Description and evaluation of a surface runoff susceptibility mapping method

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20   network

Abstract

21   Surface runoff is the hydrological process at the origin of phenomena such as soil erosion, floods out

22   of rivers, mudflows, debris flows and can generate major damage. This paper presents a method to

23   create maps of surface runoff susceptibility. The method, called IRIP (Indicator of Intense Pluvial

24   Runoff, French acronym), uses a combination of landscape factors to create three maps representing

25   the susceptibility (1) to generate, (2) to transfer, and (3) to accumulate surface runoff. The method

26   input data are the topography, the land use and the soil type. The method aims to be simple to

27   implement and robust for any type of study area, with no requirement for calibration or specific

28   input format. In a second part, the paper focuses on the evaluation of the surface runoff

29   susceptibility maps. The method is applied in the Lézarde catchment (210 km², northern France) and

30   the susceptibility maps are evaluated by comparison with two risk regulatory zonings of surface

31   runoff and soil erosion, and two databases of surface runoff impacts on roads and railways.

32   Comparison tests are performed using a standard verification method for dichotomous forecasting

33   along with five verification indicators: accuracy, bias, success ratio, probability of detection, and false

34   alarm ratio. The evaluation shows that the susceptibility map of surface runoff accumulation is able

35   to identify the concentrated surface runoff flows and that the susceptibility map of transfer is able to

36   identify areas that are susceptible to soil erosion. Concerning the ability of the IRIP method to detect

37   sections of the transportation network susceptible to be impacted by surface runoff, the evaluation

38   tests show promising probabilities of detection (73 to 90%) but also high false alarm ratios (77 to

39   92%). However, a qualitative analysis of the local configuration of the infrastructure shows that

40   taking into account the transportation network vulnerability can explain numerous false alarms. This

41   paper shows that the IRIP method can be a valuable tool to facilitate field analysis and perform

42   surface runoff zonings and opens interesting prospects for the use of the IRIP method in a context of

43   risk management.

44   **1. Introduction**

45   Intense surface water runoff is a hydrological process which can generate major damage. When the

46   surface water concentrates, it gains enough energy to erode soil particles, which makes the water

47   denser and more powerful (Wischmeier, 1959). Intense surface runoff includes phenomena such as

48   soil erosion, floods out of river networks, mudflows, and debris flows. According to the Gaspar

49   French database[1], which collects information on natural disasters at a district level, around 40% of

50   flood damage is due to intense surface runoff in France (Dehotin and Breil, 2011a). Surface runoff

51   often impacts populations and infrastructures such as homes or transportation networks (Chazelle et

52   al., 2014). The environment can also be impacted by surface runoff through soil loss and the transfer

53   of pollutants contained in soils.

54   For this study, surface runoff is defined as water from precipitation which does not infiltrate into the

55   soil and flows on the surface until it reaches a permanent river. This hydrological process can also be

56   called overland flow (Hewlett, 1982). Two surface-runoff generation processes can be distinguished:

57   infiltration excess overland flow, when the rain intensity is higher than the soil infiltration capacity,

58   called hortonian runoff (Horton, 1933); and saturation overland flow, when soil storage capacity is

59   limited or the soil is already saturated (Hewlett and Hibbert, 1967). These processes are difficult to

60   observe in the field because they occur quickly and they can occur simultaneously (Cros-Cayot,

61   1996). In general terms, surface runoff is a difficult-to-measure phenomenon (Dehotin et al., 2015).

62   Once surface water flows downstream, it can infiltrate, be transferred or be accumulated –

63   depending on topographical and micro-topographical features – or join a watercourse or drainage

64   system. Surface runoff can flow in a diffuse or concentrated manner. Many factors can influence or

65   reduce surface runoff in a catchment: soil characteristics (type, thickness, roughness, permeability)

66   (Piney, 2009), initial water content, land use (vegetation, urbanization, agricultural land), geology

67   (Onda et al., 2001), topography, geomorphology (ability to concentrate, plateau/valleys distribution)

68   (Douvinet et al., 2008), and rainfall characteristics (intensity, frequency, duration) (Galevski, 1955).

69   In the field of risk management, some terms can have a wide range of definitions, depending on the

70   field of application (Christensen et al., 2003; Thywissen, 2006). The following definitions are retained.

71   Firstly, intense surface runoff is a natural hazard, which means a natural event, potentially

72   dangerous, occurring randomly in space and time (UNDRO, 1979). Risks induced by intense surface

73   runoff are impacts that surface runoff may potentially cause to society (people, goods, environment,

74   economy, etc.). A risk is the combination of a hazard and a vulnerability (UNDHA, 1992). Vulnerability

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[1] https://www.data.gouv.fr/fr/datasets/gaspar/

75   is often defined as a measure to assess the quantity of loss potentially generated by a hazard (Buckle

76   et al., 2000; Society for Risk Analysis, 2015). In this study, the vulnerability of the transportation

77   network refers to its structural vulnerability; the higher the vulnerability, the higher the possibility of

78   being physically damaged.

79   In the scientific literature, there are many models for the simulation or mapping of surface runoff

80   processes. They may be classified into various approaches: naturalistic, topographic, a combination

81   of criteria or hydrological modeling. Naturalistic approaches often provide results consistent with the

82   reality but they require a very good understanding of the study area, can be applied to rather small

83   areas, and are difficult to replicate (Abudi et al., 2012; Dehotin et al., 2015a; Holzmann and Sereinig,

84   1997; Tetzlaff et al., 2007). Topographical approaches using information from Digital Elevation

85   Models (Delahaye et al., 2002; Langlois and Delahaye, 2002; Pons et al., 2010) have the advantage of

86   being simple and can be automated but the mapping of surface runoff needs to take into account

87   many other parameters such as land use or soil type. Criteria combination approaches also remain

88   relatively straightforward while taking into account multiple parameters. The review of existing

89   methods reveals that most of them focus on water erosion or landslide (Akgun and Türk, 2010;

90   Faulkner et al., 2010; Guillobez et al., 2000; Le Bissonnais et al., 2002; Schmocker-Fackel et al., 2007).

91   Hydrological modeling techniques are both accurate and provide quantitative results including the

92   time evolution of the processes (Carpenter et al., 1999; Cerdan et al., 2002; Dabney et al., 2011;

93   DeRoo et al., 1996; Laflen et al., 1991; Smith et al., 1995). Some are extremely complex. They require

94   significant computational time, calibration to be applied to different catchments, and a large quantity

95   of data. This rapid overview shows that there are multiple methods for surface runoff mapping but

96   the maps are either difficult to reproduce automatically, need many complex input data, or the

97   method is focused on a specific phase of the phenomenon (the accumulation areas, the low

98   infiltration areas or the erosion areas) and do not address all the aspects of the entire runoff process.

99   For this reason, a method called IRIP for Indicator of Intense Pluvial Runoff (French acronym) has

100   been developed to produce comprehensive mapping of areas susceptible to generate, to transfer,

101   and to accumulate surface runoff without explicit hydrological modeling and using open access data

102   (Dehotin et al., 2015a; Dehotin and Breil, 2011a). This automatic method can be applied to a large

103   range of study area sizes with data at various resolutions. However, the validity and relevance of the

104   produced maps must be evaluated carefully and rigorously.

105   The evaluation of hazard models is an important step in model developments. Indeed, model outputs

106   can be used for stakeholder decision-making in risk management. The stakes are very high (cost of

107   structural and organizational adjustments, safety risks) and wrong decisions can lead to serious

108   consequences. It is essential to know the exact value of model outputs, that is, the assumptions

109 made, the application range, and uncertainties related to the results. Globally, model evaluation

110 suffers from a lack of methodological guidelines (Moriasi et al., 2007). For surface runoff hazard

111 models, the evaluation is particularly complex because of the lack of surface runoff data. The

112 phenomenon rapidity and scarcity make large-scale observation and instrumentation a complex issue

113 (Dehotin et al., 2015a; Hudson, 1993). The IRIP method has already undergone numerous evaluations

114 using in-situ measurements (Dehotin et al., 2015a; Laverne, 2013) and discharge data (Arnaud and

115 Dehotin, 2011; Legros, 2014) but to go further in the evaluation procedure and to assess the

116 relevance of the IRIP method from the point of view of risk assessment, the use of proxy data is

117 suggested. Proxy data are data which are not direct measurements of the phenomenon but are

118 related to it and provide large-scale evidence of the phenomenon occurrence (IPCC, 2003). Some

119 studies in hydrology use proxy data to evaluate models, such as flooded road reports (Naulin et al.,

120 2013; Versini et al., 2010a, 2010b), observations of gravitational hazards in mountainous areas

121 (Defrance, 2014), and post-event surveys (Javelle et al., 2014; Ortega et al., 2009). Concerning the

122 IRIP method evaluation, few comparisons have been performed with proxy data such as surface

123 runoff impact locations on railways (Dehotin et al., 2015b) and natural disaster declaration locations

124 from the Gaspar French database (Dehotin and Breil, 2011a). However, these tests have been

125 performed for few case studies and remain qualitative. Indeed, the comparison between model

126 outputs and proxy data generates technical issues: for example, how can data that are different in

127 form and content and that do not carry the same information be compared reliably? The use of proxy

128 data highlights the lack of methodological framework but also shows the valuable contribution of this

129 type of data for model evaluation.

130 The first objective of this paper is to present the IRIP method for surface runoff susceptibility

131 mapping. The second objective is to evaluate the IRIP maps by comparison with different types of

132 proxy data available on the study area: regulatory zonings of surface runoff and soil erosion and

133 databases of surface runoff impacts on roads and railways. The paper proposes an evaluation

134 method that allows quantitative evaluation of the spatial information contained in the IRIP maps.

135 Finally, development paths are discussed to adapt the IRIP method as a tool for risk management.

2. Materials and Methods

2.1. The IRIP Method

138 IRIP is a method to map the spatial distribution of areas susceptible to surface runoff. The IRIP

139 method concept is based on the creation of three susceptibility maps which represent surface runoff

140 generation, transfer, and accumulation. Note that, to obtain a hazard map, the rainfall must be taken

141 into account and to get a risk map, the hazard map must be combined with the stakes of the study

142   area and their vulnerabilities. These two aspects are not considered in the present study, which only

143   focuses on the susceptibility maps provided by the IRIP method.

144   Each susceptibility map (generation, transfer, and accumulation) is created by combining five

145   indicators, summarised in Table 1 (columns 1&2). Each indicator is classified in two categories

146   favourable (1) or not favourable (0) to surface runoff (Table 1, col 3), providing a binary map. The five

147   maps are subsequently assembled to produce a surface runoff susceptibility map from 0 (not

148   susceptible) to 5 (very susceptible). This method is applied for the three IRIP maps, as represented in

149   Figure 1. After reclassification, the generation map becomes an input indicator for the two other

150   maps of transfer and accumulation. The reclassification proceeds as follows: a pixel is favourable

151   (score = 1) if the generation susceptibility levels in its relative drained area have a mode (the most

152   present value of the distribution) higher than a user-defined susceptibility level (3 by default). The

153   use of the generation map as an input for the two others means that susceptibility to transfer or

154   accumulation is conditioned by a sufficiently high susceptibility for surface runoff generation. This

155   allows the incorporation of an upstream-downstream logic in the maps. For each map, the five

156   indicators have been chosen based on field knowledge (Dehotin et al., 2015a), literature review

157   (Dehotin and Breil, 2011b), and multiple combination tests.

158   For the surface runoff generation map, the five indicators are derived from factors influencing runoff

159   generation: soil properties, topography, and land use. Three indicators represent the impact of soil

160   properties and are based on soil erosion model parameters (Le Bissonnais et al., 2002; Le Gouee et

161   al., 2010; Nearing et al., 1989). The erodibility indicator in the generation map represents the

162   possibility of the generated surface water combining with soil particles to generate a mudslide

163   (Cerdà and Doerr, 2008). For agricultural plots, the erodibility indicator also represents the

164   susceptibility of soils to create slaking crusts that are favourable to surface runoff generation. The

165   topography indicator is an "or" combination of the slope and the topographic index, that is, the

166   topography indicator is favourable if the slope is steep, if the topographic index is high, or both.

167   Steep slopes are considered as favourable to surface runoff generation reflecting the reduced ability

168   of water to infiltrate into the soil. The topographic index (Beven and Kirkby, 1979), $ln(a/tanb)$, where

169   a is the upstream drained area and b is the local slope, reflects the capacity at one point to evacuate

170   water from upstream, that is, water storage-prone areas. Although the topographic index also uses

171   the slope, the topography indicator in the IRIP method combines two different effects: slope and

172   ability to store water. In order to be able to apply the method in every catchment without local

173   knowledge, relative thresholds (t_1, t_2) are used to distinguish topographic indicators (slopes,

174   topographic index) as favourable or not. For each indicator, the distinction is made thanks to

175   classification algorithms (MacQueen, 1967; Reuter et al., 2006). It permits dividing the study area

176   into two categories of slopes or topographic indices depending on the local and surrounding pixel

177   values. The land use indicator reflects the fact that urban and agricultural areas are considered as

178   favorable to surface runoff generation. For urban areas, the generation map is recalculated to force

179   soil permeability and thickness to be favourable in those areas, in the event that the areas have not

180   been classified as favourable from the indicators derived from the soil map.

