USING MAPS OF SURFACE RUNOFF SUSCEPTIBILITY FOR OPTIMIZING RISK DIAGNOSES ON RAILWAYS

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SUMMARY

Water-related risk management is a multidisciplinary issue for railway systems. Risk diagnoses are crucial steps in risk management from infrastructure design to railway operation, monitoring and maintenance. Risk diagnoses are performed by crossing hazard exposure and vulnerability assessment, considering train traffic safety and regularity. Diagnoses aim at identifying sections at risk, prioritizing actions and recommending specific works.

Railway systems are particularly exposed to weather conditions. Heavy rainfall can generate intense surface runoff out of rivers able to carry mud, wood or debris. Intense surface runoff can cause major damage when impacting vulnerable railway sections, such as infrastructure flooding, ballast transport, embankment slope failure, erosion, or hydraulic structures clogging. For risk diagnoses, surface runoff hazard assessment suffers from a lack of dedicated method.

IRIP, “Indicator of Intense Pluvial Runoff” (French acronym), is an innovating method to map surface runoff susceptibility for all types of lands intercepted by railways.

In this article, the IRIP maps reliability is validated by comparison at different scales with results from diagnoses performed on a 20 km railway section in Normandy, known for its intense surface runoff issues. The analysis shows that the areas identified by the IRIP method agree with the sections identified by the diagnosis as in need of drainage regeneration works. Moreover, there is a good correlation between the spatial information of the IRIP maps and the field observations along with the recommended works outside the railway right-of-way.

Besides optimizing the actual diagnosis method, the IRIP maps offer the opportunity to push them forward by opening up water related risk management toward a systemic view.

1. INTRODUCTION

Hazards related to water can induce economic loss and create safety concern on the railway network [1], [2]. This study focuses particularly on intense surface runoff hazards. Surface runoff is the part of precipitation which does not infiltrate into the soil and which flows at ground surface outside the permanent river network [3]. Railways are linear and continuous features in the landscape and they intercept natural water flow paths [4]. When intense surface runoff occurs, the railway infrastructure can be affected by flooding, ballast transport, mudslides, embankment slope failures or erosion (Figure 1) [5]. These risks can have an impact on traffic safety and regularity. Besides the challenge of corrective maintenance, especially the warning procedure, there is a concern about improving the preventive part of risk management, both on existing or project railways.

Methods for surface runoff risks management on railways remain rather cursory. In terms of infrastructure dimensioning, the difficulties are that standard formulas for flow rates estimates are not really suitable when applied on small ungauged catchments, which are generally prone to surface runoff. Moreover, surface runoff flows are generally highly concentrated in soil particles. Hydraulic structures can be clogged by mud or damaged by large debris carried by the flows. This effect is not well rendered by a peak discharge's estimation. In terms of infrastructure maintenance, surface runoff impacts are difficult to anticipate. Sensitive sections are identified through the incident history and by field expertise. But, in order to decide the best prevention strategy, it is necessary to visualize the spatial distribution, at a watershed scale, of the intense runoff stages. While several methods and models exist, there is a lack of reference method that could be used for an extensive analysis of the exposure of a whole transportation network to the intense runoff hazards.

Figure 1: Photos of incidents on railways caused by surface runoff. From left to right: flood, ballast transport, mudslide and slope failure.

Surface runoff modelling is a scientific challenge for hydrologist. This natural hazard is influenced by multiple factors, such as topography, land use or soil properties and can be generated by intense or long duration, localized rainfall that are still difficult to forecast by meteorological models [6]. Existing surface runoff models either require multiple input parameters that are not available or enough precise on large territories, either focus on a single process of surface runoff such as talweg detection [7] or agricultural erosion [8]. The IRIP method, for Indicator of Intense Pluvial Runoff (French acronym), has been developed by the IRSTEA research institute in collaboration with SNCF (French Rail Company). It allows producing maps of surface runoff susceptibility [9]. The IRIP method combines computed surface runoff indicators and provides three maps, each one representing a key hydrological process, namely the generation, transfer and accumulation of the overland runoff. It uses readily accessible information layers which are DEM (Digital Elevation Model), a land use map and a soil map.

The objective of this paper is to show how the IRIP method can be a tool for decision making in terms of surface runoff risk management in the railway context. This work is part of a global process of evaluation and development of the IRIP method in the railway context. It follows previous studies that have demonstrated the value of the IRIP method for working on impacted area detection on large territories [10] and for post-incident survey, to develop a local interpretation of the runoff flow pathways [5], [11]. The present paper focuses on showing the contribution of the IRIP method to perform risk diagnoses at a railway line scale. This work is an additional contribution to the IRIP method evaluation but also to its use in problem solving and prevention strategy against the runoff hazard. For the purpose, we use the comparison to the recent diagnoses on the “Bréauté-Fécamp” railway line (Seine-Maritime County). First, the IRIP method and the diagnoses are presented. Then, the IRIP maps are compared to the diagnoses’ results in order to see if the field expertise and the recommended works agree with the surface runoff susceptibility maps. Finally, this paper provides guidelines for IRIP map interpretation and opens interesting prospects for using the IRIP method in risk diagnoses, and, beyond that, as a tool to support decision making.

