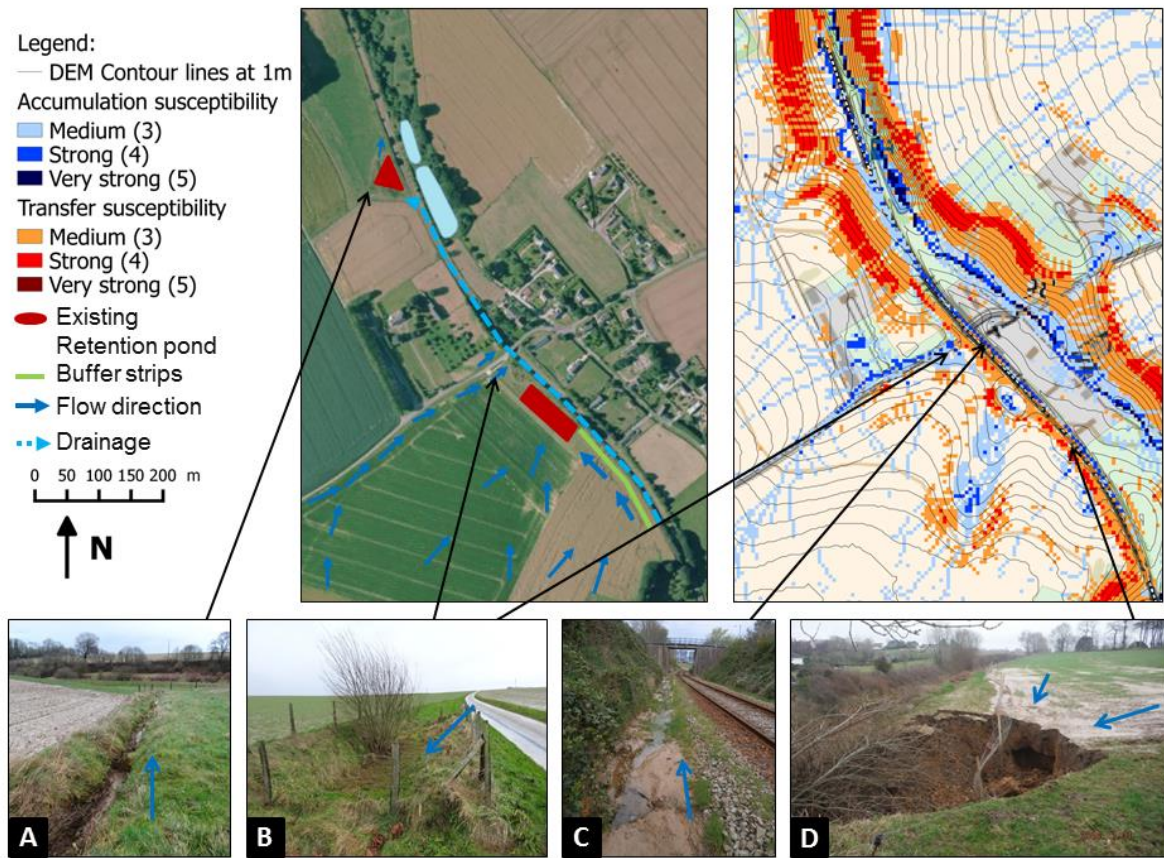

503

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 km², 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.
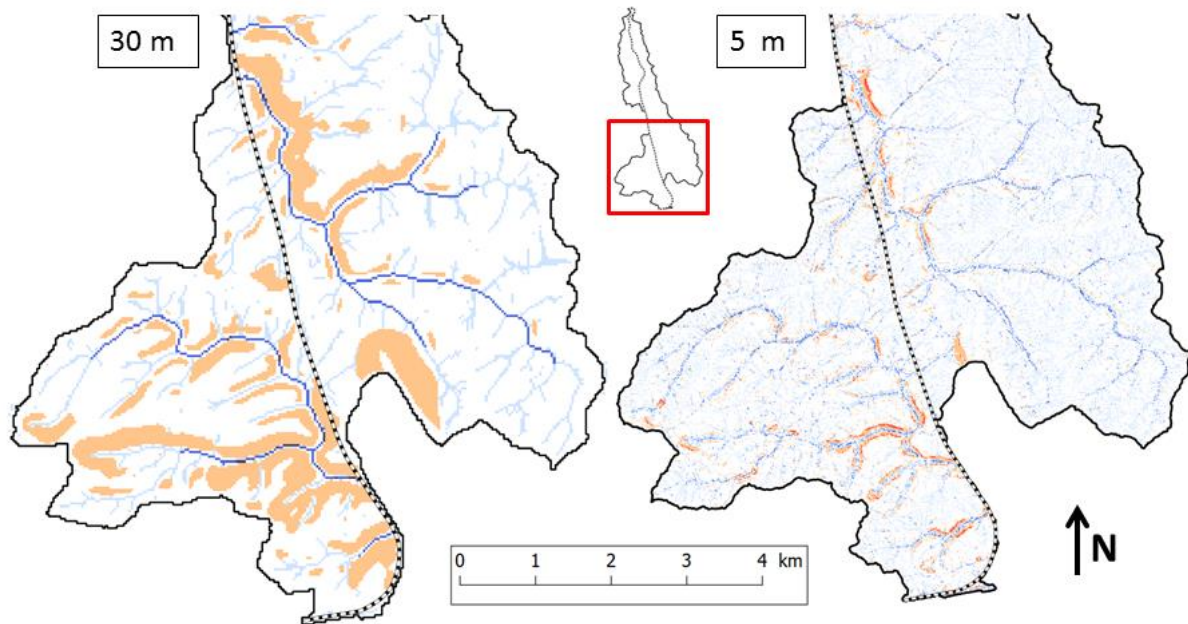
621

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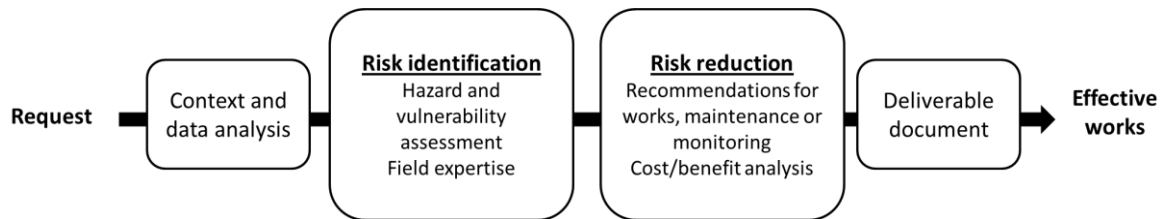
639   Figure 10: General scheme of the risk assessment process to manage hydraulic risks on the railway

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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