181   The susceptibility maps of surface runoff transfer and accumulation reflect surface water natural-

182   flow dynamics. Both involve different mechanisms, acting often in the opposite direction, such as

183   slope and break of slope. This is why two maps are created. The choice of the corresponding

184   indicators is based on detailed analyses of past intense surface runoff events (Dehotin and Breil,

185   2011b) where slope, break of slope, catchment compactness, and artificial linear axes appeared as

186   main factors to produce intense phenomena. The computation of the break of slope proceeds as

187   follows: in each pixel, the mode of the slope value distribution in the upstream area drained by this

188   pixel is computed and compared to the local slope value of the pixel. If the upstream slope mode is

189   smaller (respectively higher) than the local slope, the pixel is indicated as convex (respectively

190   concave), and is assigned 1 for the transfer map (1 for the accumulation map). The transfer map uses

191   the Horton form factor (Horton, 1932), which is the ratio of area to length of the sub-watershed

192   defined by the drained area at the considered pixel. The artificial linear axes are taken into account in

193   the transfer map because of their role in surface runoff interception and displacement (Cerdà, 2007;

194   Pams-Capoccioni et al., 2015).

195   Finally, the input data of the IRIP method are: a DEM, a land use map, a soil map, and optionally the

196   artificial drainage network (Figure 1). The input data resolution can be adapted to the size of the

197   study area. For a relatively large study area, the analyst can proceed as follows: maps can be initially

198   produced for the whole study area with a coarse resolution DEM (i.e. cells larger than 10 meters) and

199   then areas susceptible to surface runoff can be focussed on with a higher resolution DEM (i.e. cells

200   smaller than 10 meters). These susceptibility maps reflect a certain description of the surface runoff

201   mechanisms in a watershed. Given the considered indicators, the IRIP map of surface runoff

202   generation highlights the areas more susceptible to generate water on the soil surface. The IRIP

203   transfer map highlights the areas where surface water can move and gain speed, and the IRIP map of

204   accumulation highlights the areas where there is a tendency for a reduction in surface water velocity

205   and water level increases. The method aims to be simple to implement, using open-access input data

206   and to be robust regardless of the data quality and uncertainty. This is the reason why more complex

207   methods such as weighting the indicators or classifying them into more than two categories were not

208   retained in the first version of the method. However, the method remains open for adaptation

209   regarding the user knowledge, but the default parametrization permits applying the method

210   whatever the study area. In this paper, the relevance of the IRIP maps is assessed based on this first

211   version of the method.

2.2. The Study Area

213   The Lézarde catchment (210 km²), located between the English Channel and the Seine river, is well-

214   known for being subject to flooding predominantly generated by surface runoff (Delahaye et al.,

215   2002; Douvinet et al., 2014; Le Gouee et al., 2010). The catchment morphology is composed of large

216   plateaux and narrow valleys (Figure 2). The permanent hydrographic network is very short but the

217   temporary network consists of an extremely dense talweg network. The area was formed during the

218   last glacial era during which the ice melt eroded the soil surface (Auzet et al., 1993). Soil

219   characteristics of the catchment are mostly silt and clay with flint stones. Locally, there are sandy

220   loams that increase soil erosion processes. The geology of the territory is composed of karst which

221   forms a complex active underground river network (Hauchard and Laignel, 2008). The climate of the

222   whole Seine-Maritime region is characterised by two main rainfall seasons: summer and autumn. In

223   summer, rainfall durations are shorter than in autumn but more intense, whereas in autumn the

224   rainfall patterns are less intense but last for long periods, leading to soil saturation (Douvinet, 2008).

225   These two rainfall patterns can both generate storm runoff floods but involve different mechanisms.

226   In terms of land use, a large part of the Lézarde catchment is made up of agricultural areas. A soil

227   crusting process takes place between planting cycles, influenced by an exposed and high silt rate in

228   the top soil, making the soil surface almost impervious (Robinson and Phillips, 2001). In addition,

229   roads and villages were built in exposed areas: many roads are located in talwegs and villages are

230   located at the downstream end of catchments or sub-catchments. Consequently, flooding in the

231   catchment tends to generate major damage.

232   In the Lézarde catchment, the IRIP maps were produced using a 25-meter DEM from the French

233   National Institute of Geograhy[2]. The land use map[3] is on the scale of 1/5000 in rural areas and 1/2000

234   in urban areas. The soil map is the pedologic map from the French National Institute for Agronomic

235   Research (INRA) at the scale of 1/1000000 (Dupuis, 1969). To calibrate the method in the Lézarde

236   catchment, some assumptions are made based on literature review, discussions with local

237   stakeholders and multiple tests on the IRIP maps. For the soil indicators, the distinction between

238   favorable or not is based on soil data analysis (Daroussin and King, 1997; Jamagne et al., 1995). The

239   slope threshold for the distinction between favorable or not was fixed at 4%, based on surface runoff

240   studies on the Lézarde catchment (Hauchard, 2002). For the land use indicator, the urbanized and

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[2] http://professionnels.ign.fr/bdalti
[3] http://mos.hautenormandie.fr/Presentation

8

241   the agricultural areas are considered as favorable to surface runoff (Hauchard et al., 2002). For the

242   Horton form factor, the index is considered as favorable to surface runoff transfer for values larger

243   than 0.15 (fixed from tests with IRIP maps). Only roads and railways are used for the artificial linear

244   axes, as data on agricultural drainage are not available at this scale. The flow accumulation threshold

245   was chosen at 0.5 ha, a value small enough to detect surface runoff close to the catchment head.

246   These choices are explained further in the discussion and perspectives section.

2.3. The Comparison Data

248   The data sets used for the evaluation of the surface runoff susceptibility maps are presented here.

249   Four data sets are used: two regulatory zonings of surface runoff and erosion risks and two data sets

250   of surface runoff impacts on roads and railways networks. The two regulatory zonings are provided

251   by the agglomeration of Le Havre[4] and the local association of the Pointe de Caux Catchment[5]

252   (SMBV) respectively. They are part of the natural risk prevention plan (Departmental Directorate of

253   Seine-Maritime, 2013a; Departmental Directorate of Seine-Maritime, 2013b). These regulatory

254   zonings take into account both exposure of assets at risk and their probability of damage. The

255   database of surface runoff impacts on roads is provided by the SMBV and the database of surface

256   runoff impacts on railways is provided by the French National Railway Company (SNCF Réseau).

2.3.1.   The Surface Runoff Regulatory Zoning

258   The surface runoff zoning was established in a qualitative manner. All the surface runoff axes, where

259   water can concentrate (i.e. the dry talwegs), were identified by field expertise and historical

260   information on past events (Hauchard, 2002). Then, to create the surface runoff zoning, a buffer area

261   around surface runoff axes was designed. The buffer size ranges from 5 to 80 meters and the value

262   was locally chosen thanks to field knowledge. Finally, hydrological modeling was used only in areas

263   with high exposure levels to obtain water levels and flow velocities, but the latter information is not

264   used in the evaluation procedure, where only the zoning map is used. This zoning map does not take

265   into account the presence of protection structures against floods.

266   For the comparison with IRIP, the surface runoff zoning is compared with the IRIP map of surface

267   runoff accumulation susceptibility. The zoning is created from the dry talweg axes, which are axes of

268   water concentration and where, locally, water velocity reduces and subsequently water depth

269   increases. This effect is included in the IRIP map of accumulation and is represented by the IRIP

270   indicators: flow accumulation, topographic index, and concave break of slopes. For the comparison

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[4] http://www.codah.fr/article/lutte-contre-les-inondations
[5] http://www.smbv-pointedecaux.fr/web/decret_erosion2.html

271   tests, the permanent hydrographic network is also masked. Indeed, the accumulation map also

272   detects the rivers but the comparison rather focuses on hillslopes where surface runoff occurs.

2.3.2.   The Soil Erosion Regulatory Zoning

274   The soil erosion zoning was created using two soil erosion models: the RUSLE model from USDA

275   (Dabney et al., 2011) and the STREAM model from INRA (Cerdan et al., 2002). The models have been

276   adjusted using erosion traces from aerial photographs. The results of the two models have been

277   combined and validated by knowledge from local experts. The soil erosion hazard map was crossed

278   with a map of the territory vulnerabilities to obtain the soil erosion zoning map.

279   For the comparison with IRIP, the soil erosion zoning is compared with the IRIP map of surface runoff

280   transfer susceptibility. Indeed, the soil erosion is a process influenced by the occurrence of surface

281   runoff with a water level and a speed sufficient to transport materials. This effect is included in the

282   IRIP map of transfer and is represented by the IRIP indicators: compactness index and convex break

283   of slopes. For the comparison tests, the urban areas are masked because the regulatory zoning

284   focuses on rural areas.

2.3.3.   The Databases of Impacts on Transportation Networks

286   The database of flooded roads is made up of 31 road sections and was created after an intense

287   rainfall event by witness interviews and field expertise. On October 13, 2013, the Lézarde catchment

288   was subject to a significant rainfall event, generating intense surface runoff. The return period of the

289   event was estimated to be more than a hundred years by the Predict weather services (Gouvazé and

290   SMBV, 2013). The high-intensity rainfall affected mainly the three sub-catchments located in the

291   north of the Lézarde catchment, upstream of the Lézarde River (highlighted in yellow in Figure 3). Up

292   to 70 mm fell in 6 hours in this area and the three rain gages (1, 2, 3) recorded 160, 156 and 100 mm

293   respectively in 24 hours. Thus the comparison tests focus only on these 3 sub-catchments. The road

294   sections in the database were temporarily cut off by floodwater and impracticable or even swept

295   away by floodwater (photos at the bottom of Figure 3).

296   The database of impacts on the railway is made up of 41 incidents listed from 1995 to 2012. These 41

297   incidents are observed in 21 railway sections, the incidents occurring sometimes at the same

298   location. This database is not exhaustive and contains uncertainties on incident locations, particularly

299   in relation to the source of flooding and the length of railway that was affected. The recorded types

300   of incidents are embankment erosion, flooded platforms or mudslides. For the comparison tests,

301   these two databases are compared to the IRIP maps of transfer and accumulation susceptibility,

302   because we assume that accumulation as well as transfer of water can generate damage.

303   This section highlights that the four data sets differ greatly in form and content. The next section

304   describes the methodology used to compare these four data sets to the IRIP surface runoff

305   susceptibility maps.

306   **2.4. The Evaluation Method**

307   To evaluate the IRIP method, the surface runoff susceptibility maps are compared to a set of

308   comparison data. In this section, the comparison tests and the verification indicators are presented,

309   as well as the data formatting process that is required to compare different data types.

310   2.4.1.   Comparison Tests

311   To assess the correspondence between the IRIP maps and the comparison data, contingency tables

312   are created and associated verification indicators are computed. This method is inspired by the

313   standard verification methods for dichotomous (yes/no) forecasts (Hogan and Mason, 2012; Stanski

314   et al., 1989). Table 2 shows the theoretical contingency table created for each comparison test. The

315   "observed event" columns represent information from the comparison data. For example, in the case

316   of the zonings, "yes" means inside the zoning and "no" means outside. In the case of the impact

317   databases, "yes" means the impacted network section and "no" means the remaining parts of the

318   transportation network that were not impacted. The "IRIP" lines represent information from the IRIP

319   maps. For the tests, the IRIP maps are converted into dichotomous results, with "yes" being pixels

320   with a susceptibility level greater than or equal to 4 and "no" being pixels lower than 4. The

321   threshold of 4 is chosen regarding the low proportion of susceptibility level values of 4 and 5 over the

322   catchment. Pixel values of 4 and 5 represent 4% of the study area in average, whereas pixel values of

323   3 represents 30% of the study area. In the theoretical contingency table, for comparisons with the

324   regulatory zonings (respectively, comparisons with the impacts on the transportation network), true

325   positives are IRIP pixels with high susceptibility levels located inside the zonings (resp. inside the

326   impacted network sections). True negatives are IRIP pixels with low susceptibility levels located

327   outside the zonings (resp. inside the not impacted network sections). False positives are IRIP pixels

328   with high susceptibility levels located outside the zonings (resp. inside the not impacted network

329   sections). Finally, false negatives are IRIP pixels with low susceptibility levels located inside the

330   zonings (resp. inside the impacted network sections). From the contingency tables, five verification

331   indicators are computed: accuracy, bias, success ratio (SR), probability of detection (POD), and false

332   alarm ratio (FAR). POD and FAR are computed only when comparing with the impacts on the

333   transportation network, in order to assess the ability of the IRIP method to detect areas susceptible

334   to be impacted. The indicators are presented in Table 3 along with the formulas and the result

335   interpretations.

336   2.4.2.   Data Formatting

337   Concerning comparison tests with the regulatory zonings, the surface runoff regulatory zoning is

338   compared with the IRIP map of accumulation susceptibility. The soil erosion zoning is compared with

339   the IRIP map of transfer susceptibility. For each comparison, the contingency table is computed by

340   using two different thresholds of IRIP susceptibility level: for pixel values greater than or equal to 4

341   and for pixel values of 5 only. Moreover, for each comparison, the contingency table is computed by

342   using three different sizes of buffer area around the zonings: 0, 25, and 50 meters. Buffer areas are

343   used in order to compensate for uncertainties in data comparison. Uncertainties can come from the

344   fact that different data formats are compared (raster for the IRIP map and polygons for the zonings).