2. MATERIALS AND METHODS

2.1. The IRIP method

The IRIP method allows producing three maps representing three key stages of the surface runoff processes. The surface runoff generation susceptibility map helps revealing where infiltration and/or storage capacity on large hillslopes are limited, so that it will favor the formation and motion of a free water layer at ground surface. Add to this, the soil erodibility contributes to the induced hazard, by increasing the water density though sediment transport. When moving along the hillslopes, this high density water can put in motion heavy materials. The surface runoff transfer susceptibility map outlines where the runoff can speed up and induce erosion and mudflows. The runoff generation map is one of the indicators used in producing the transfer map, because it is required to have an intense runoff input to induce strong erosion. The surface runoff accumulation susceptibility map shows areas where the runoff water can concentrate into talwegs, depressions, behind obstacles, or to slow down at concave break of slope. These conditions can locally increase the water depth and promote the deposition of the transported material. The score method is described in Table 1 [9], [10]. Five indicators are used for the creation of each map. Each indicator is calculated at each cell of the rasterized domain, and then ranked in a binary as follows : favorable to surface runoff (1) or not favorable (0). Note that each indicator is computed for each pixels and the final map takes the resolution of the input DEM. Finally, the 5 indicators are added to yield a 6 level map, from 0 (not susceptible) to 5 (very susceptible). Note that the final map takes the resolution of the input DEM. The input data used for this study are: the 5m resolution Lidar DEM from IGN (French National Geographic Institute), the European Soil Database at 500 meters resolution created from the LUCAS database [12] and the regional land use map (Mode d’Occupation des Sols Haute-Normandie 2009) at the scale of 1/5000 in rural areas and 1/2000 in urban areas.

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 (with respect to the pedo-transfer rules [13])
		1: Crustability ≥ 3
	Topography	0: Slope ≤ 0.5% AND topographic index [14] ≤ (mean + standard deviation) over the catchment
		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) over the catchment
		1: Drained area > (mean + standard deviation)
	Soil erodibility	0: Erodibility < 3 (with respect to the pedo-transfer rules [13])
		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) over the catchment
		1: Drained area > (mean + standard deviation)

Table 1: The 5 indicators used per map with the conditional values making them favorable or not to surface runoff. Note that first the map of surface runoff generation is created and then it is reclassified and used as an input indicator for the maps of transfer and accumulation.

2.2. The Bréauté-Fécamp Diagnosis

In the context of the regional policy of the Haute-Normandie region for the infrastructure and transport development, the Bréauté to Fécamp railway line has been identified as a substantial mean of transportation for the territory development. This railway line is 20 km long, is non-electrified and the maximum speed is 80 km/h. The railway traffic was slowed, to 60 km/h, then to 40 km/h and then has been stopped due to an advanced level of the infrastructure deterioration. Regarding the local environment, the catchment intercepted by the railway line is about 55 km², has an altitude from 6m to 146m OSL (Over Sea Level), and is composed of large plateaus (south and start of the line) and a narrow valley (north and end of the line) (Figure 2). The catchment soil is mainly composed of silt and clay on the plateaus, with colluvial deposit in the valley and the bedrock is composed of chalk and flint stones. There is no perennial river in the catchment but intermittently, during rainfall, small streams can arise within the main valley. The crossed land uses are dominated by agriculture with rural households and the small city of Fécamp in the north has about 20000 inhabitants.

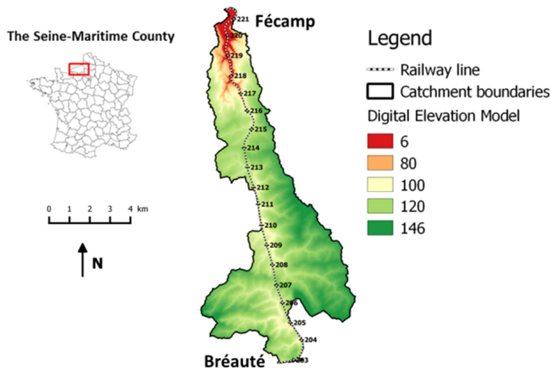

Figure 2: The Bréauté to Fécamp Railway line

In view of the many disorders and incidents, induced by surface runoff on this line, the infrastructure's manager planned substantial regeneration works in 2016. Two missions of hydraulic risk diagnoses were carried out. The first diagnosis performed in 2014, aimed at identifying sections at risk of stopping train circulation before 2016, for provisional measures before works. The second diagnosis, performed in 2015, aimed at recommending hydraulic and drainage works to be realized in the context of the regeneration works of 2016, in order to upgrade the railway to current standard. For the first diagnosis, the whole railway was investigated, considering the infrastructure configuration and its environment. The railway line was divided into sections based on hydraulic consistency. Then, the risk levels were assessed per section, regarding the level of hazard exposure and the level of infrastructure vulnerability. Finally, four sections were selected for provisional measures before the 2016 regeneration works. The second diagnosis is based mainly on the first risk analysis and focus only on drainage regeneration works, following schedule and budget constraints, expressed in infrastructure manager's instructions. Field expertise was conducted on each selected section focusing on the catchment inflows and on the existing hydraulic structures. Finally, recommended hydraulic works were described for twelve sections (which include the four of the previous mission), providing schemes and hydraulic structure dimensioning. A distinction is made between the works inside the railway right-of-way to be realized during the regeneration works and the works in the environment, upstream the railway to be realized in a second part.

