Dear Professor Hildebrant,

Following our mail exchange and the clarifications during skype conversation, we have modified the manuscript in the following way:

- Consideration of the comments of reviewer 2 (see below for detailed answers)
- Explicit discussion that the modelling allows to assess a “worst-case scenario” and a relative ranking of the potential impact
- Significant tightening of the text in response to the comments of reviewer 2

After careful consideration we decided to keep the current order of discussing the field experiment first and then the modelling.

Thank you again for handling the paper.

Answers to your specific comments in your mail from the 23.8.2019:

For example, in section 3.1 the manuscript states that one of the preferential pathways at site SCH was due to the L-drain and the other was unrelated. This may suggest that the L-drain creates flow paths that are of similar impact as the natural heterogeneity. Or worse, both flow path could actually be due to natural heterogeneity.

The natural heterogeneity under the road no longer exists. The road was constructed in a way to concentrate flow through the drain. This is exactly what we see in the example of SCH.

In my reading of section 3.1 and presented data, the field study does not contribute to “show” that the L-drain constitutes the largest perturbation (this is a statement from the abstract), and also not that modeling and field study are coherent (from the abstract). I agree that the field observations do not contradict the modeling study, but this is a substantially more careful phrasing as currently.

Following your suggestion, we have adjusted the legend in Figure 7 to highlight the relative importance of the drains. The field results clearly show that the relative impact (in terms of concentration the flow) is most pronounced with the L-drain. We have added explanations highlighting that the models present a “worst-case” scenario. This is also considered in the abstract and in the conclusions.

The main conclusion of the abstract is that L-drains constitute the largest perturbation to the ground water flow, and the other investigated structures less so. My main criticism is that the word “perturbation” implies moving the system away from its natural state. The natural state is one marked with substantial heterogeneity causing flow paths. That natural heterogeneity is substantial, as shown be the experiment.

As discussed with you on skype, we feel the word perturbation is appropriate as a constructed road through a wetland is always moving the system away from its natural state.

In my letter, I also proposed a way forward which does not imply new model runs. In response in your e-mail below you state “heterogeneity can, if one is lucky, reduce the influence of the drain”. This type of statement should absolutely enter the manuscript. The homogeneous case is more or less the worst-case scenario. This is ok. But the overall tone of the manuscript needs to reflect this. Also, how can you quantify “if one is lucky”, based on the field study?

We discuss this in the context of Figure 7. For the L-drain case one can see that a “plume” is forming downstream of the drain, i.e. that the concentrated flow is, to a certain extent redistributed. If no gullies form, it is indeed possible that the influence of the road downstream is reduced due to the horizontal redistribution of water through heterogeneous pathways.

Personally, I would switch the order of presentation to first show the model results and follow up with the field study and discuss how it actually supports the model conclusions and where it is maybe inconclusive.

We have carefully considered this point and decided to stick to the original order. However, we added an additional explanation concerning the field- and modelling approach which also better explains the order.

Reviewer 2

Second Revision on „Assessing the perturbations of the hydrogeological regime in sloping fens through roads" by Fabien Cochand, Daniel Käser, Philippe Grosvernier, Daniel Hunkeler, Philip Brunner

General Comments

I appreciate the detailed response of the authors to the comments I raised in the first round of review. They addressed all points and adapted the manuscript accordingly in most places.
We thank the reviewer for this positive feedback.

The manuscript and figures have been improved significantly. At some positions, the added text requires further revision. Sometimes, the authors gave explanations as response to the reviewer which should be given in the manuscript to clarify these points also for the reader who might wonder at the same aspects while reading. There are also few remaining open questions from the first round of review. These issues are addressed in the comments below.
See our response to the comments below. We have gone the text very carefully and tightened the text and presentation in several places.

Although the author stated that they reworked the text (specifically in some sub-sections of 2 & 3), it appears to me that they only added few lines/words/brackets at critical points for some parts. Several paragraphs are still written in a repetitive and elongated manner which is not reader-friendly. You could easily cut out redundant phrases and repetitions to increase the readability (some examples given below). The authors should consider professional language support or at least a proper proofreading and revision by a native speaker.
The document has been carefully checked and the wording has been improved.

Specific Comments

Background information on the three road structures developed in Switzerland is still missing [introduction].
We are aware of this. However, such data are not available. Most road constructions are on private grounds and there is no central data-based bringing together all of these data.