345   This can lead to uncertainty when overlapping the data. Uncertainties can also come from the input

346   data used for the creation of the IRIP maps and the zonings (i.e. DEM resolution). Buffer area sizes of

347   0, 25, and 50 meters correspond to a shift of zero, one or two pixels of the IRIP maps.

348   Concerning the impact databases, comparison tests are performed separately for roads and railways,

349   and for each test, the impact locations are compared with the IRIP maps of transfer and

350   accumulation simultaneously. The comparisons are performed using the transportation network as

351   the reference study area, and not the whole catchment. In order to perform the comparison, the

352   linear transportation networks are transformed to polygons, using a buffer. Two buffer area sizes of

353   25 and 50 meters on both sides of the transportation network were considered. Concerning the IRIP

354   maps, an area is considered susceptible to surface runoff if there is a spatial persistence of pixels

355   with high susceptibility levels, and not if there is only one isolated pixel with a high value. The pixel

356   spatial persistence on the IRIP maps of transfer and accumulation is taken into account as follows: a

357   buffer area of 25 meters is drawn around all pixels of values 4 and 5 and, if an isolated pixel with its

358   buffer area is not intercepted by another buffer, the pixel is removed (Figure 4a). Finally, four

359   contingency tables are computed for roads and railways with two different buffer area sizes around

360   the transportation network, focusing on the overlapping surface between the IRIP maps and the

361   impacted road sections, as presented in Figure 4b.

362

363   **3.   Results**

364   **3.1. Application of the IRIP method in the Lézarde catchment**

365   The susceptibility map of surface runoff generation (Figure 5) shows that the catchment presents a

366   high susceptibility to generate surface runoff. About 88% of the study area has pixels with a score

367   above 3, on a scale ranging from 0 to 5. The pixels with a highest score are located in the urban areas

368 of Le Havre and Montivilliers. We can also see high susceptibility levels in the western part of the

369 catchment and in the valley sides. Although the valley sides are occupied by forest, they present a

370 high susceptibility to generate surface runoff because of soil properties and steep slopes. Despite the

371 flat topography of the plateaux upstream of the catchment, they present a high susceptibility to

372 surface runoff generation with values of 3 and 4 locally because of the soil properties and the

373 agricultural land use. Occupying approximately two thirds of the catchment, these plateaux are

374 responsible for the largest part of the generated surface water.

375 The susceptibility map of surface runoff transfer (Figure 6) mainly shows high levels in the valley

376 sides, where slopes are steep and break of slopes are convex. This map shows low susceptibility

377 values of transfer in the plateaux and in the valley bottom. The high susceptibility areas actually

378 highlight the sides of the main talwegs and a great deal of small talwegs even very close to the head

379 of the catchment.

380 The susceptibility map of surface runoff accumulation (Figure 7) shows that plateaux are prone to

381 accumulate surface runoff with values equal or greater than 3 on a large part of the catchment.

382 These susceptibility levels are due to low slopes, concave break of slopes, and a high topographic

383 index in the upstream portions of the catchment. Permanent rivers are identified with the level 5,

384 and an extremely dense talweg network can be distinguished with the susceptibility levels 4 and 5. In

385 upstream talwegs, susceptibility levels 4 and 5 are still visible but seem to be more spread out. The

386 map highlights that the valley sides are not favorable to surface runoff accumulation in contrast to

387 the map of transfer.

3.2. Evaluation of the IRIP maps

389 In this section, the IRIP maps are first compared to the regulatory zonings, in order to assess the

390 ability of the map of accumulation to identify areas prone to concentrated surface runoff (Figure 8)

391 and to assess the ability of the map of transfer to identify areas prone to soil erosion (Figure 9). Then,

392 the IRIP maps are compared to the databases of impacts on the transportation network to assess the

393 ability of the IRIP method to identify road and railway sections susceptible to be impacted by surface

394 runoff (Figure 10).

395 The superimpositions of the IRIP maps and the two regulatory zonings (Figures 8 and 9) show a good

396 visual correlation and a relevance of the spatial distribution of the IRIP susceptibility levels. Table 4

397 presents the results of the comparison between the two regulatory zonings and the IRIP maps. Six

398 comparison tests are performed for the surface runoff zoning and six for the soil erosion zoning: with

399 the three buffer area sizes and considering pixels of value 4 and 5, and 5 only. Three indicators are

13

400   computed for each test: accuracy, bias, and success ratio. Results show that for that comparison with

401   the surface runoff zoning, the accuracy ranges from 0.68 to 0.86 and, for the comparison with the

402   soil erosion zoning, accuracy ranges from 0.36 to 0.69. Biases for all the tests are lower than 1 and

403   range from 0 to 0.41. The success ratio represents the number of high susceptibility level pixels that

404   are located inside the zoning, regarding the whole study area. It ranges from 0.41 to 0.92. The best

405   success ratio for the accumulation map is 0.92 and is obtained when using a 50-meter buffer around

406   the surface runoff zoning and when considering only pixels with a value of 5. The best success ratio

407   for the transfer map is also 0.92 and obtained with the same conditions. Moreover, a success ratio of

408   0.91 is obtained when considering pixels of value 4 and 5, using a 50-meter buffer. Concerning the

409   comparison with the impacts on the transportation network, Table 5 shows the results of the five

410   verification indicators for the four tests: comparison with the database of impact on roads and with

411   the database of impacts on railways, using two different buffer area sizes for both of 25 and 50

412   meters around the transportation network. For the analysis of impacts on roads, comparison tests

413   show accuracy of about 0.6 and 0.3 for impacts on railways. Biases are greater than 1 and range

414   approximately from 3 to 9. Success ratios are lower than 0.25 for both transportation networks.

415   Probabilities of detection range from 0.7 to 0.9, and figures are similar for the false alarm ratios. The

416   best probability of detection for the impacted road sections is 0.73 using a 25-meter buffer around

417   roads, and the best one for the impacted railway sections is 0.9 using a 50-meter buffer around

418   railways.

419   These results are discussed in the next section in the light of the assumptions made for the

420   comparison tests and in the light of the high false alarm ratios for the comparison tests with the

421   impact databases. Moreover, suggestions are presented to go further in the evaluation method and

422   in the development of the IRIP method.

423

424

425

426   **4.   Discussion and Perspectives**

427   **4.1. Result Discussion**

428   **4.1.1. Comparisons with the Regulatory Zonings**

429   The success ratio is the number of pixels with high susceptibility levels located inside the zonings

430   regarding the total number of pixels with high susceptibility levels in the catchment. So, without

431   using a buffer, obtaining success ratios of 0.72 and 0.64 is already promising. Using a buffer area of

432   50 meters around the zonings makes it possible to obtain success ratios above 0.9. This shows that a

433   large number of high susceptibility IRIP pixels are located very close to the regulatory zonings and

434   that uncertainties in the high susceptibility level locations could be interpreted as between 0 and 2

435   pixels. These success ratios are extremely promising considering that the two maps are created using

436   very different techniques and that they do not focus exactly on the same areas. The soil erosion

437   zoning focuses on agricultural areas, and the surface runoff zoning focuses on talweg axes, whereas

438   the IRIP method takes into account the whole catchment. Different results are obtained when

439   considering pixel values of 5 and pixel values of 4 and 5 together. The choice of the susceptibility

440   level depends on the information sought. Few pixels with a value of 5 are present in the catchment.

441   They underestimate the global sensitivity of the catchment (bias close to zero), but they are more

442   likely to indicate the localization of the areas that are highly susceptible to surface runoff. Concerning

443   the IRIP map of accumulation, Figure 8 shows that the pixels are located precisely inside the zoning in

444   the downstream part of the catchment but, in the catchment headwaters, pixels with a value of 4 are

445   spread and are located outside the zoning. This spatial persistence of pixel values of 4 could indicate

446   the beginning of a talweg that is not well defined in the landscape. Further comparison tests and field

447   analysis must be undertaken to confirm this hypothesis.

448   Moreover, Figure 9 shows that a considerable section of areas contained in the erosion zoning is not

449   correlated with the IRIP map of transfer, but seems to fit with the IRIP map of accumulation (Figure

450   11). Indeed, these areas present lower slopes, concave break of slopes, high topographic indices, and

451   high flow accumulations. The soil erosion zoning gives a map of soils prone to erosion but, depending

452   on the areas, erosion mechanisms and impacts can be different. The transfer map could emphasize

453   incision susceptibility and the accumulation map could localize the deposit areas. Field analysis must

454   be undertaken to better assess the ability of the IRIP maps to identify different erosion processes,

455   but knowing the spatial distribution of the dominant processes could permit adapting the erosion

456   prevention techniques in terms of the mechanisms involved.

457   Finally, the comparison with the two regulatory zonings shows that the maps produced with the IRIP

458   method seems to be relevant in identifying areas susceptible to surface runoff. Moreover,

459   susceptibility levels of 5 seem to indicate with a certainty of 90% an area susceptible to concentrative

460   surface runoff (for the IRIP map of accumulation) and an area susceptible to soil erosion (for the IRIP

461   map of transfer) with a spatial accuracy from 0 to 2 pixels.

462

463

464   **4.1.2. Comparisons with Impacts on the Transportation Network**

465

466   The probability of detection is the ratio of good detection over the total observed impacts. Obtaining

467   probabilities of detection of 0.7 for road impacts and 0.8 for railway impacts is promising. The IRIP

468   method seems to be relevant in identifying areas susceptible to surface runoff. However, success

469   ratios are low due to a significant number of false alarms (i.e. false positives). The highly significant

470   false alarm ratios and the overestimation are discussed.

471   First, these results come from the fact that the IRIP method gives susceptibility maps regarding soil

472   surface predisposition, but the occurrence of a surface runoff-related impact depends on the rainfall

473   spatial variability. For the rainfall event of October 13, 2013, it is assumed that rainfall was spatially

474   homogeneous in the three sub-catchments, but this hypothesis is no more realistic for the railway

475   network because the study area is wider and the database ranges in time from 1995 to 2012, when

476   rainfall events are not likely to have been homogeneous. This can explain why higher false alarm

477   ratios are obtained for the analysis of railway impacts. Moreover, working with proxy data involves

478   uncertainties. For example, the databases may suffer from a lack of exhaustiveness in the number of

479   reported impacts. In that case, impacts only are reported, whereas some network sections could

480   have been affected by floodwater without being damaged and without network managers being

481   informed. In addition to this, high false alarm ratios can come from the fact that the IRIP maps, which

482   represent a susceptibility of surface runoff occurrence, are compared to an impact which is an

483   effective risk. It is essential to take the structural vulnerability of roads and railways into account for

484   a better assessment of the IRIP maps' ability to identify impacted sections.

485   Concerning the impacted roads analysis, more than 40 hydraulic structures are present over the

486   three sub-catchments where intense rainfall occurred on October 13, 2013. They probably played an

487   important role in the protection of the road network. Figure 10 shows the road network of the three

488   sub-catchments along with the hydraulic structure locations. Post-event investigation allowed

489   reporting whether or not the hydraulic structures have played their protective role. Green points

490   indicate that the structure did not overflow; orange points indicate that it overflowed. This

491   information can already explain why some road sections that appear susceptible to surface runoff

492   with the IRIP method have not been reported as impacted. For example, in Figure 12, the A photo

493   (corresponding to the A area on Figure 10) was taken just after the event and shows that the dam

494   closing a reservoir is at one meter below the overflow. Thus, it could have protected this road section

495   against floodwater. Further discussions with the river basin managers helped to explain some other

496   false alarms. Figure 12 shows photos of three road sections (B, C, and E areas can be seen in Figure

497   10) that are considered as false alarms, despite the absence or dysfunction of protective structures.

498   These photos show the configuration of roads within their environment, and give some clues about

499   the vulnerability level of the sections regarding surface runoff. Photo B shows a large drainage ditch

500   along the road. Photo C shows the road slightly elevated and the low point located in the grassland.

501   These observations have been confirmed by the river basin managers. They also attested that the

502   road section in the A area is regularly flooded by surface runoff during intense rainfall events and

503   that the low point in the D area is not located on the road but in the nearby field. The three impacts

504   in the E area present the same configuration, that is, they transversally cut a dry talweg without any

505   crossing structure. Photo E shows one of these intersections which still have the marks of an intense

506   rainfall event, with standing water and soil deposits gathered in a mound. This configuration can

507   explain why IRIP detects smaller susceptible areas than the reported section for these three impacts.

508   The road may act as a barrier to the water flow path. Water can spread on both sides along the road

509   and consequently flood a large section of the road. Using a DEM with a better resolution could help

510   in identifying the local configuration. Finally, according to the river basin managers, the F area has

511   been less exposed to the rainfall event, which can explain why it has not been reported as impacted.

512   For railways, the infrastructure configuration is more complex. Indeed, railway structures are highly

513   constrained to keep a steady inclination and do not follow the natural topography. Railways are

514   often built on embankments or in cuttings of varying height or depth. These configurations make

515   railways vulnerable to surface runoff. To protect the railway infrastructure, multiple drainage devices

516   or crossing structures are present all along the tracks to intercept flow paths and redirect them

517   downstream. Therefore, to better identify railway sections susceptible to being impacted by surface

518   runoff, the vulnerability must be characterized. The configuration of the infrastructure itself must be

519   defined but the level of maintenance of the hydraulic structures must also be taken into account.