To summarize, these two diagnoses had different objectives and constraints but provide complementary results: a comprehensive risk analysis on the whole railway and detailed analyses of twelve catchments along with their layout plans. Sources of uncertainties are steps which require expert opinions such as hazard and vulnerability assessment, section prioritization process. Field analysis are essential for experts and bring valuable information but can be time consuming and must be rigorously prepared to be efficient. Furthermore, dealing with infrastructure's manager constraints (budgets, work schedules,…) restrict what could be drawn from diagnoses' results. These diagnoses are not absolute representation of the railway exposure and are not an exhaustive guide for water related risk management on this railway line, out of some emergency measures and regeneration works. However, both diagnoses provide meaningful information about the inflows coming from the crossed hillslopes, and a fair source of comparison for the IRIP maps.

3. COMPARISON BETWEEN THE DIAGNOSES RESULTS AND THE IRIP MAPS

The objective of the comparison between the diagnosis results and the IRIP maps of surface runoff susceptibility is to explore and validate the map relevancy. It is also to judge the interest of the proposed regeneration works in a more holistic approach. Firstly, the comparison is made at the railway line scale, to see whether the twelve railway sections selected for regeneration works are detected as exposed to intense runoff by the IRIP method. A section is considered as detected by the IRIP method if there are susceptibility levels greater than or equal to 4/5 on the transfer map or on the accumulation map [10]. Then, for railway sections detected by the IRIP method but which were not selected for works, justifications are brought using the risk analysis on the whole railway. Secondly, the detailed analysis of each section allows focusing on spatial information of the IRIP maps. The objective is to show how the recommended works and the field expertise agree with the surface runoff spatial dynamic illustrated on the IRIP maps. Three sections are illustrated in details in this paper.

3.1. Railway line scale analysis

On the 12 railway sections selected for drainage regeneration works, all of them are correlated with high susceptibility levels of surface runoff transfer and/or accumulation. Table 2 describes the twelve sections, the types of risks to which they are exposed along with the types of recommended works, and the maximum susceptibility level of the IRIP maps of surface runoff transfer and accumulation. One can notice that types of runoff hazard which are related to the IRIP maps seem to well match to the types of risks the section is exposed to. For example, the line-section n°3 is located in an area strongly sensitive to surface runoff accumulation according to the IRIP method. This is consistent with the diagnosis report, which indicates this line-section is exposed to flooding with stagnation of water observed in the field. Likewise, section n°10 seems to be more sensitive to surface runoff transfer. This is confirmed, again, by the diagnosis mentioning the occurrence of an embankment slope on the section, with no particular signs of water at the railway surroundings.

Sections			Diagnoses		IRIP maps	
N°	**Type**	**Linear (m)**	**Risks**	**Recommended works**	**Max accumula-tion levels**	**Max transfer levels**
1	excavation	950	Flood, erosion and slope failure	Drainage system regeneration, geotextile consolidation, buffer strips and earthen bund creation, and proposal of two locations for a	4	4

				retention pond		
2	excavation	285	Flood, mudslide and slope failure	Drainage system regeneration and buffer strips creation	4	4
3	excavation	940	Flood, mudslide and stagnation of water at the ridge embankment	Drainage system regeneration, buffer strips creation and proposal of two locations for a retention pond	4	3
4	excavation	1165	Flood, mudslide and slope failure	Drainage system regeneration and buffer strips creation	4	4
5	excavation	500	Mudslide	Drainage system regeneration, buffer strips and earthen bund creation	4	4
6	excavation	1620	Flood, slope failure, mudslide and ballast transport	Drainage system regeneration, buffer strips and earthen bund creation, and cleaning of the aqueduc	5	4
7	excavation	525	Flood with mud	Drainage system regeneration, buffer strips creation and connection of drainage to an existing retention pond	5	5
8	excavation	1150	Flood, slope failure, mudslide and ballast transport	Drainage system regeneration, buffer strips creation and connection of drainage to an existing retention pond	5	4
9	excavation	350	Flood, erosion, mudslide and slope failure	Drainage system regeneration, buffer strips and earthen bund creation	5	5
10	excavation	270	Slope failure	Drainage system regeneration	3	4
11	excavation	190	Mudslide and slope failure	Ditch and earthen bund creation	4	4
12	excavation	1565	Flood, slope failure and ballast transport	Drainage system regeneration (urban area)	4	4

Table 2: The twelve railway sections selected by the diagnoses as in need of drainage regeneration works. The first main column presents the different railway sections, in the second main column is the summary of the diagnoses and the third main column indicates the maximum IRIP susceptibility levels obtained on the railway sections.

Moreover, seven sections are also detected by IRIP as sensitive to surface runoff transfer or accumulation. Table 3 shows the risks identified on each section along with the infrastructure vulnerability of the section according to the two diagnoses and the maximum susceptibility levels in transfer and in accumulation along with the catchment size according to the IRIP method. This table shows that these sections were not retained for drainage regeneration works because of a low vulnerability level of the infrastructure or a low level of exposure regarding water related hazards. Large tracksides were observed on sections 14 to 17. Regarding the catchment sizes which are lower than 0.5 Ha and the section lengths which are lower than 300 linear meters, the tracksides capacities were considered as sufficient for storing the potential runoff inflow volumes. Sections 18 and 19 were already impacted by surface runoff but since then were protected by earth works or hydraulic structures. Sections 20 and 21 are rocky excavations, little water related risks are identified according to the diagnoses but there is a risk of rock falls. Finally these sections were not retained because of small catchment sizes. The others sections of the railway line have IRIP susceptibility levels lower than or equal to 3, except for transversal accumulation axes (i.e. talwegs) but where an hydraulic structure allow water flowing below the railway.