Typo in l. 71-72
Thank you

Integrate your response to the text as background information on the model setup for the road types, e.g. When a road construction takes place, impermeable material is excavated upstream and filled downstream which is represented by an increased number of inactive cells below the road. (from answer to "The mesh modifications for cases 5d, 5e and 5f show an artificial increase of inactive cells below the road (step shape instead of continuous slope form).
We have now included a slightly modified version of this sentence in the introduction and the model setup:

Shouldn't there be soil cells below the road construction? This might significantly modify the simulation results.")
No, in the cases we know this is not the case. The roads are constructed in a way to avoid this. The depth of the road construction does not have to go deep, as the soil layer above the clay is very thin (e.g. 40cm) in the sloping fens in Switzerland.

Section 2.2.3:
It is not done by just renaming the subsection title; the text should be adapted as well (e.g. the first sentence in the section still starts with "The sensitivity analysis...")
As highlighted above, we have modified and tightened the text.

Many newly added sentences require improvement in language (line 212-216, l. 2018-220), please perform a proper proofreading
As highlighted above, we have modified and tightened the text.

The authors still have a lot of redundant text which inhibits the readability:
As highlighted above, we have modified and tightened the text.

Phrases like "In order to simulate each parameter combination" (l.224) could easily be cut out without any loss of information.
You could cut the entire sentences in l. 229-232: the method section should contain the specific information, not elaborate explanations on the motivation (which is anyway clear at that point of the paper).
As highlighted above, we have modified and tightened the text.

Section 3
Figure 7: First column: Head profile for the second and third site are still missing head values above and below the road which inhibits a proper picture of the hydraulics at these sites. I agree with the authors that the original form of display is preferable.
Note that the hydraulic head downslope the road in the Stouffe site is about 25cm and upslope the road in the Schöniseischwand is about 225cm and. The isolines are drown each 50cm, therefore these isolines are not presented in the figure.

Section 3.2 could still be condensed to focus on key facts and major results.
We have condensed this section

The discussion on gully erosion is a valuable addition. However, the text requires proper proofreading and shortening (e.g. the sentence in l. 341 is basically redundant).
The section was carefully reworked and shortened

Typo in l. 322 "and"
Thank you

Figure 11: is interesting, however only for the no-road and L-drain comparison. The authors might consider different scaling to see differences also in the no-excavation and wood-log structures.
We have decided to remove Figure 11 and added a brief description to the text. Even with additional scaling, the perturbations are minor and thus can be discussed in the text.

Specific recommendations (l.335) are rather part of the conclusion section.
We have removed this information from this section

L 344-358 are also rather part of a summary and/or conclusion.
Parts of this section were moved to the conclusions. We kept the model-specific point only

I still cannot agree with the sentence "Models results have to be interpreted as an average across multiple preferential flow paths." (l. 353-354) The simulation results in a homogeneous medium do not represent mean results of simulations in heterogeneous domains with preferential flow path! (Maybe just skip the sentence, the previous one gives a proper explanation.)

Thank you, we have deleted this sentence, as you suggested.

Assessing the perturbations of the hydrogeological regime in sloping fens through roads

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Abstract

Roads in sloping fens constitute a hydraulic barrier for surface and subsurface flow. This can lead to the~~a~~the drying out of downslope areas of the sloping fen as well as gully erosion. Different types of road construction have been proposed to limit the negative implications of the roads on flow dynamics. However, so far no systematic analysis of their effectiveness has been carried out. This study presents an assessment of the hydrogeological impact of three types of road structures in semi-alpine, sloping fens in Switzerland. Our analysis is based on a combination of field measurements and fully integrated,~~-~~physically-~~-~~based modelling. In the field approach, the influence of the road was examined through tracer tests where the ~~upslope~~upslope of the road was sprinkled with a saline solution. The spatial distribution of electrical conductivity downslope provided a qualitative assessment of the flow paths and thus the implications of the road structures on subsurface flow. A quantitative albeit not site-specific assessment was carried out using numerical models simulating surface and subsurface flow in a fully coupled way. ~~-~~The different road types were implemented in the model and flow dynamics were simulated for a wide range of slopes and hydrogeological conditions such as different hydraulic conductivity of the soil. The results of the field and modelling analysis ~~are coherent.~~clearly indicate that~~ R~~ roads designed with an L-drain (i.e. collecting water ~~upslope~~upslope and releasing it in a concentrated manner downslope) constitute the largest perturbations in terms of flow dynamics. The other investigated road structures were found to have less impact. The developed methodologies and results ~~are useful~~can be used for the planning of future road projects.