520

521   **4.2. Further Analysis with the Evaluation Method**

522   In the evaluation method, we need to compare data that do not have the same shape, do not give

523   the same information, and that have been acquired using different techniques. Suitable indicators

524   must be used to show the correspondence between data and to quantify it. For example, the success

525   ratio gives information on whether or not the pixels with a high susceptibility level are located inside

526   the zoning, but do not inform on the spatial distribution of the pixels regarding the zoning. For

527   further evaluation, more complex indices could be used in order to improve the correlation analysis,

528   for example by focusing on the shape of strong pixel areas or by analyzing pixel surroundings and

529   mitigating isolated pixel effects (Hagen-Zanker, 2009; Hargrove et al., 2006).

530 For the comparison tests, assumptions have been made and preliminary treatments have been

531 carried out on the comparison data and on the IRIP map. Choices have been made for this study and

532 must be discussed. First, pixels with a value of 4 and 5 are considered as high susceptibility levels.

533 The significance of the susceptibility level 5 has been shown, but the significance of level 4 must be

534 assessed. The significance of level 3 must also be assessed. Is it really not significant? Do levels 0, 1,

535 and 2 indicate no surface runoff sensitivity? Moreover, for the comparison tests, buffer areas have

536 been used. In order to avoid arbitrary choice on the buffer area size, the tests have been performed

537 using 2 different sizes of 25 and 50 meters but more sizes could be tested, particularly negative

538 buffer areas (reducing the zoning). For the comparison with the impacts on the transportation

539 network, the hypothesis on the spatial persistence of high susceptibility levels indicating areas

540 susceptible to be impacted must be assessed, along with the significance of isolated pixels. Do they

541 bring valuable information or noise due to eventual input data inaccuracy?

542 Moreover, this study focuses on the transfer and the accumulation maps. For further evaluation, it

543 would be interesting to focus on the susceptibility map to surface runoff generation and evaluate its

544 ability to detect areas susceptible to generate significant quantities of surface water. For example,

545 for the impact databases, it would be interesting to use the map of generation in a second phase, to

546 help in distinguishing the sections most susceptible to be impacted among the ones detected by the

547 maps of transfer and accumulation. Sections with a large area upstream with high susceptibility

548 levels of surface runoff generation could be susceptible to be impacted with relatively major

549 quantities of water or more often, or to be impacted first during a rainfall event. This hypothesis

550 must be evaluated.

551 For further evaluation of the ability of the IRIP method to detect sections of the transportation

552 network susceptible to be impacted by surface runoff, the structural vulnerability of the network

553 must be characterised. A vulnerability indicator with different levels could be defined on the whole

554 network, in order to combine hazards and vulnerability better and to correlate the location of

555 impacts more effectively. Concerning the impacts, for such a comparison, further research must be

556 undertaken to improve the completeness of the databases. In addition to these tests, particular

557 events must be analyzed in greater detail in order to consider the influence of rainfall characteristics

558 and better assess the surface runoff flow dynamic. To confirm the results obtained in this study,

559 further comparison tests must be performed with different comparison data and for different study

560 areas with other hydrological contexts.

561

562 **4.3. Further Analysis with the IRIP Method Development**

563   Several options for further developing and improving the IRIP method can be proposed. Concerning

564   the map of susceptibility to surface runoff generation, the valley sides appear as favorable to surface

565   runoff whereas in reality the plateaux are the most important sources of surface runoff generation

566   due to their relative importance in terms of proportion of the catchment size and to the fact that

567   they are cultivated. They can generate substantial quantities of surface runoff which can be

568   transferred to the valley throughout the extremely dense dry talweg network. It would be interesting

569   to be able to integrate these geomorphology features in the IRIP method. For example, a

570   computation of geomorphologic indexes could permit calibrating the method in terms of the

571   plateau/valley distribution. The default configuration of the method is that steep slopes are

572   favorable to surface runoff generation, which is relevant for mountainous areas, for example, but

573   this choice could be inversed when working on large flat areas with large agricultural fields.

574   Furthermore, the susceptibility map of surface runoff generation could be improved with better data

575   accuracy. Especially the soil map, which is used for three of the five indicators, has a resolution of

576   1/1000000 and gives only six different soil units in the Lézarde catchment. Moreover, it has been

577   shown that the geology has an influence on surface runoff generation and transfer (Onda et al.,

578   2001); it would be interesting to use this parameter in the IRIP method.

579   The map of susceptibility to surface runoff transfer takes the artificial linear axes as an input indicator

580   because they can modify surface runoff directions, but if the data are available it would be

581   interesting to add the urban and agricultural drainage network in this indicator. For the creation of

582   this map, we currently use the Horton form factor to reflect the compactness effect of the sub-

583   catchment drained by each pixel (0.15 for our study). This index is not particularly satisfying because

584   of its instability when computed on small drained areas. More adapted compactness indexes must be

585   tested (Gravelius, 1914; Schumm, 1956), although their implementation can be complex with GIS

586   techniques (Bardossy and Schmidt, 2002; Bendjoudi and Hubert, 2002). It would be better to use an

587   index that is more adapted to a distributed computation.

588   In addition to these suggestions, the IRIP method could also be improved by making additional tests.

589   For example, stability tests on the indicator thresholds could be performed to evaluate the threshold

590   computation method. Changes in the input data resolution (DEM, land use map, and soil map) could

591   be studied to evaluate how it affects the resulting maps. It would also be interesting, from a risk

592   point of view, to cross the IRIP maps with meteorological data or land use change monitoring to

593   provide real-time probability maps.

594

595   **5. Conclusions**

596   This paper presents the IRIP method for surface runoff susceptibility mapping and its evaluation by

597   comparison with different datasets. The method makes it possible to produce three maps

598   representing different surface runoff mechanisms: generation, transfer, and accumulation. The

599   maps' evaluation shows a significant correspondence between the IRIP map of accumulation and the

600   surface runoff regulatory zoning and between the IRIP map of transfer and the soil erosion zoning.

601   The comparison with data of impacts on the transportation network show promising probabilities of

602   detection which confirm the relevance of the susceptibility maps. For an operational need of network

603   monitoring, the structural vulnerability must be characterized to better discriminate the false alarms.

604   The IRIP method has shown promising results during the comparison tests, but can it be used as a

605   tool for risk management? The IRIP method aims to be simple to implement and requires few input

606   data that are widely available. Neither specific study area size nor calibration is required for a first

607   use. In this sense, the IRIP method can be a useful tool to get a first understanding of the surface

608   runoff mechanisms involved in a catchment and of their spatial distribution. Nonetheless, to go

609   further in the map analysis, field expertise is required. The use of the IRIP maps regarding the usual

610   hazard assessment methods can be complex because of the three types of maps and the

611   susceptibility scale. In the other hand, working with three susceptibility maps of generation, transfer,

612   and accumulation gives the opportunity to adapt risk mitigation techniques depending on the areas.

613   In the areas prone to surface runoff generation, one can avoid soil imperviousness or facilitate

614   infiltration with reservoir basins. In the surface runoff transfer areas, one can avoid bare soils and

615   obstacles susceptible to be swept away. For accumulation areas, one can try to reduce stake

616   vulnerabilities. Finally, this study highlights that a multidisciplinary approach is essential to assess

617   surface runoff hazards. Likewise, a systemic view of the whole catchment is required, along with

618   interactive work with the catchment stakeholders, to improve surface runoff risk management and

619   to sustainably develop territories.

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References

633   Abudi, I., Carmi, G., Berliner, P., 2012. Rainfall simulator for field runoff studies. J. Hydrol. 454, 76–81.

634   Akgun, A., Türk, N., 2010. Landslide susceptibility mapping for Ayvalik (Western Turkey) and its
635   vicinity by multicriteria decision analysis. Environ. Earth Sci. 61, 595–611.

636   Arnaud, P., Dehotin, J., 2011. Surface runoff hazard estimation methods - Comparison of the SHYREG
637   and the IRIP methods. IRSTEA Aix-en-Provence et IRSTEA Lyon.

638   Auzet, A.V., Boiffin, J., Papy, F., Ludwig, B., Maucorps, J., 1993. Rill erosion as a function of the
639   characteristics of cultivated catchments in the north of France. Catena 20, 41–62.
640   doi:10.1016/0341-8162(93)90028-N

641   Bardossy, A., Schmidt, F., 2002. GIS approach to scale issues of perimeter-based shape indices for
642   drainage basins. Hydrol. Sci. J.-J. Sci. Hydrol. 47, 931–942. doi:10.1080/02626660209493001

643   Bendjoudi, H., Hubert, P., 2002. The Gravelius compactness coefficient: critical analysis of a shape
644   index for drainage basins. Hydrol. Sci. J. 47, 921–930. doi:10.1080/02626660209493000

645   Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin
646   hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin
647   versant. Hydrol. Sci. J. 24, 43–69. doi:10.1080/02626667909491834

648   Buckle, P., Mars, G., Smale, S., 2000. New approaches to assessing vulnerability and resilience. Aust.
649   J. Emerg. Manag. 15, 8.

650   Carpenter, T.M., Sperfslage, J.A., Georgakakos, K.P., Sweeney, T., Fread, D.L., 1999. National
651   threshold runoff estimation utilizing GIS in support of operational flash flood warning
652   systems. J. Hydrol. 224, 21–44. doi:10.1016/S0022-1694(99)00115-8

653   Cerdà, A., 2007. Soil water erosion on road embankments in eastern Spain. Sci. Total Environ. 378,
654   151–155. doi:10.1016/j.scitotenv.2007.01.041

655   Cerdà, A., Doerr, S.H., 2008. The effect of ash and needle cover on surface runoff and erosion in the
656   immediate post-fire period. Catena 74, 256–263. doi:10.1016/j.catena.2008.03.010

657   Cerdan, O., Souchere, V., Lecomte, V., Couturier, A., Le Bissonnais, Y., 2002. Incorporating soil surface
658   crusting processes in an expert-based runoff model: Sealing and Transfer by Runoff and
659   Erosion related to Agricultural Management. Catena 46, 189–205. doi:10.1016/S0341-
660   8162(01)00166-7

661   Chazelle, B., Lambert, L., Capoccioni, C.P., 2014. Railway vulnerability in case of extremes floods.
662   Knowledge and risk management. Houille Blanche 48–54. doi:10.1051/lhb/2014016

663   Christensen, F.M., Andersen, O., Duijm, N.J., Harremoës, P., 2003. Risk terminology—a platform for
664   common understanding and better communication. J. Hazard. Mater. 103, 181–203.
665   doi:10.1016/S0304-3894(03)00039-6

666   Cros-Cayot, S., 1996. Distribution spatiale des transferts de surface à l'échelle du versant. Contexte
667   armoricain. Ecole Nationale Supérieure Agronomique de Rennes.

668   Dabney, S.M., Yoder, D.C., Vieira, D.A.N., Bingner, R.L., 2011. Enhancing RUSLE to include runoff-
669   driven phenomena. Hydrol. Process. 25, 1373–1390. doi:10.1002/hyp.7897

670   Daroussin, J., King, D., 1997. A pedotransfer rules database to interpret the soil geographical
671   database of Europe for environmental purposes. Presented at the the workshop on the use
672   of pedotransfer in soil hydrology research in Europe, Orléans, FRA, pp. 25–40.

673   Defrance, D., 2014. Adaptation and evaluation of a flash flood warning system in ungauged
674   mountainous catchments (Earth Sciences). Université Pierre et Marie Curie - Paris VI.

675   Dehotin, J., Breil, P., 2011a. Technical report of the IRIP project: mapping the flooding by runoff
676   (Technical report). IRSTEA Hydrology-Hydraulic Research Unit.

677   Dehotin, J., Breil, P., 2011b. IRIP project: Research bibliographic report on surface runoff mapping
678   (Literature review). IRSTEA Hydrology-Hydraulic Research Unit.