Sections			**Diagnoses**		**IRIP maps**		
N°	**Type**	**Linear (m)**	**Risks**	**Infrastructure vulnerability**	**Max accumula-tion levels**	**Max transfer levels**	**Catchment area (Ha)**
14	Excavation	135	Little water related risk	large draining track sides	4	3	0.4
15	Excavation	280	Little water related risk	large draining track sides	4	3	1.2
16	Excavation	160	Little water related risk	large draining track sides	4	3	0.4
17	Excavation	260	Little water related risk	large draining track sides	4	3	0.4
18	Excavation	265	Mudslide	Railway protected by an earthen bund over 50 linear meters that keep runoff along the embankment ridge	4	4	1
19	Excavation	75	Slope failure	Large hydraulic structures before	5	4	0.5

				the excavation which redirect flows toward a retention pond			
20	Excavation	150	Little water related risk and rock fall risk	/	2	4	0.5
21	Excavation	270	Little water related risk, rock fall risk and mud observed on tracks	/	4	4	0.6

Table 3: The eight railway sections detected by the IRIP method as sensitive to surface runoff but that were not retained by the diagnoses. The first main column presents the railway sections, the second main column presents the risk and vulnerability analysis from the diagnoses, and the third main column presents the data from the IRIP maps.

3.2. Railway section scale analysis

In the following, three sections are presented in details, sections n°3 (Figure 3), 7 (Figure 4) and 8 (Figure 5). The comparisons of these sections and the IRIP maps are particularly interesting because of a high level of details, reported in the diagnoses. On each of the three following figures, 2 maps of the same area are shown. The map on the left side comes from the diagnosis and represents aerial views with the field observations and the recommended works. The map on the right side represents the two IRIP maps of accumulation and transfer susceptibility. Only the three highest susceptibility levels are represented. Besides the two maps, photos from the field illustrate the remarkable points.

3.2.1. Section n°3

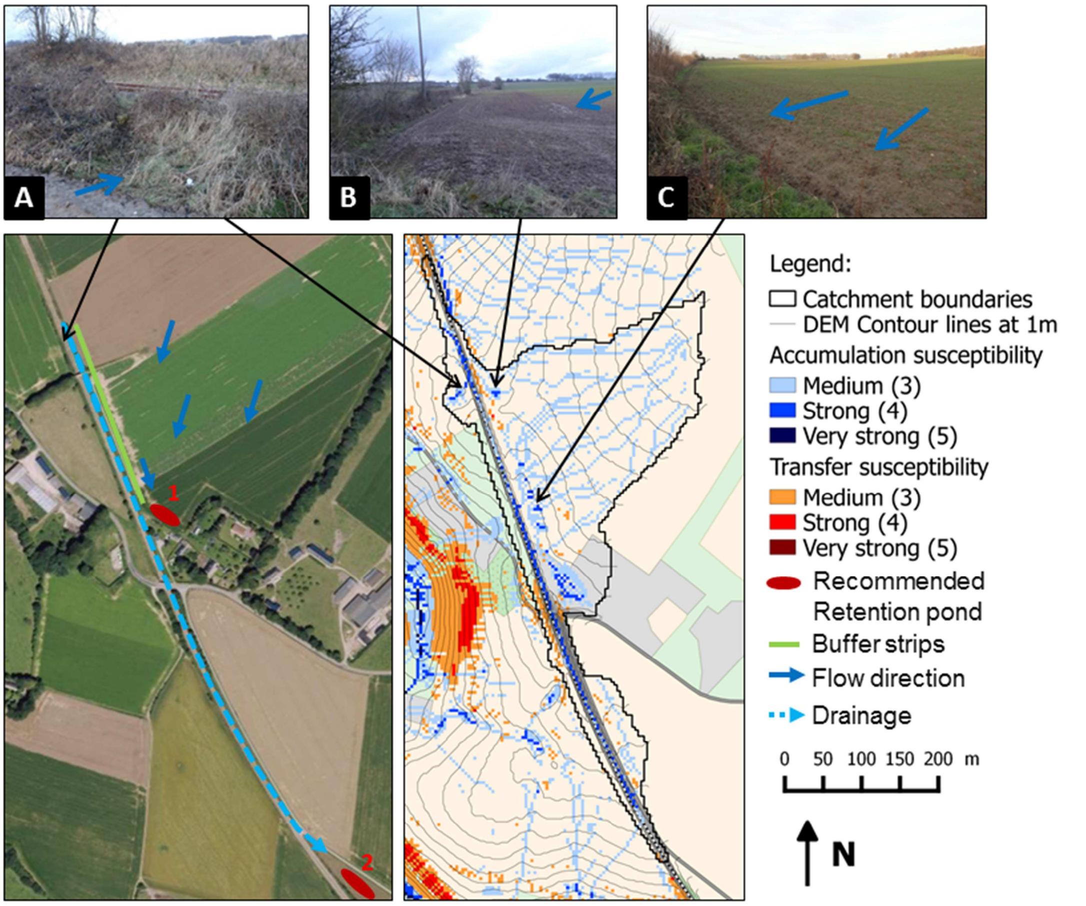

Figure 3: Comparison at section n°3 of the diagnosi s results and recommendation with the IRIP maps of surface runoff accumulation and transfer