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1 Introduction

Wetlands can play a significant role in flood control (Baker, 2009;Zollner, 2003;Reckendorfer, 2013);~~Reckendorfer, 2013)~~, mitigate climate change impacts (Cognard Plancq et al., 2004;Samaritani et al., 2011;~~;Samaritani et al., 2011;~~Lindsay, 2010;Limpens, 2008) and feature great biodiversity (Rydin, 2005). However, the world has lost 64% of its wetland areas since 1900 and an even greater loss has been observed in Switzerland (Broggi, 1990)~~(Broggi, 1990)~~. Therefore, wetland conservation has received considerable attention. However, the sprawl of human infrastructure, land-use changes, climate change or river regulations remain serious factors that threaten wetlands. For instance, roads can substantially modify the surface-subsurface flow patterns of sloping fens. The changes in flow patterns can influence sediment transport, moisture dynamics and biogeochemical processes as well as ecological dynamics.

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The link between hydrological changes and sediment dynamics has been studied in various contexts see e.g. Partington et al. (2017).Partington et al. 2017~~.~~ From a civil engineering perspective, erosion of the road must be avoided. A common strategy to avoid erosion of the road foundation is to collect water in drains and then release it in a concentrated manner downslope. This, however, can lead to erosion of the downslope area, a phenomenon known as « gully erosion ». A number of studies specifically focused on identifying the controlling processes and relevant parameters of gully erosion (Capra et al. (2009);Valentin et al. (2005);~~);Valentin et al. (2005a);~~Descroix et al. (2008);Poesen et al. (2003);~~);Poesen et al. (2003);~~Martínez-Casasnovas (2003);~~);~~Daba et al. (2003);~~);~~Betts and DeRose (1999);~~);~~Derose et al. (1998)~~)~~, among others). Nyssen et al. (2002)~~Nyssen et al. (2002)~~ investigated the impact of road construction on gully erosion in the northern Ethiopian highlands, with a focus on surface water. In their study area, they observed the formation of a gully after the road construction ~~downslope culvert and~~downstream of the outlets of ~~lateral~~ the ~~road~~ drains. Based on fieldwork and ~~a~~ subsequent statistical analysis, they concluded that the main causes for gully development are a~~the~~ concentrated runoff, the diversion of concentered runoff to other catchments and the modifications of drainage areas induced by the road. The role of groundwater was not considered in this study.

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Reid and Dunne (1984)~~Reid and Dunne (1984)~~ developed an empirical model for estimating road sediment erosion of roads located in forested catchments in the Washington state (USA). They concluded that a heavily used road produced 130 times more sediment that an abandoned road. Wemple and Jones (2003)~~Wemple and Jones (2003)~~ also developed an empirical model for estimating runoff production of a forest road at a catchment scale. They demonstrated that during large storm events, subsurface flow can be intercepted by the road. The intercepted

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water, if directly routed to ditches, increases the rising limb of the catchment hydrograph. At a smaller spatial scale (0.1 km^2) Loague and VanderKwaak (2002)~~Loague and VanderKwaak (2002)~~ assessed the impact of a road on the surface and subsurface flow using an integrated surface-subsurface flow model InHM (Integrated Hydrology Model) (VanderKwaak, 1999)~~(VanderKwaak, 1999)~~ in a rural catchment. The results showed that the road induced a slight increase of runoff and a decrease of surface-subsurface water exchange around the road. Dutton et al. (2005)~~Dutton et al. (2005)~~ investigated the impact of roads on the near-surface subsurface flow using a variability saturated subsurface model. They concluded that the permeability contrast caused by the road construction leads to a disturbance of near-surface subsurface flow which may significantly modify the physical and ecological environment.

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Road construction can also impact the development of vegetation (Chimner, 2016). Von Sengbusch (2015)~~von Sengbusch (2015)~~ investigated the changes in the growth of bog pines located in a mountain mire in the black forest (south-west Germany). The author suggests that the increase of bog pine cover is caused by a delayed effect of a road construction in 1983 along a margin of the bog. The road affects the subsurface flow and therefore prevents the ~~upslope~~upslope water to flow to the bog. According to Von Sengbusch (2015)~~, von Sengbusch (2015),~~ the road disturbances induce a larger variability in water table elevations during dry periods and consequently increase the sensitivity of the bog to climate change.