679   Dehotin, J., Breil, P., Braud, I., de Lavenne, A., Lagouy, M., Sarrazin, B., 2015a. Detecting surface
680   runoff location in a small catchment using distributed and simple observation method. J.
681   Hydrol. 525, 113–129. doi:10.1016/j.jhydrol.2015.02.051

682   Dehotin, J., Chazelle, B., Laverne, G., Hasnaoui, A., Lambert, L., Breil, P., Braud, I., 2015b. Applying
683   runoff mapping method IRIP for flooding risk analysis on railway infrastructure. Houille
684   Blanche 56–64. doi:10.1051/lhb/20150069
685   Delahaye, D., Guermond, Y., Langlois, P., 2002. Spatial interaction in the run-off process. Cybergeo
686   Eur. J. Geogr. doi:10.4000/cybergeo.3795
687   Departmental Directorate of Seine-Maritime, 2013a. Flood Risk Prevention Plan - Presentation
688   report.
689   Departmental Directorate of Seine-Maritime, 2013b. Flood Risk Prevention Plan of the Lezarde
690   Catchment - Application rules.
691   DeRoo, A.P.J., Wesseling, C.G., Ritsema, C.J., 1996. LISEM: A single-event physically based
692   hydrological and soil erosion model for drainage basins .1. Theory, input and output. Hydrol.
693   Process. 10, 1107–1117. doi:10.1002/(SICI)1099-1085(199608)10:8<1107::AID-
694   HYP415>3.0.CO;2-4
695   Douvinet, J., 2008. Les bassins versants sensibles aux « crues rapides » dans le Bassin Parisien –
696   Analyse de la structure et de la dynamique de systèmes spatiaux complexes. Université de
697   Caen/Basse-Normandie.
698   Douvinet, J., Delahaye, D., Langlois, P., 2008. Modélisation de la dynamique potentielle d'un bassin
699   versant et mesure de son efficacité structurelle. Cybergeo Eur. J. Geogr.
700   doi:10.4000/cybergeo.16103
701   Douvinet, J., Wiel, M.J.V.D., Delahaye, D., Cossart, E., 2014. A flash flood hazard assessment in dry
702   valleys (northern France) by cellular automata modelling. Nat. Hazards 75, 2905–2929.
703   doi:10.1007/s11069-014-1470-3
704   Dupuis, J., 1969. La carte pédologique de la France au millionième. Rev. Géographie Alp. 219–219.
705   Faulkner, H., Boardman, J., Ruiz, J.-L., 2010. A simple validated GIS expert system to map relative soil
706   vulnerability and patterns of erosion during the muddy floods of 2000–2001 on the South
707   Downs, Sussex, UK. Land Degrad. Dev. 21, 310–321. doi:10.1002/ldr.1005
708   Galevski, M., 1955. La corrélation entre les pluies torrentielles et l'intensité de l'érosion (Field
709   observation report).
710   Gouvazé, J., SMBV, 2013. Floods of 13 & 14 October 2013: feedback on this unusual weather event.
711   Gravelius, H., 1914. Grundriss der gesamten Gewässerkunde: in vier Bänden. 1. Flusskunde,
712   Compendium of Hydrology, vol. 1: Rivers. Göschen, Berlin, Germany.
713   Guillobez, S., Lompo, F., De Noni, G., 2000. Le suivi de l'érosion pluviale et hydrique au Burkina Faso.
714   Utilisation d'un modèle cartographique. Sci. Chang. Planétaires Sécher. 11, 163–9.
715   Hagen-Zanker, A., 2009. An improved Fuzzy Kappa statistic that accounts for spatial autocorrelation.
716   Int. J. Geogr. Inf. Sci. 23, 61–73. doi:10.1080/13658810802570317
717   Hargrove, W.W., Hoffman, F.M., Hessburg, P.F., 2006. Mapcurves: a quantitative method for
718   comparing categorical maps. J. Geogr. Syst. 8, 187–208. doi:10.1007/s10109-006-0025-x
719   Hauchard, E., 2002. Risk Prevention Plan for floods and surface runoff. Methodol. Defin. Surf. Runoff
720   Hazard Hydrogeomorphological Approach Dep. Equip. Dir. 76.
721   Hauchard, E., Delahaye, D., Freiré-Diaz, S., 2002. Fractal organization of the soil occupation:
722   consequences on the runoff and gully erosion in arable cropping areas. Géomorphologie
723   Relief Process. Environ. 8, 181–196.
724   Hauchard, E., Laignel, B., 2008. Morphotectonic evolution of the north-western margin of the Paris
725   Basin. Z. Für Geomorphol. 52, 463–488. doi:10.1127/0372-8854/2008/0052-0463
726   Hewlett, J.D., 1982. Principles of forest hydrology. University of Georgia Press.
727   Hewlett, J.D., Hibbert, A.R., 1967. Factors affecting the response of small watersheds to precipitation
728   in humid areas. For. Hydrol. 275–290.
729   Hogan, R.J., Mason, I.B., 2012. Deterministic forecasts of binary events. Forecast Verification Pract.
730   Guide Atmospheric Sci. Second Ed. 31–59. doi:10.1002/9781119960003.ch3
731   Holzmann, H., Sereinig, N., 1997. In situ measurements of hillslope runoff components with different
732   types of forest vegetation. IAHS PRESS WALLINGFORD ENGL 317–324.

733   Horton, R.E., 1933. The role of infiltration in the hydrologic cycle. Trans. Am. Geophys. Union 14,
734   446–460. doi:10.1029/TR014i001p00446
735   Horton, R.E., 1932. Drainage-basin characteristics. Trans. Am. Geophys. Union 13, 350.
736   doi:10.1029/TR013i001p00350
737   Hudson, N., 1993. Field measurement of soil erosion and runoff. Food & Agriculture Org.
738   IPCC, 2003. IPCC Third Assessment Report - Climate Change 2001: 2.3.2.1 Palaeoclimate proxy
739   indicators.
740   Jamagne, M., Hardy, R., King, D., Bornand, M., 1995. La base de données géographique des sols de
741   France. Etude Gest. Sols 2, 153–172.
742   Javelle, P., Demargne, J., Defrance, D., Pansu, J., Arnaud, P., 2014. Evaluating flash-flood warnings at
743   ungauged locations using post-event surveys: a case study with the AIGA warning system.
744   Hydrol. Sci. J. 59, 1390–1402. doi:10.1080/02626667.2014.923970
745   Laflen, J., Lane, L., Foster, G., 1991. Wepp - a New Generation of Erosion Prediction Technology. J.
746   Soil Water Conserv. 46, 34–38.
747   Langlois, P., Delahaye, D., 2002. RuiCells, automate cellulaire pour la simulation du ruissellement de
748   surface. Rev. Int. Géomat. 12, 461–487.
749   Laverne, G., 2013. Application and validation of a runoff areas mapping tool in the railway context:
750   identification of sites subject to flooding by runoff (Master thesis). IRSTEA Hydrology-
751   Hydraulic Research Unit.
752   Le Bissonnais, Y., Montier, C., Jamagne, M., Daroussin, J., King, D., 2002. Mapping erosion risk for
753   cultivated soil in France. Catena 46, 207–220. doi:10.1016/S0341-8162(01)00167-9
754   Le Gouee, P., Delahaye, D., Bermond, M., Marie, M., Douvinet, J., Viel, V., 2010. SCALES: a large-scale
755   assessment model of soil erosion hazard in Basse-Normandie (northern-western France).
756   Earth Surf. Process. Landf. 35, 887–901. doi:10.1002/esp.1942
757   Legros, J., 2014. Study of datas given by a method of flooding harzard by surface runoff in flow
758   discharge modelling linked with this kind of flooding (Master thesis). IRSTEA Hydrology-
759   Hydraulic Research Unit.
760   MacQueen, J., 1967. Some methods for classification and analysis of multivariate observations.
761   Presented at the the fifth Berkeley symposium on mathematical statistics and probability,
762   Oakland, CA, USA., pp. 281–297.
763   Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model
764   evaluation guidelines for systematic quantification of accuracy in watershed simulations.
765   Trans. Asabe 50, 885–900. doi:10.13031/2013.23153
766   Naulin, J.-P., Payrastre, O., Gaume, E., 2013. Spatially distributed flood forecasting in flash flood
767   prone areas: Application to road network supervision in Southern France. J. Hydrol. 486, 88–
768   99. doi:10.1016/j.jhydrol.2013.01.044
769   Nearing, M.A., Foster, G.R., Lane, L.J., Finkner, S.C., 1989. Erosion Prediction Project Technology.
770   Onda, Y., Komatsu, Y., Tsujimura, M., Fujihara, J., 2001. The role of subsurface runoff through
771   bedrock on storm flow generation. Hydrol. Process. 15, 1693–1706. doi:10.1002/hyp.234
772   Ortega, K.L., Smith, T.M., Manross, K.L., Kolodziej, A.G., Scharfenberg, K.A., Witt, A., Gourley, J.J.,
773   2009. The severe hazards analysis and verification experiment. Bull. Am. Meteorol. Soc. 90,
774   1519–1530.
775   Pams-Capoccioni, C., Nivon, D., Amblard, J., De cesare, G., Ghilardi, T., 2015. Risk analysis for railway
776   traffic of overflowing of the drainage system on High Speed Lines. Houille Blanche 39–45.
777   doi:10.1051/lhb/20150044
778   Piney, S., 2009. Etude bibliographique de trois méthodologies appliquées au risque érosion: synthèse
779   et perspective en vue d'une cartographie départementale du risque de ruissellement.
780   Pons, F., Delgado, J.-L., Guero, P., Berthier, E., Kerloc'h, B., Piney, S., Felts, D., 2010. A method for the
781   assessment of the flood risk related to direct runoff and flash floods. SimHydro 2010 Sophia
782   Antipolis.
783   Reuter, H.I., Wendroth, O., Kersebaum, K.C., 2006. Optimisation of relief classification for different
784   levels of generalisation. Geomorphology 77, 79–89. doi:10.1016/j.geomorph.2006.01.001

785   Robinson, D.A., Phillips, C.P., 2001. Crust development in relation to vegetation and agricultural
786   practice on erosion susceptible, dispersive clay soils from central and southern Italy. Soil
787   Tillage Res. 60, 1–9. doi:10.1016/S0167-1987(01)00166-0

788   Schmocker-Fackel, P., Naef, F., Scherrer, S., 2007. Identifying runoff processes on the plot and
789   catchment scale. Hydrol. Earth Syst. Sci. 11, 891–906. doi:10.5194/hess-11-891-2007

790   Schumm, S.A., 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New
791   Jersey. Geol. Soc. Am. Bull. 67, 597–646. doi:10.1130/0016-
792   7606(1956)67[597:EODSAS]2.0.CO;2

793   Smith, R.E., Goodrich, D.C., Woolhiser, D.A., Unkrich, C.L., 1995. KINEROS-A kinematic runoff and
794   erosion model. Comput. Models Watershed Hydrol. 20, 627–668.

795   Stanski, H.R., Wilson, L.J., Burrows, W.R., 1989. Survey of common verification methods in
796   meteorology. World Meteorological Organization Geneva.

797   Tetzlaff, D., Soulsby, C., Waldron, S., Malcolm, I.A., Bacon, P.J., Dunn, S.M., Lilly, A., Youngson, A.F.,
798   2007. Conceptualization of runoff processes using a geographical information system and
799   tracers in a nested mesoscale catchment. Hydrol. Process. 21, 1289–1307.
800   doi:10.1002/hyp.6309

801   Thywissen, K., 2006. Components of risk: a comparative glossary. UNU- EHS.

802   UNDHA, 1992. Internationally agreed glossary of basic terms related to disaster management. UN
803   DHA U. N. Dep. Humanit. Aff. Geneva.

804   UNDRO, 1979. Natural disasters and vulnerability analysis : report of Expert Group Meeting (No.
805   naturaldisasters00offi). Geneva.

806   Versini, P.-A., Gaume, E., Andrieu, H., 2010a. Assessment of the susceptibility of roads to flooding
807   based on geographical information - test in a flash flood prone area (the Gard region,
808   France). Nat. Hazards Earth Syst. Sci. 10, 793–803. doi:/10/793/2010/

809   Versini, P.-A., Gaume, E., Andrieu, H., 2010b. Application of a distributed hydrological model to the
810   design of a road inundation warning system for flash flood prone areas. Nat. Hazards Earth
811   Syst. Sci. 10, 805–817. doi:/10/805/2010/

812   Wischmeier, W.H., 1959. A Rainfall Erosion Index for a Universal Soil-Loss Equation. Soil Sci. Soc. Am.
813   J. 23, 246. doi:10.2136/sssaj1959.03615995002300030027x

814

Figure captions:

Figure 1: Scheme of the IRIP method to create the three susceptibility maps of surface runoff generation, transfer, and accumulation, with the input data

Figure 2: Description of the Lézarde catchment which is located in the Seine-Maritime County and which ranges from 1 to 138 meters of elevation with a short permanent hydrographic network

Figure 3: Description of the rainfall event of October 13, 2013 that impacted the northern part of the Lézarde catchment

Figure 4: Explanative schemes of the data formatting for the comparison with the impact databases, a) Process to detect pixel persistence and remove isolated pixels, b) presentation of the surfaces taken into account for the computation of the contingency table.