This section is an excavation on 940 linear meters. The catchment intercepted by the section is on the right side and is about 11 Ha. The blue arrows represent the flow direction observed in the field. The blue dotted arrow represents the extent for the drainage regeneration works. The green line represents the buffer strip which here is recommended to be a grass strip to slow down surface runoff and to deposit soil sediments. The red features are the two proposed locations to construct a retention pond. Regarding the IRIP maps, the strong susceptibility of accumulation on the railway tracks correspond to the planned drainage works extent. The medium levels of accumulation within the catchment represent the preferential surface water paths and are correlated with the blue arrows. The medium and strong susceptibility levels at the ridge of the excavation (which potentially can generate a mudslide) correspond to areas of sediment deposit illustrated by photo C and confirmed by the recommended buffer strip. The 1st retention pond location is correlated with an important area of accumulation, which means that the IRIP map of accumulation agrees with what was entailed from field expertise. Moreover, the IRIP maps detect 2 accumulation areas (photos A and B) which are small but very close to the railway, and which correspond to water stagnation areas observed in the field.

3.2.2. Section n°7

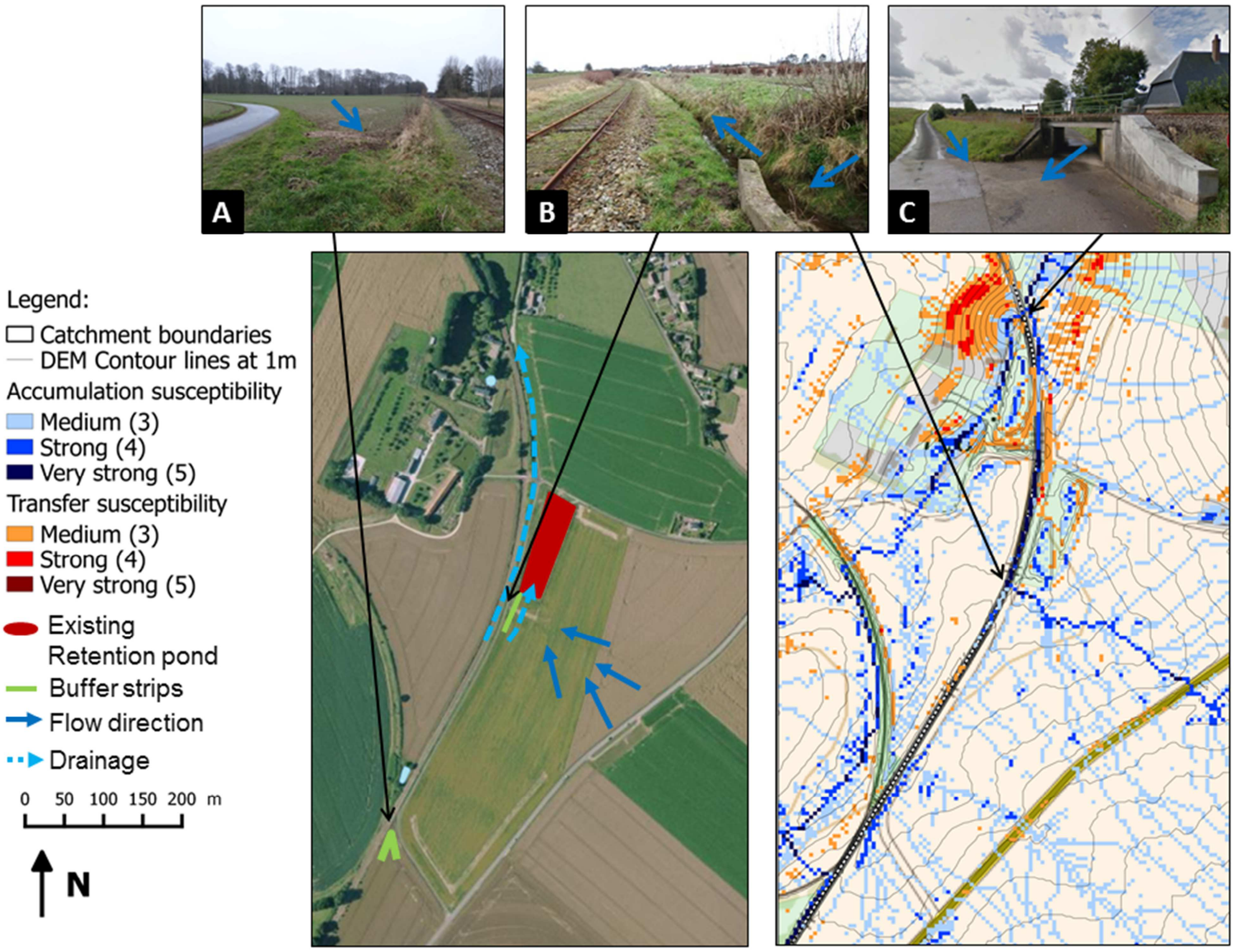

Figure 4: Comparison at section n°7 of the diagnosi s results and recommendations with the IRIP maps of surface runoff accumulation and transfer