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Based on these previous studies, ~~and basic principles of subsurface flow (Darcys' law),~~ a simple conceptual model describing the influence of roads on the flow system can be drawn (Figure 1). ~~– Common to all road types are the physical laws that describe subsurface flow (Darcy's law) and surface flow (a surface flow equation such as the diffusion wave approximate to the Saint Venant equations). Roads are generally built with materials of low hydraulic conductive and therefore act as a~~constitute a ~~hydrogeological barrier.~~ In natural conditions, rainwater infiltrates the soil and follows the topographical gradient. In case of heavy precipitation events, water can also directly flow on the surface (runoff in ~~(~~Figure 1~~Figure 1~~a). To~~a~~, overland flow)~~)~~ ~~as overland flow~~. ~~When a road construction takes place~~To construct the foundation of the a road, a~~impermeable~~ material with a very low permeability is used.~~is excavated upstream and filled downstream to avoid erosion of the construction~~used ~~material under the road~~. This subsequently blocks the flow from the upslopeupstream towards the downslopedownstream. However, due to the buildup of hydraulic heads in the upslopeupstream of the road (Figure 1b), the road)~~without the presence of a drain to connected the upstream and the downstream,~~ the road ~~would~~is can be innundated during precipitation events. ~~, due to the buildup of hydraulic heads in the upstream of the road (Figure 1b).~~ To reduce the occurrence of inundations, drains are installed under all roads (Figure 1c). The design and the materials of drains

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have~~significantly~~have potentially a significant effect~~a~~effect on flow dynamics. Figure 1~~Figure 1~~c presents a typical condition where a non-continuous drain (i.e., drains are perpendicularly installed at regular distances along the road) is installed.~~used to connect both sides of the road~~installed. The drain captures the ~~Upstream ~~flow upslopeupstream along the road and the discharge is released in a concentrated manner downslope. Thisdownstream. ~~and downstream subsurface flows are deviated and the drain becomes the main outlet. ~~Theis concentration of ~~subsurface ~~flow downslopedownstream ~~of the drain ~~may induce gully erosion and disturb the hydraulic regime of the sloping fens~~.~~. For example, the wetland is at risk of drying out downslopedownstream of the road as the flow is concentrated to a small strip downslopedownstream of the drain. Note~~,~~, however, ~~however,~~ that a gully must not necessarily develop because the flow-velocity at the drain-exit might not be sufficiently large to trigger erosion. Also, the drying out of the wetland beyond the direct vicinity of the downslopedownstream area of the drain must not necessarily happen. The~~ and t~~The concentrated release from the drain can water, to a certain extent, spread out horizontally. In any case, a~~s~~

~~If a~~Aa road~~ thus is constructed, it ~~constitutes a hydrogeological barrier which~~(Figure 1b) and consequently affects witch~~whitch perturbs the natural ~~the ~~flow dynamics. ~~Drains installed underneath the road Figure 1c) can mitigate the effect of this hydrogeological barrier. The design and the materials of drains significantly affect flow dynamics. Figure 1c presents a typical condition where a non-continuous drain (i.e., drains are perpendicularly installed at regular distances along the road) is used to connect both sides of the road. Upstream and downstream subsurface flows are deviated and the drain becomes the main outlet. The concentration of subsurface flow downstream of the drain may induce gully erosion and disturb the hydraulic regime of the sloping fens.~~

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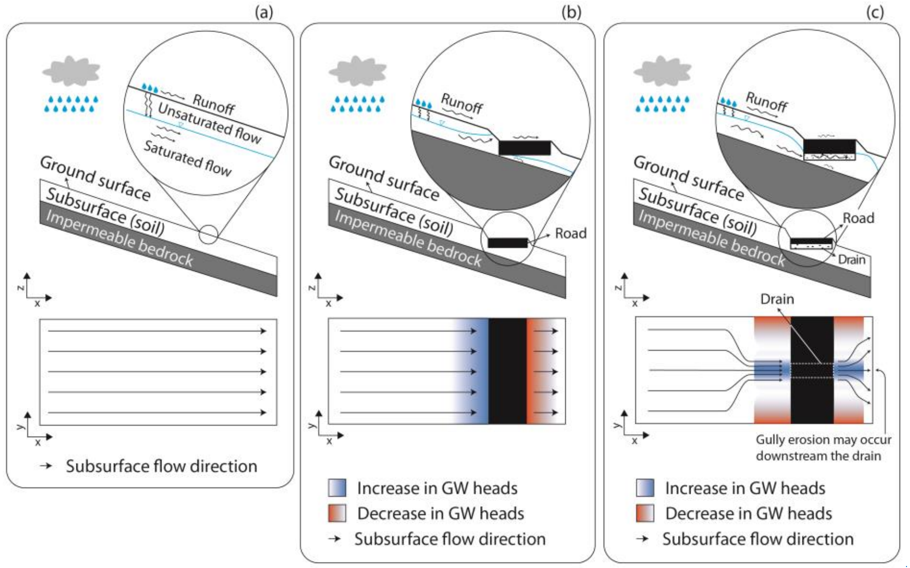