Figure 5: The IRIP map of susceptibility of the Lézarde catchment to surface runoff generation

Figure 6: The IRIP map of susceptibility of the Lézarde catchment to surface runoff transfer

Figure 7: The IRIP map of susceptibility of the Lézarde catchment to surface runoff accumulation

Figure 8: Superimposition of the high susceptibility levels of the IRIP map of accumulation and of the surface runoff regulatory zoning

Figure 9: Superimposition of the high susceptibility levels of the IRIP map of transfer and of the soil erosion regulatory zoning

Figure 10: Superimposition of the high susceptibility levels of the IRIP map of transfer and accumulation after processing and of the road network of the three sub-catchments impacted by the rainfall event, along with the road sections impacted by surface runoff and the hydraulic structure locations

Figure 11: Superimposition of the high susceptibility levels of the IRIP map of transfer and accumulation and of the soil erosion regulatory zoning

Figure 12: Photos from Google Street View illustrating the environment configuration around four impacted road sections in order to explain the reason of the IRIP false alarms

Table 1: List of the 5 indictors per map used to create the 3 IRIP maps of generation, transfer, and accumulation susceptibility, with the criteria of favourability for each indicator

Table 2: The theoretical contingency table to analyze the correlation between the IRIP maps and the comparison data

Table 3: The five verification indicators computed to analyze the correlation between the IRIP maps and the comparison data

Table 4: Result summary of the comparison between the regulatory zonings and the high susceptibility levels of the IRIP maps of transfer and accumulation, using buffer area sizes of 0, 25 and 50 meters

Table 5: Result summary of the comparison between the impact locations on the transportation network and the high susceptibility level locations on the IRIP maps of transfer and accumulation, using buffer area sizes of 25 and 50 meters
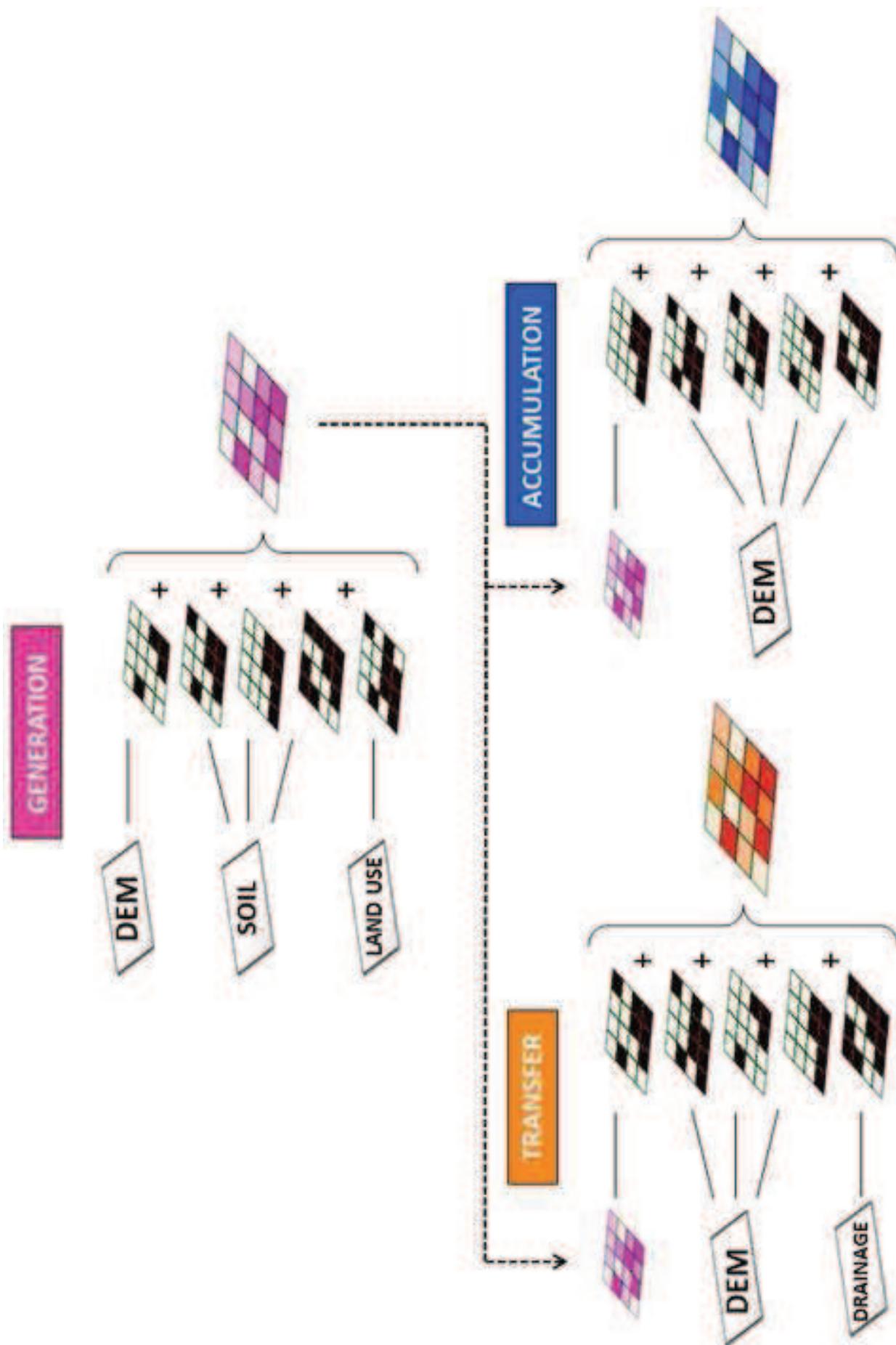
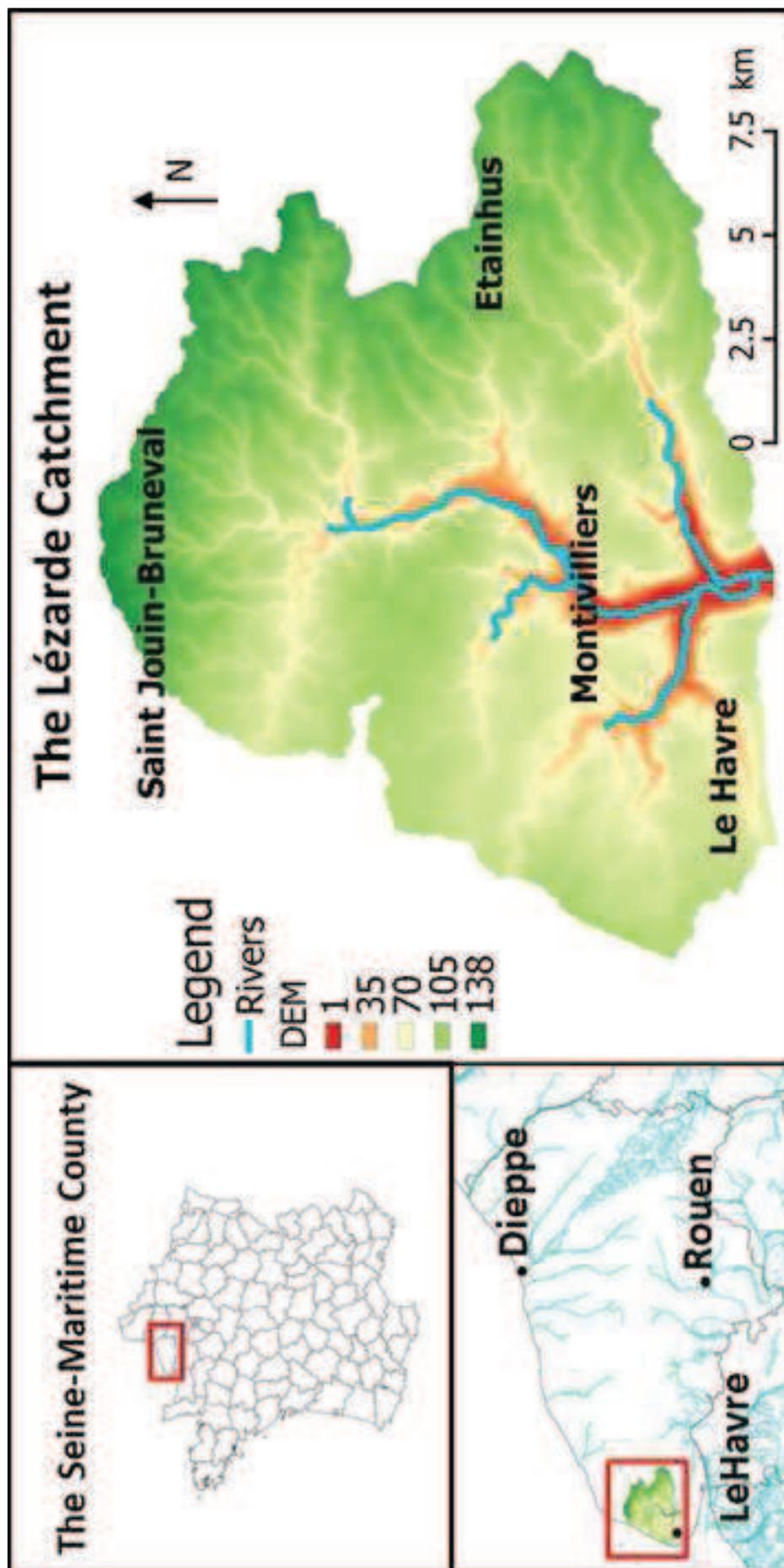**Fig2_the_study_area**
Click here to download high resolution image
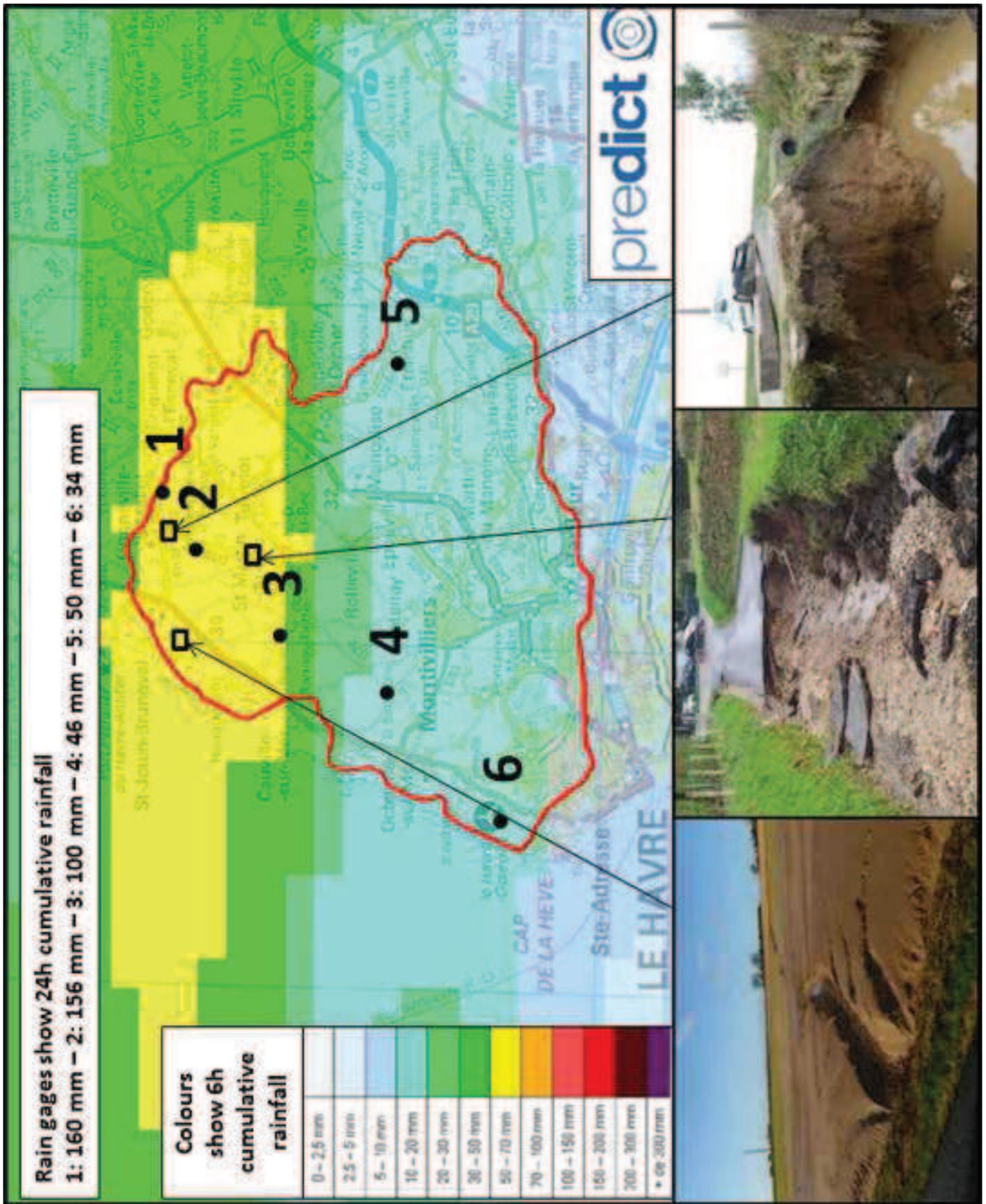
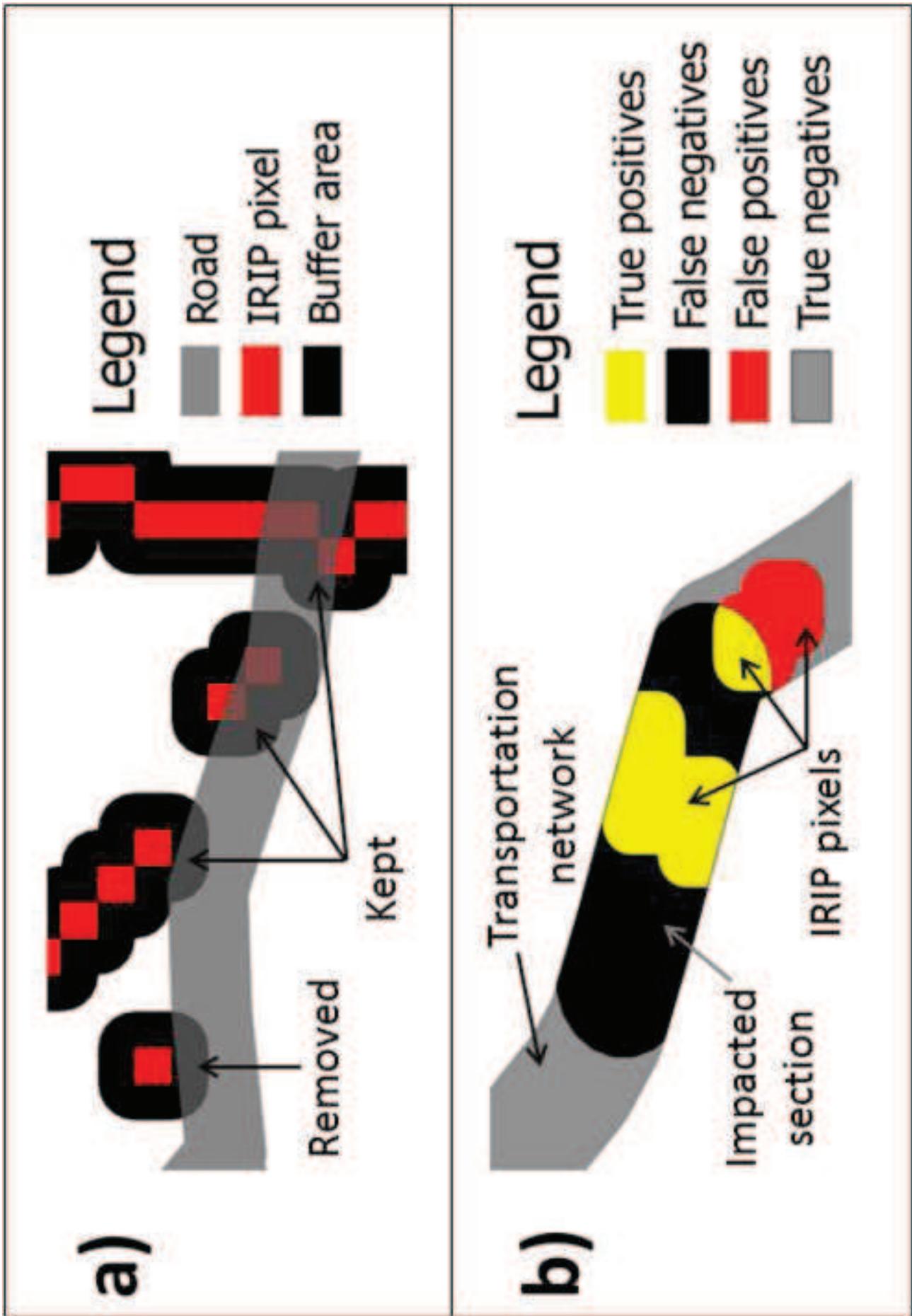**Fig3_Rainfall_13_oct**
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Rain gages show 24h cumulative rainfall
1: 160 mm – 2: 156 mm – 3: 100 mm – 4: 46 mm – 5: 50 mm – 6: 34 mm