This section is at ground level in the south part of the section and in an excavation in the north part. The section is about 800 meters long. The catchment intercepted by the section is on the right side and is about 1.2 km². On the maps, the blue arrows correspond to the main talweg identified by the IRIP map of accumulation. The IRIP map also shows two other talwegs, north of the main talweg along the road and south of the main talweg cutting transversally the yellow road. These water flow paths were confirmed by the experts. The buffer strip at the road corner corresponds to an area of strong water accumulation according to the IRIP map (photo A). The buffer strip allows stopping surface runoff before reaching the railway which is at ground level. The planned drainage works extent corresponds to the strong levels of accumulation on the railway track. The planned drainage ditch along the railway helps water flowing toward the existing retention pond. So, as observed in the field, the IRIP map shows that water from the main talweg is intercepted by the railway and flows downward within the railway drainage (photo B) until reaching the road on the right side at the end of the excavation (photo C). Before the road, the IRIP maps indicate levels of 5/5 for surface runoff accumulation and transfer (below the accumulation pixels). Considering the infrastructure configuration at this point (excavation), there is a very high risk of flooding in the excavation's part and slope erosion out of it in case of important water incomes.

3.2.3. Section n°8

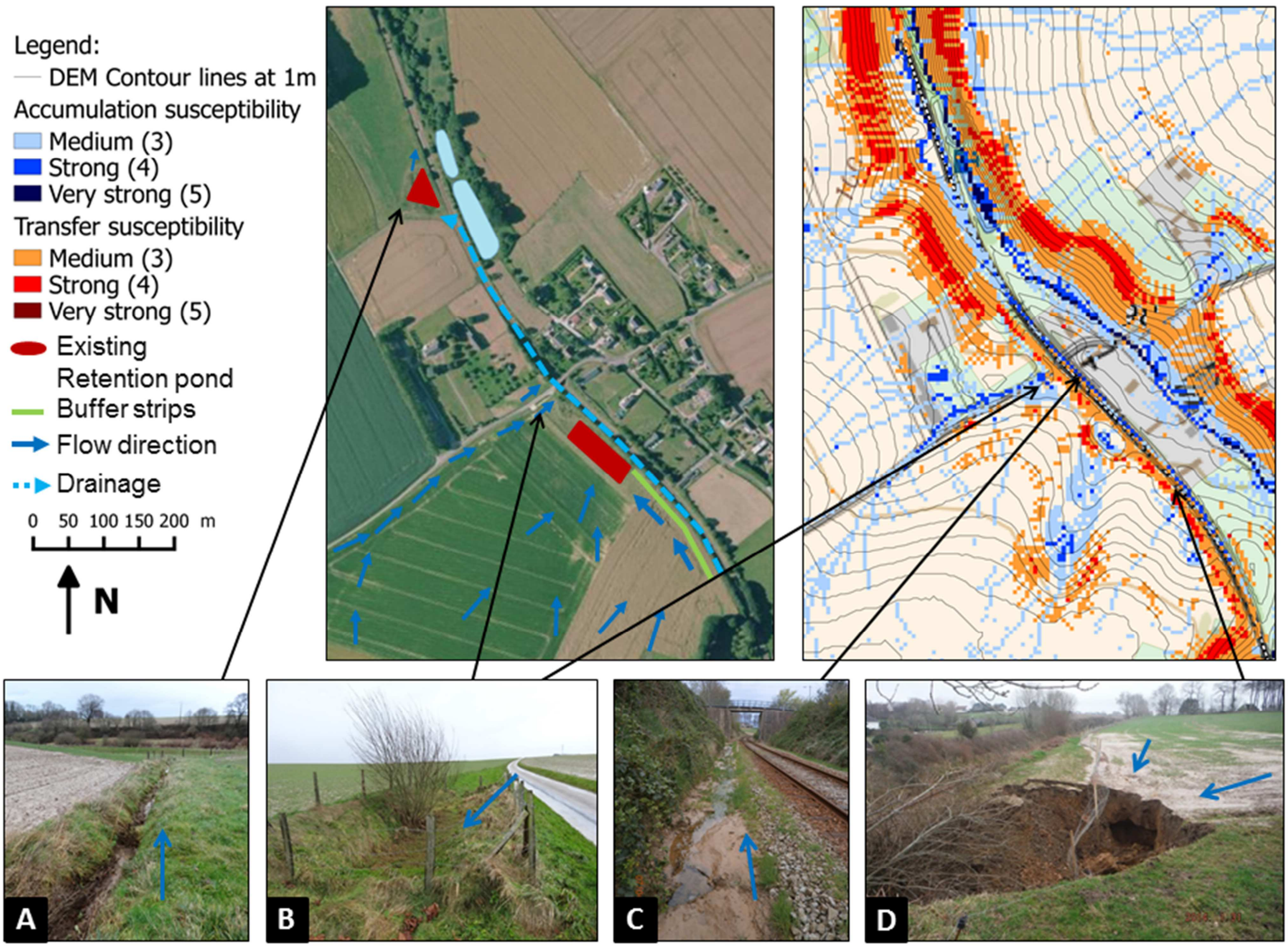

Figure 5: Comparison at section n°8 of the diagnosi s results and recommendation with the IRIP maps of surface runoff accumulation and transfer