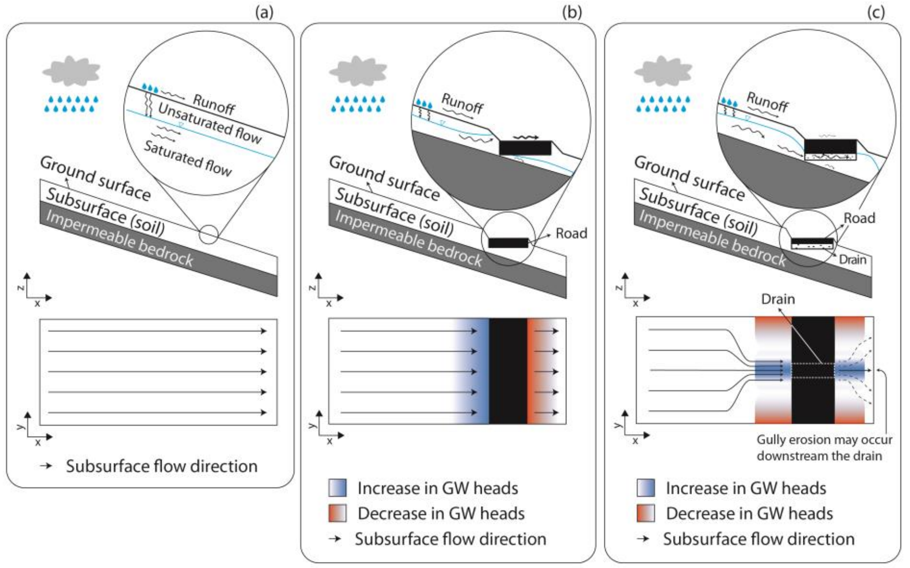

Figure 1: Conceptual subsurface dynamics in sloping fens: a) natural conditions, b) ~~with~~ a road without a drain (only shown for illustrative reasons as essentially all roads have drains). In this case, water will flow both across and under the road. Uncontrolled flow beneath the road can cause erosion of the road foundation. ~~and~~ c) ~~with~~ a road ~~and~~ with a drain: In this design, surface water flow is reduced and flow beneath road occurs in a controlled manner through the drain. Water is released downslopedownstream in a concentrated manner with the risk of gully erosion and the drying out of parts of the wetland. While it is possible that the concentrated groundwater flowsflow fens our horizontally downslopedownstream through natural heterogeneity, there is a high risk of gully erosion. ~~.~~

The design of the roads and especially the drains is expected to have a significant influence on the degree of perturbation. ~~While these studies clearly indicate that roads can have adverse effects on the surface and subsurface flow dynamics and the associated ecosystems, a detailed study on how roads perturb the flow system and dynamics in a sloping fen has not been carried out. In Switzerland, more than 20’000 ha are included in the national inventory of fens of national importance (Broggi 1990), most of them are located in the mountainous regions of the northern Prealps. Hence, the majority of Swiss fens is composed of sloping fens, which developed on nearly impermeable geomorphological layers such as silty moraine material or a particular rock layer named “flysch”. Although organic, soils are not necessarily peaty and most of the time quite superficial, not exceeding a few decimeters in thickness. Water flow is therefore mostly consisting of runoff and partly occurring in the shallow part of the subsurface. The construction of a road in this kind of sloping fens removes completely the soil layer in which subsurface flow occurs, thus constituting a major perturbation of the hydraulic regime. Construction techniques to limit these adverse impacts have been proposed but their efficiency has so far not been investigated.~~ Three fundamentally different road structures ~~with various construction techniques and materials (hereinafter further detailed)~~ were developed in Switzerland to reduce the impacts of roads. These three road types are conceptually illustrated in Figure 2~~Figure 2~~. The efficiency of developed road structures was so far not assessed after completion~~,~~, neither in the field through field-based experiments, nor on a conceptual level.~~.~~ This study focuses on these three road structures~~ described hereafter~~:

- The *no-excavation* structure (Figure 2~~Figure 2~~a) aims at preserving soil continuity under the road. It consists of a leveled~~levelled~~ layer of gravel, anchored to the ground, and underlying 0.16m thick concrete slabs. Soil compaction is limited by using ~~a~~ low-density gravel, made of expanded glass chunks (Misapor™) - approximately fivefold lighter than conventional material.
- The *L-drain* structure (Figure 2~~Figure 2~~b) aims at collecting subsurface water upslope~~upstream~~ the road and redirecting it to discrete outlets on the other side. The setup consists of a trench, approximately 0.4m deep, filled with a matrix of sandy gravel that contains an L-shaped band of coarse gravel acting as the drain. This is the most common approach to build roads in Switzerland.
- The *wood-log* structure (Figure 2~~Figure 2~~c) aims at promoting homogeneous flow under the road but does not preserve soil continuity. Embedded in a trench, approximately 0.4m deep, the wooden framework is filled with wooden logs forming a permeable medium. The wooden logs are then covered with mixed gravel.

In Switzerland, more than 20’000 ha are included in the national inventory of fens of national importance (Broggi 1990), most of them are located in the mountainous regions of the northern Prealps. These fens developed on nearly impermeable geomorphological layers such as silty moraine material or a particular rock layer named “flysch”. The majority of remaining Swiss fens are sloping fens in this particular geological environment. To protect the remaining wetlands it is important to reduce the impact of these constructions, be it in the context of replacing existing, old roads or for the construction of new roads.

The aim of this study is to investigate~~, document and assess~~ the hydrogeological impact of the threethree~~various~~ road structures and their effects on fen water dynamics to support decision-makers in choosing road structures with minimal impact. ~~A~~A combination of fieldwork and hydrogeological modelling tasks was employed. Fieldwork was used to document ~~and obtain the required information on~~ the hydrogeological impact of existing road structures on fen water dynamics. It is the first time that these road-types are systematically analysed under field conditions.~~ and thus provide important information on their effectiveness.~~ Sites with similar natural conditions were chosen to compare the influence of different road constructions on flow processes. The field studies allow for assessing the effectiveness of a given road structure at a particular location, however, they cannot provide a generalizable analysis of the different road types under different environmental and physical conditions, e.g. the slope or the hydraulic properties of the fen. This gap was filled by the development of generic numerical models. The models are kept deliberately simple in terms of the heterogeneity of the soil. This~~The main advantage of the modelling approach is~~This allows to comparatively explore the potential impact of the different road structures. ~~with regard to the~~ ~~the possibility to generate a multitude of different models with various characteristics such as different road structures, influence of~~ The modelling allows a systematic comparisoncomparion of this potential impact for different conditions for the most important hydraulic properties: the slopes of~~o~~f~~r~~ fens and the bulk hydraulic conductivity. ~~hydraulic conductivity and to test their impacts on the flow dynamics. These model results can help in the planning of new roads.~~ However, as the heterogeneity of the soil is not considered in the models and the horizontal redistribution due to field-specific heterogeneity cannot be considered (see figure 1c), the),~~.~~ t~~T~~he simulations ~~thus~~ thus constitute a “worst-case “ scenario, which ~~nevertheless~~ allows a ranking the different road structures in terms of perturbation and the risk~~perturbation~~risk for gully erosion.

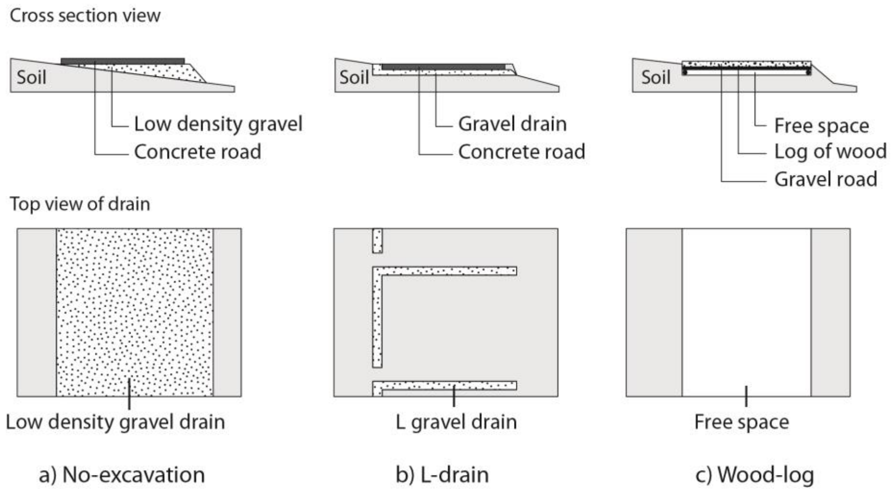

Figure 2 : Conceptual road structures, a) No-excavation road structure, b) L-drain road structure and c) Wood-log road structure.