Colours show 6h cumulative rainfall

0 – 2.5 mm
2.5 – 5 mm
5 – 10 mm
10 – 20 mm
20 – 30 mm
30 – 50 mm
50 – 70 mm
70 – 100 mm
100 – 150 mm
150 – 200 mm
200 – 300 mm
ce 300 mm

Fig4_detailed_scheme_impact_analysis
Click here to download high resolution image
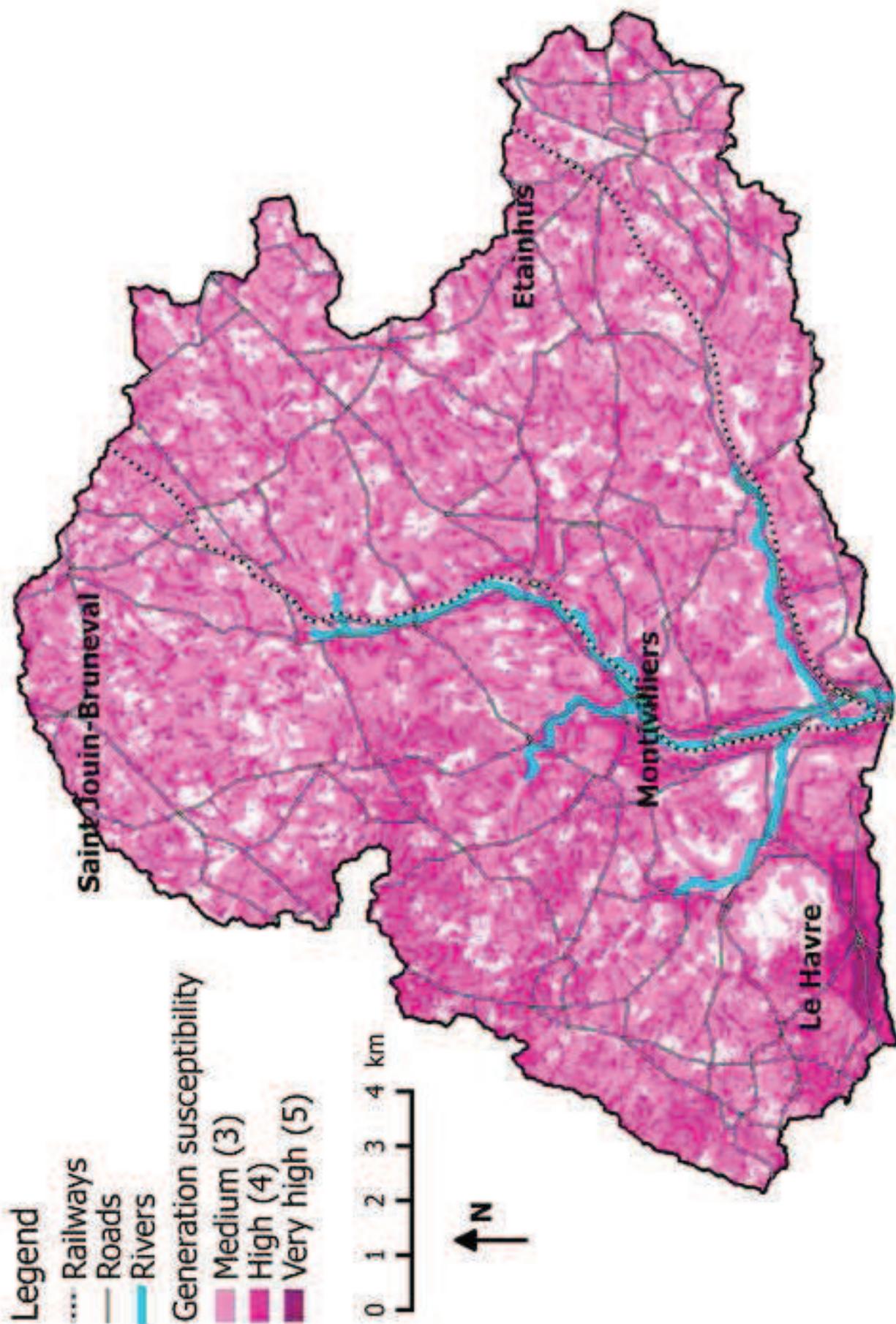
Fig6_IRIP_map_transfer
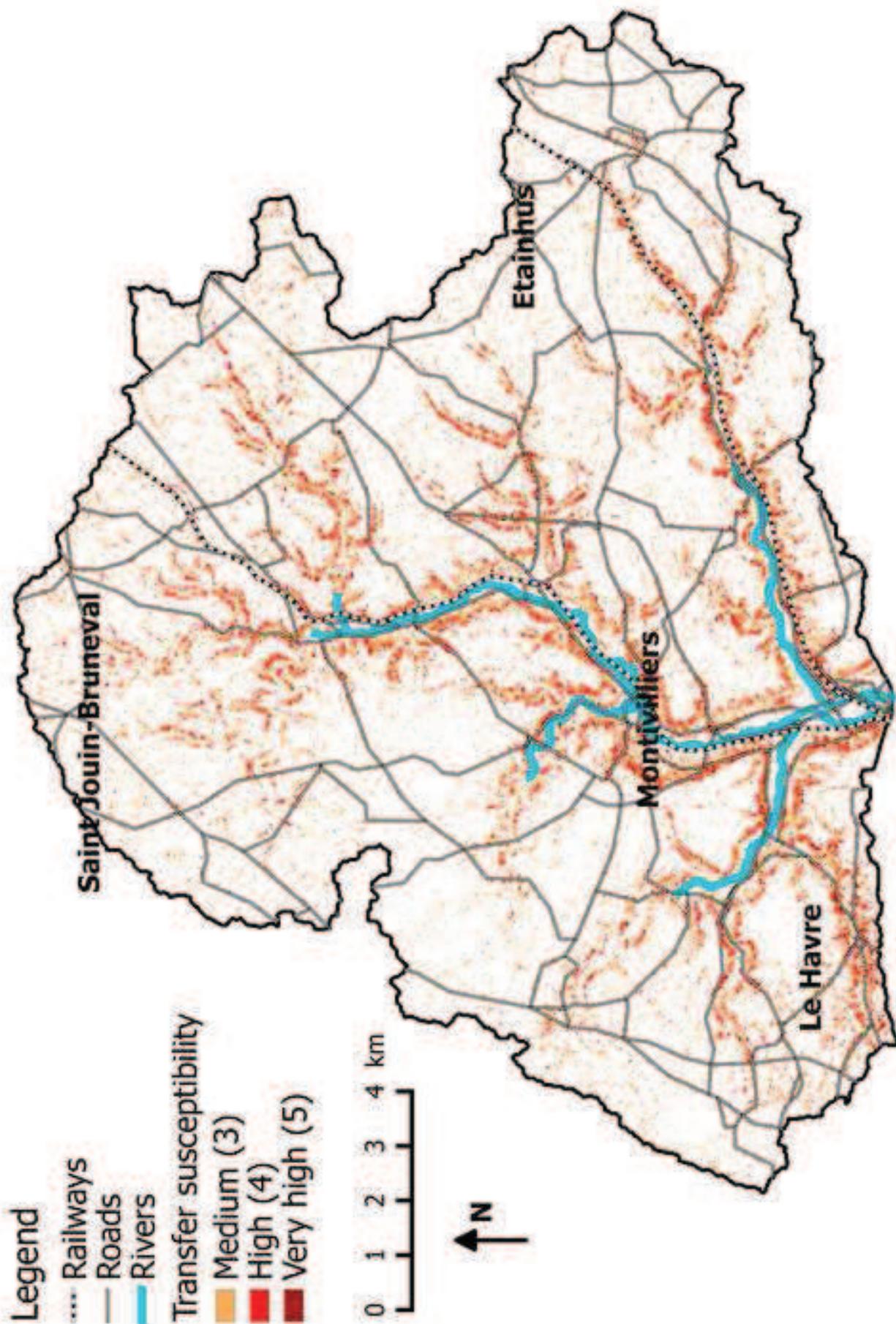**Click here to download high resolution image**

Legend
∙∙∙∙ Railways
—— Roads
—— Rivers
Transfer susceptibility
Medium (3)
High (4)
Very high (5)

0 1 2 3 4 km

N
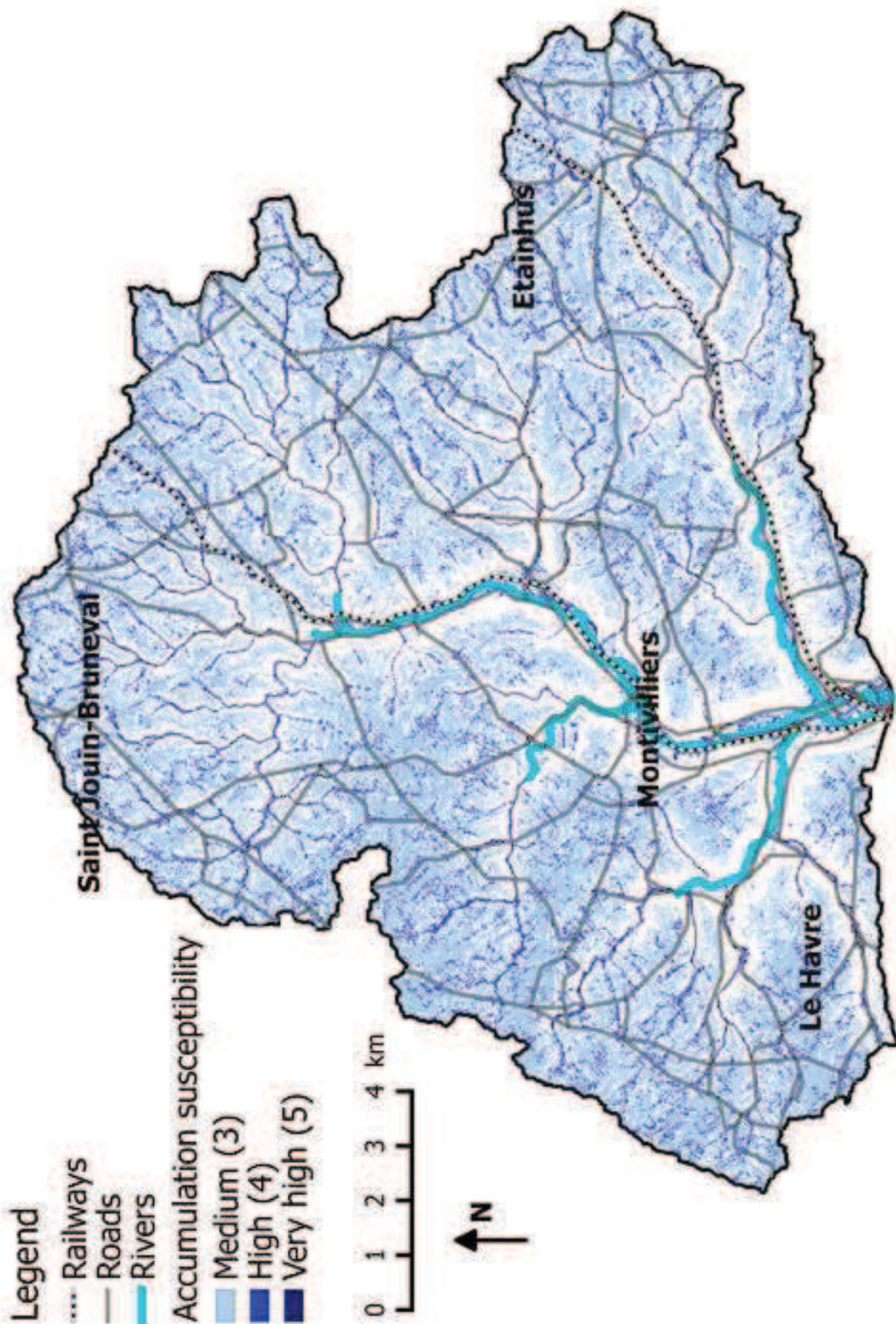
Fig7_IRIP_map_accumulation
Click here to download high resolution image