This section is an excavation on 1150 linear meters. The catchment intercepted by the railway is on the left side and is about 46 Ha. The flow direction (blue arrows) observed in the field correspond to the IRIP map of accumulation which shows three main talwegs: one on the road with an accumulation area illustrated on photo B, one on the north of the road with an existing retention pond (photo A, triangle shape), and one on the south of the road with an existing retention pond upstream the railway (rectangle shape). The accumulation map shows smaller surface runoff flow paths within the catchment with medium levels (3/5). The planned drainage works extension corresponds to the strong accumulation levels on the railway tracks (photo C). The buffer strip is located at a previous slope failure location (photo D). It is interesting to see that at this point, the IRIP maps indicate strong levels of surface runoff transfer surrounded by strong levels of accumulation upward (sediment deposit area on photo D). The slope failure could have been generated both by a long term saturation of the slope by water and by a locally important income of water over the embankment that could have eroded the slope. Moreover, on the IRIP map, an important talweg is detected on the right side of the map, downstream the railway. This is not a river but an intermittent talweg that was subject to intense flash floods several times. The two large retention ponds (in light blue) downstream were built by the urban agglomeration to protect from flooding.

To conclude, this comparison between the diagnoses and the IRIP maps shows that the 12 railway sections selected for drainage regeneration works are also detected by the IRIP method as sensitive to surface runoff in accumulation and/or in transfer. 8 other sections are detected by the IRIP method but are considered as less vulnerable according to the diagnoses. The detailed analysis of three areas shows that there is a good agreement between the field expertise and the spatial information provided by the IRIP maps.

4. DISCUSSION

In terms of IRIP maps' interpretation guidelines, some standard combinations of high runoff hazard and vulnerable configurations can be inferred from the previous comparisons in order to consider an area as at risk. It must be noticed first that all the railway sections identified as needing drainage works present strong or very strong levels of surface runoff accumulation susceptibility along the railway tracks in the excavation. This type of IRIP information could indicate a risk of track flooding or mud and material deposits on track. Some significant correlations are also observed between slope failure locations and strong accumulation levels at the ridge of an excavation. This could indicate a risk of soil saturation with water stagnation, potentially leading to generation of a slope failure. Moreover, strong levels of transfer susceptibility on the sides of an excavation could indicate a risk of soil erosion and then risk of materials on tracks. It must be noticed also that strong levels of transfer or accumulation at a junction between an excavation and an embankment could indicate a risk of erosion of the embankment slope. Another configuration at risk is a surface runoff path cutting transversally an embankment. Experts must make sure that there is an aperture below the railway, for example a rail bridge as illustrated on Figure 4, photo C.

In terms of practical solution, a general method is proposed to embed the IRIP method into the actual risk diagnosis process : 1) Gather all the information available about the study site on a GIS software; 2) Create the IRIP maps with the iRIP software, and add them in the GIS map basis in order to get a global view of the catchment functioning in terms of surface runoff processes. Concerning resolution, using coarse resolution DEM (cells greater than 25 m) will yield maps of the main processes (the main surface runoff paths, the main erosion prone areas and the main surface water stagnation areas). Coarse resolution maps can bring valuable information at the start of a study, in order to better assess the catchment characteristics. Using a higher resolution DEM (cells lower than 25 m) will yield detailed maps and will allow identifying exposed railway sections; 3) Make a segmentation of the railway line in sections based on hydraulic consistency, as it has been done in previous diagnoses. One could define a hydraulic unit from the area where water arrives inside the railway right-of-way to the downstream water outlet, including the hydraulic structures and drainage systems in-between. The exposure of any vulnerable point to a surface runoff hazard could have a systemic impact across all the whole hydraulic unit; 4) Identify all the sensitive sections, worth to be visited. Regarding the IRIP maps, areas with high susceptibility levels (greater than or equal to 4) in accumulation or in transfer, on or close to a railway section (including the whole hydraulic unit) can be selected for visit. If the available information on the railway configuration is sufficient, the selection could be based on the standard combinations of high runoff hazard and vulnerable configurations, as explained in the previous paragraph. Some areas with low vulnerability can be discarded (i.e. high embankments, surface runoff axes at railway bridge locations); 5) Carry out the field expertise, still an indispensable step to better assess the hazard exposure levels, especially focusing on micro-topography. The IRIP method can guide the expert for its field analysis by computing the catchment boundaries of a railway section and by identifying the key points of the catchment to be analyzed and what is expected to be observed at these points (i.e. saturated soil or sediment deposits in accumulation areas and erosion traces or slope failure in transfer areas); 6) Deliver the diagnoses results according to the expectations of infrastructure's manager, by crossing the hazard exposition level and the vulnerability assessment (i.e. local infrastructure configuration, technical conditions of protective structures). What could be produced is a prioritization of sites (or sections) needing a corrective or preventive action, and recommendations of hydraulic works. The IRIP maps can be a tool to support these recommendations, especially for works outside the railway right-of-way. For example, accumulation areas can be potential locations for retention ponds or to install grass strips in order to make a sediment deposit area upstream the railway. Transfer areas can be potential location to install hedges or natural fences in order to prevent erosion or to stabilize a slope.