2 Methods

2.1 Study areas and fieldwork

Four sloping fen areas located in alpine or peri-alpine regions of Switzerland (Table 1~~Table 1~~) were selected. All areas are situated in protected fen areas, and their selection was based on two main criteria:

1. The subsurface water flow must occur only in the topsoil layer and as runoff (as described in the introduction).
2. The types of installed road structures (no-excavation, L-drain and wood-log).

To fulfil the first criteria, soil profiles were analysed to ensure that each area with different road types had the comparable soil stratigraphy: It had to be composed of organic soil on top of a layer of impermeable clay and similar hydraulic regimes (e.g., runoff and subsurface flow occurring only in the topsoil layer). In addition, to ensure that subsurface water is forced to cross the road instead of flowing in parallel of the road (and thus not being affected directly by the road), another important criterion for the selection of the study areas was that subsurface flow is perpendicular to the road.

To evaluate the hydraulic connection provided by the roadbed~~road bed~~ structures, tracer tests were carried out. As illustrated schematically in Figure 3, ~~a saline solution was spread on~~ the ~~upslope~~upstream area was irrigated with a saline solution and the occurrence of the tracer was monitored downslope the road. In the absence of surface runoff, the occurrence of a tracer downslope demonstrates the hydrogeological connection through the road. Furthermore, the spatial distribution of the tracer front reflects the heterogeneity of the flow paths.

Table 1. Field site locations and features.

	St-Antonien (STA)	**Schoeniseischwand (SCH)**	**Stouffe (STO)**	**Höhmad (HMD)**
Road type	No excavation	L-Drain	Wood-log	Wood-log
Terrain slope	0.27	0.13	0.13	0.15
WGS84 coordinates	46.96760°N 9.84843°E	46.78872°N 7.96805°E	46.72957°N 7.83861°E	46.74027°N 7.89871°E

~~Each area~~ On each fieldsite, an area of a ~~corresponds to an~~ 8 x 20m rectangle that includes a 2.5 to 3.5m wide road segment was selected. A network of approximately 30 mini-piezometers on both sides of the road (Figure 3~~Figure 3~~) was installed to monitor the hydraulic heads and was used to obtain samples for the tracer test.

The mini-piezometers are high-density polyethene (HDPE) tubes no longer than 1.5m (ID: 24mm). Each tube was screened with 0.4mm slots from the bottom end to 5cm below ground level. It was inserted into the soil after extracting a core with a manual auger (diameter: 4-6cm). The gap between the tube and the soil was filled with fine gravel and sealed on the top with a 4cm thick layer of bentonite or local clay. Hydraulic heads were measured using a manual water-level meter (± 0.3cm). At each point, the terrain and the top of the piezometer were levelled using a level (± 0.3cm), whereas the horizontal position was measured with a tape measure (± 5cm).

The tracer tests were conducted using two oscillating sprinklers designed to reproduce a 30mm rain event during 2-3 hours. This is equivalent to an intense rain event. Prior to the experiment, the sprinklers were activated for 15-60 minutes to wet the soil surface. Sodium chloride was added to the irrigated solution to obtain an electrical conductivity of 5-10mS/cm which is approximately ten times higher than the natural electrical conductivity of the groundwater. Subsequently~~Then~~Subsequently, the area (60m^2) ~~upslope~~upslope of the road (upslope injection area of Figure 3~~Figure 3~~) was irrigated with the salt solution using the two sprinklers. The electrical conductivity (EC) of soil water was manually measured using a ~~conductimeter~~ conductivity meter in all mini-piezometers prior to the experiment, immediately after, and 24h later. An increase in EC in piezometers located in the downslope area indicates that the injected salt water flowed from the ~~upslope~~upstream area to the downslope area below the road and clearly shows a hydraulic connection. Conversely, if no changes in EC are observed in piezometers, this indicates a strongly hampered hydraulic connection below the road.