Legend
···· Railways
—— Roads
—— Rivers
Accumulation susceptibility
Medium (3)
High (4)
Very high (5)

0 1 2 3 4 km

N

Legend
☐ Surface runoff regulatory zoning
Accumulation susceptibility
■ High (4)
■ Very high (5)

2250 m

N

0   750   1500   2250 m
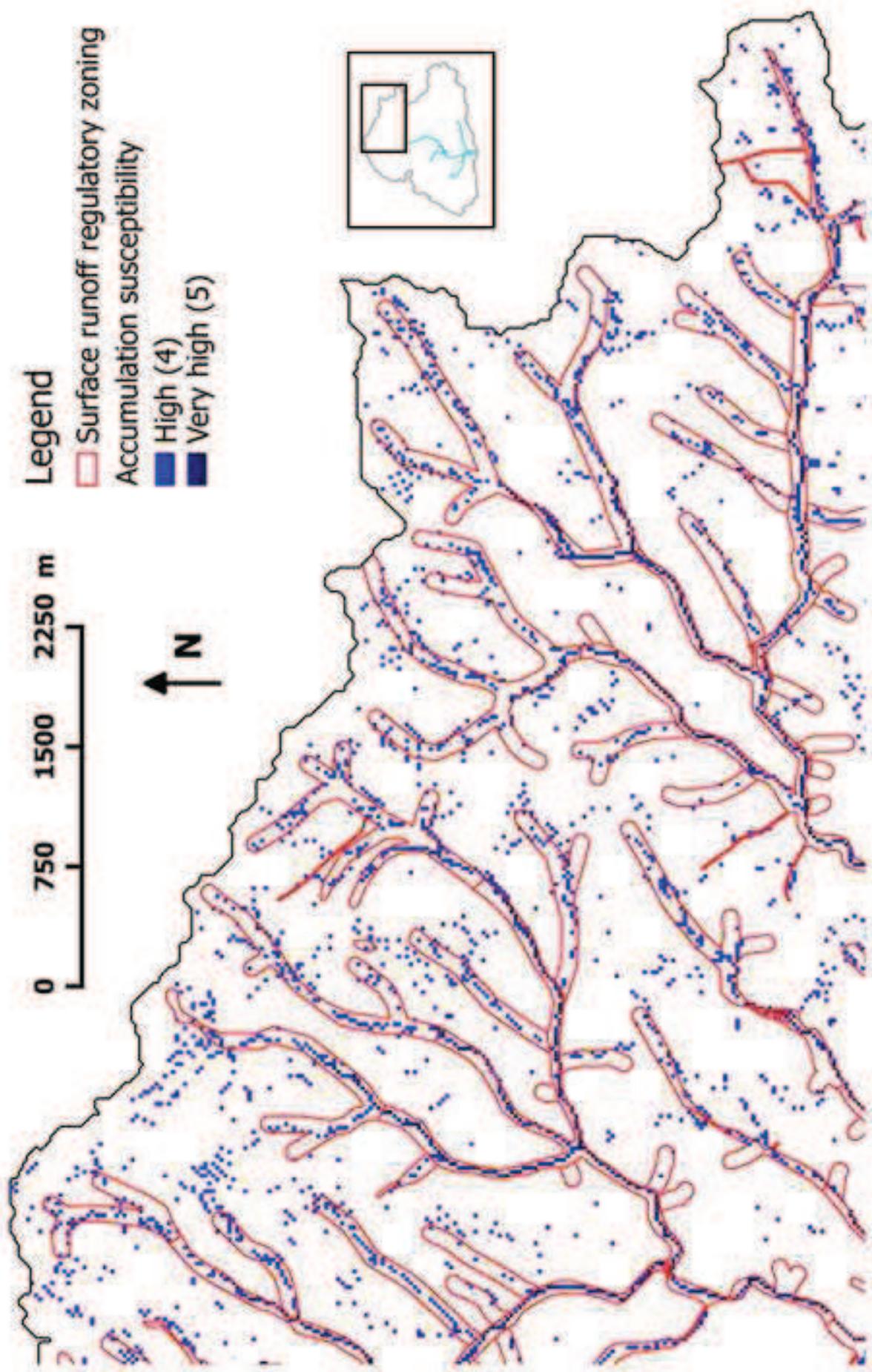
Fig8_comparison_runoff_zoning
Click here to download high resolution image

Legend

Soil erosion regulatory zoning

Transfer susceptibility

High (4)
Very high (5)

N

0   750   1500   2250 m

Fig10_road_IRIP_analysis
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Legend

Hydraulic structures
- ● Has not overflowed
- ● Has overflowed

Roads (T-)
- Impacted roads (F-)
- Susceptibility from IRIP (F+)
- Intersection IRIP and impacted roads (T+)
- Contour lines at 5 m
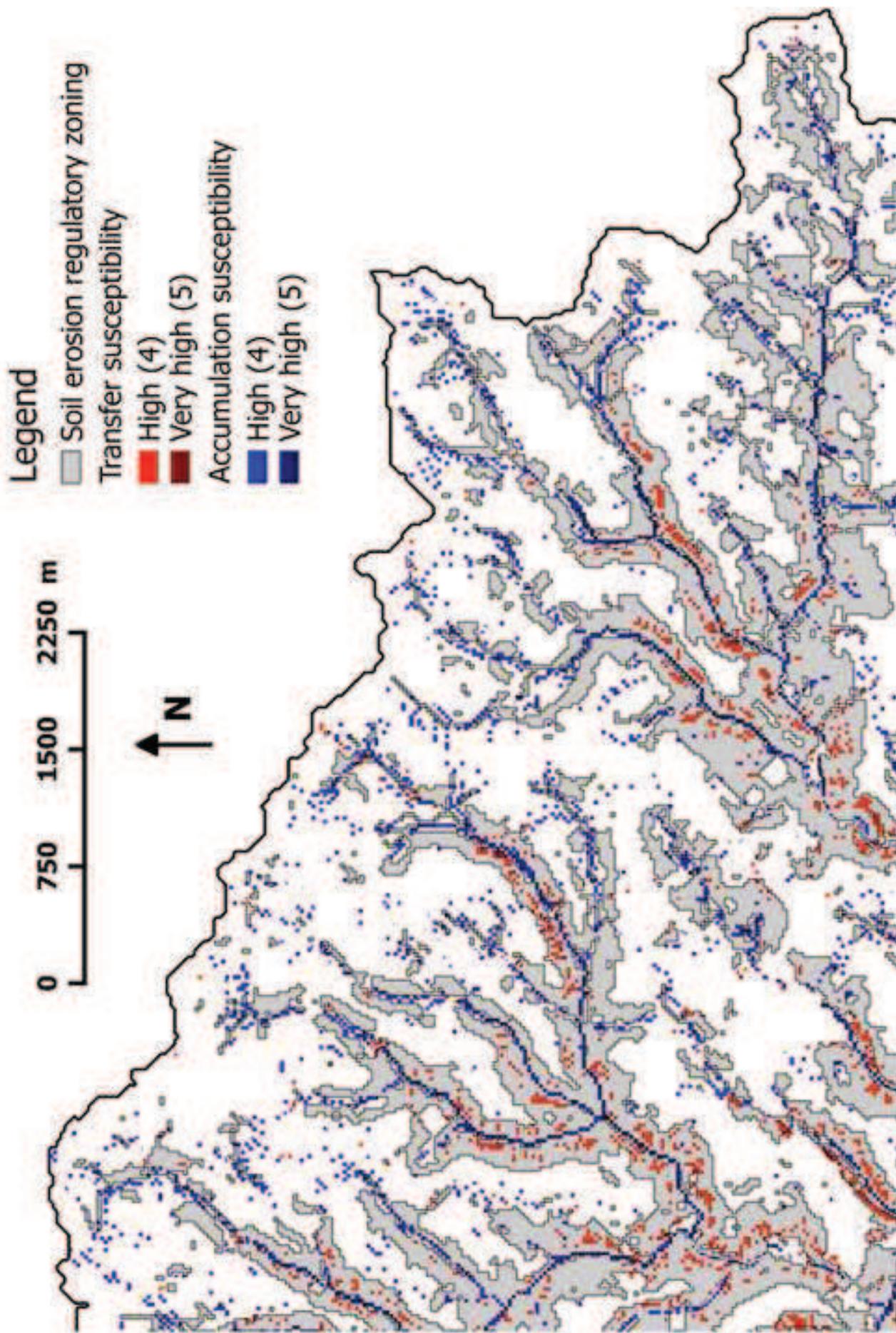
Fig11_comparison_acc_trans_erosion_zoning
Click here to download high resolution image

Legend
Soil erosion regulatory zoning
Transfer susceptibility
High (4)
Very high (5)
Accumulation susceptibility
High (4)
Very high (5)

N

0   750   1500   2250 m

Table1_IRIP_indicators

IRIP maps	Indicators	Values
Generation	Soil permeability	0: High permeability
		1: Low permeability
	Soil thickness	0: Thick soil
		1: Thin soil
	Soil erodibility	0: Low erodibility
		1: High erodibility
	Topography	0: Slope $< t_1$ AND topographic index $< t_2$
		1: Slope $> t_1$ OR topographic index $> t_2$
	Land use	0: Infiltrative surfaces
		1: Impervious surfaces
Transfer	Upstream generation susceptibility	0: Low upstream generation susceptibility
		1: High upstream generation susceptibility
	Slope	0: Slope $< t_1$
		1: Slope $> t_1$
	Break of slope	0: Concave break of slope
		1: Convex break of slope
	Catchment compacity	0: Low Horton form factor
		1: High Horton form factor
	Artificial linear axes	0: No linear axes
		1: Presence of linear axes
Accumulation	Upstream generation susceptibility	0: Low upstream generation susceptibility
		1: High upstream generation susceptibility
	Slope	0: Slope $> t_1$
		1: Slope $< t_1$
	Break of slope	0: Convex break of slope
		1: Concave break of slope
	Topographic index	0: Topographic index $< t_2$
		1: Topographic index $> t_2$
	Flow accumulation	0: Low flow accumulation
		1: High flow accumulation

Table2_theoretical_contingency_table

		Observed event		
		Yes	No	Total
IRIP	Yes	True positives	False positives	Forecast yes
	No	False negatives	True negatives	Forecast no
	Total	Observed yes	Observed no	Total

Verification indicators	Formulas	Interpretation
Accuracy	$\dfrac{True\ positives + True\ negatives}{Total}$	Range: 0 to 1 Perfect score: 1
Bias	$\dfrac{True\ positives + False\ positives}{True\ positives + False\ negatives}$	Range: 0 to ∞ Perfect score: 1 <1 underforecast, >1 overforecast
Success ratio	$\dfrac{True\ positives}{True\ positives + False\ positives}$	Range: 0 to 1 Perfect score: 1
Probability of detection	$\dfrac{True\ positives}{True\ positives + False\ negatives}$	Range: 0 to 1 Perfect score: 1
False alarm ratio	$\dfrac{False\ positives}{True\ positives + False\ positives}$	Range: 0 to 1 Perfect score: 0

IRIP pixels	Verification indicators	Surface runoff zoning / Map of accumulation			Soil erosion zoning / Map of transfer		
		0 m	25 m	50 m	0 m	25 m	50 m
≥4	Accuracy	0.84	0.76	0.68	0.69	0.51	0.39
	Bias	0.41	0.25	0.18	0.12	0.07	0.06
	Success ratio	0.41	0.53	0.59	0.64	0.82	0.91
=5	Accuracy	0.86	0.77	0.68	0.68	0.48	0.36
	Bias	0.06	0.04	0.03	0.01	0.00	0.00
	Success ratio	0.72	0.89	0.92	0.55	0.84	0.92

Verification indicators	Impacts on the transportation network / Maps of transfer and accumulation			
	Roads		Railways	
	25 m	50 m	25 m	50 m
Accuracy	0.68	0.65	0.34	0.30
Bias	3.22	3.10	9.58	7.73
Success ratio	0.23	0.23	0.08	0.12
Probability of detection	0.73	0.72	0.80	0.90
False alarm ratio	0.77	0.77	0.92	0.88