As shown above, the IRIP method could be used by expert at different diagnosis stages to optimize their methods. Moreover, the IRIP maps can be a visual basis for communication between experts, infrastructure's manager, but also other territory stakeholders. Thus, the spatial information of the surface runoff processes can help working toward a systemic management of water related risks. By illustrating how each local actor interferes with surface runoff, the IRIP maps could be a mean to suggest collaborative optimized mitigation solutions in terms a cost and sustainability.

CONCLUSION

This study focuses on the risk diagnosis process and shows the relevance and the value of the IRIP maps for this use. The IRIP maps are correlated with the diagnosis results all along the railway line and there is a strong correspondence between the field observation and the IRIP spatial information. Meaningful discussions with experts confirm the benefit of the surface runoff maps to support the analysis and to communicate with the project stakeholders. They also confirm the value of such maps for works outside the railway right-of-way, which is an essential solution for surface runoff risk management and for the network development in balance with its environment.

AKNOWLEDGEMENTS

We address a special thanks to Loïc Raigondeau, SNCF hydraulic specialist and Bréauté-Fécamp diagnosis supervisor, for his support throughout this work and his relevant advices. We also thank other contributors to Breauté-Fécamp's diagnoses' results we use in our comparisons (especially Yoni Poitevin and Ahlem Hasnaoui). Many thanks to all our reviewers whose opinions contributed to improve this article : Pascal Breil and Isabelle Braud, water science researchers at IRSTEA, Blandine Chazelle and Cicely Pams-Cappocioni, hydraulic engineers at SNCF Réseau. More generally speaking, we thank all the IRIP project contributors, especially Judicaël Dehotin, key proponent of the IRIP method development. Finally, we thank ANRT (Agence Nationale de la Recherche et de la Technologie) for partial funding of this work.

REFERENCES

[1] H. Maurer, L. Rudzikaite, J. Kiel, I. Partzsch, V. Pelikan, N. Sedlacek, E. Mitsakis, I. Stamos, A. Papanikolaou, and M. Celano, 'Weather Extremes: Assessment of Impacts on Transport Systems and Hazards for European Regions', *Weather project synthesis report*, 2012.

[2] M. Gonzva, B. Barroca, P. E. Gautier, and Y. Diab, 'A modelling of disruptions cascade effect within a rail transport system facing a flood hazard', in *48th ESReDA Seminar on Critical Infrastructures Preparedness: Status of Data for Resilience Modelling, Simulation and Analysis*, 2015.

[3] J. Dehotin and P. Breil, 'IRIP project: Research bibliographic report on surface runoff mapping', IRSTEA Hydrology-Hydraulic Research Unit, Literature review, 2011.

[4] B. Chazelle, L. Lambert, and C. P. Capoccioni, 'Railway vulnerability in case of extremes floods. Knowledge and risk management', *La Houille Blanche*, no. 2, pp. 48–54, 2014.

[5] J. Dehotin, B. Chazelle, G. Laverne, A. Hasnaoui, L. Lambert, P. Breil, and I. Braud, 'Applying runoff mapping method IRIP for flooding risk analysis on railway infrastructure', *La Houille Blanche*, no. 6, pp. 56–64, 2015.

[6] J. Dehotin, P. Breil, I. Braud, A. de Lavenne, M. Lagouy, and B. Sarrazin, 'Detecting surface runoff location in a small catchment using distributed and simple observation method', *Journal of Hydrology*, vol. 525, pp. 113–129, Jun. 2015.

[7] F. PONS, J.-L. DELGADO, P. GUERO, and E. BERTHIER, 'EXZECO: a gis and dem based method for pre-determination of flood risk related to direct runoff and flash floods', presented at the 9th International Conference on Hydroinformatics, Tianjin, CHINA, 2010.

[8] Y. Le Bissonnais, C. Montier, M. Jamagne, J. Daroussin, and D. King, 'Mapping erosion risk for cultivated soil in France', *Catena*, vol. 46, no. 2–3, pp. 207–220, Jan. 2002.

[9] J. Dehotin and P. Breil, 'Technical report of the IRIP project: mapping the flooding by runoff', IRSTEA Hydrology-Hydraulic Research Unit, Technical report, Jul. 2011.

[10] L.-R. Lagadec, P. Patrice, B. Chazelle, I. Braud, J. Dehotin, E. Hauchard, and P. Breil, 'Description and evaluation of an intense surface runoff susceptibility mapping method', *Journal of Hydrology*, 2016.

[11] L.-R. Lagadec, P. Breil, B. Chazelle, I. Braud, and L. Moulin, 'Use of post-event survey of impacts on railways for the evaluation of the IRIP method for surface runoff susceptibility mapping', presented at the FloodRisk, Lyon, France, 2016.

[12] C. Ballabio, P. Panagos, and L. Monatanarella, 'Mapping topsoil physical properties at European scale using the LUCAS database', *Geoderma*, vol. 261, pp. 110–123, Jan. 2016.

[13] O. Cerdan, Y. Le Bissonnais, V. Souchère, C. King, V. Antoni, N. Surdyk, I. Dubus, D. Arrouays, and J.-F. Desprats, 'Guide méthodologique pour un zonage départementale de l'érosion des sols Rapport n°3 : Synthèse et recommandations générales', BRGM - INRA, BRGM-RP-55104-FR, Dec. 2006.

[14] K. J. Beven and M. J. Kirkby, 'A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant', *Hydrological Sciences Journal*, vol. 24, no. 1, pp. 43–69, 1979.