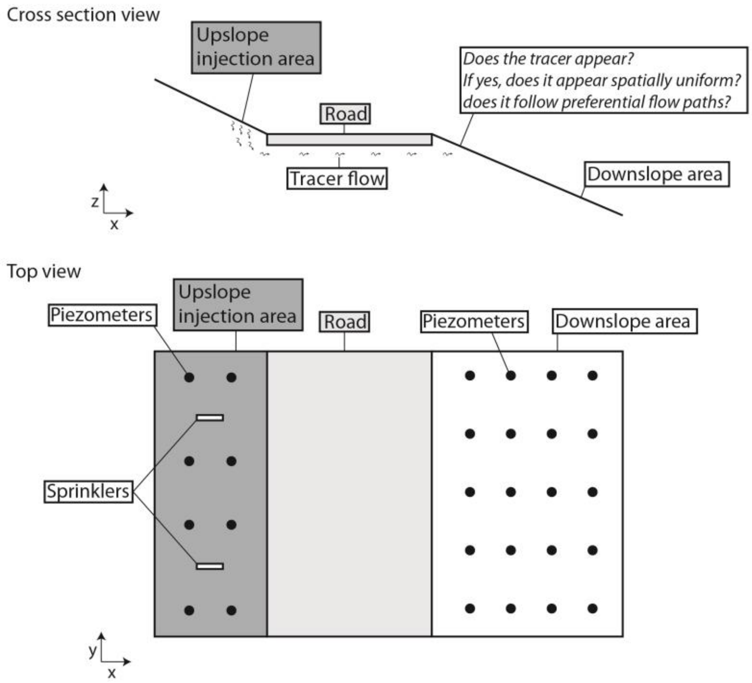

Figure 3 : Schematic view of the fieldwork areas.

2.2 Numerical modelling

The~~To simulate and quantify the impact of the roads on the flow dynamics in sloping fens~~ in a generalized way, ~~t~~T~~he~~ modelling approach was structured in three steps. First, a 3D base case model representing surface and subsurface water flow in a sloping fen was elaborated. Subsequently~~Then~~Subsequently, the base case model was modified to represent the three different types of ~~investigated~~ road structures. For each model, various slopes, ~~organic~~ soil and road drain hydraulic conductivities were implemented to produce a sensitivity analysis and explore their sensitivities in the sloping fen flow dynamics (see section 2.2.3 for details). ~~Finally, a comparison of all model results was made in order to assess the impact of road structures and quantify the dynamics and the physical controls of subsurface flow in these environments.~~ ~~These controls include the slope of the fen and the hydraulic properties of the subsurface material.~~

2.2.1 Numerical simulator

The model used in the study is HydroGeoSphere (HGS) (Aquanty, 2017)~~(Aquanty, 2017)~~. HGS is a physically-based surface–subsurface fully-integrated model using the control volume finite element approach. HGS solves a modified Richards' equation describing the 3D subsurface flow. If the subsurface flow is unsaturated~~not~~

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~~saturated~~unsaturated, HGS employs the Van Genuchten (1980)~~Van Genuchten (1980)~~ functions to relate pressure head to saturation and relative hydraulic conductivity. Simultaneously, HGS ~~also~~ solves the 2D depth-~~-~~averaged diffusion-wave approximation of the Saint-Venant equation for describing the surface flow. To couple surface and subsurface and simulate the water exchanges between both domains, the “dual node approach” is used. In this approach, the top nodes representing the ground surface are used for calculating both subsurface and surface flow, the exchange flux between the two domains is calculated on the basis of the head-difference between the surface and the subsurface and a coupling factor~~. The water exchanges are calculated as hydraulic head differences of the two domains and multiplied by the vertical hydraulic conductivity of the top layer and a coupling factor.~~.

The iterative Newton-Raphson method is used to solve the nonlinear equations. At each subsurface node, saturation and groundwater heads are calculated, which allows for the calculation of the Darcy flux. For further details on the code, HGS capabilities and application, see Aquanty (2017), Brunner and Simmons (2012) or Cochand et al. (2019).~~The iterative Newton-Raphson method is used to solve the nonlinear equations. At each subsurface node, saturation and groundwater heads are calculated, which allows for the calculation of the Darcy flux. On the surface domain, the surface water heights are calculated at each node to determine surface water flux. Rivers and lakes are characterized by a surface water depth larger than 0. For further details on the code, HGS capabilities and application, see Aquanty (2017), Brunner and Simmons (2012) or Cochand et al. (2019).~~

2.2.2 Conceptual models and model implementation

Figure 4~~Figure 4~~ illustrates the conceptual model of each case. Existing engineering sketches were used as a basis for the implementationimplemetion of the drain and road. Geometry, topography, and slopes are based on the ~~physical~~ conditions in the field. In each model, the soil layer has a thickness of 0.4m and the surface and subsurface water ~~are~~ is only supplied by precipitation. The upslope~~upstream~~ boundary is the catchment boundary (water divide) and the downslope~~downstream~~ boundary represents the outlet of the model. Finally, it was assumed that the layer beneath the soil was impermeable (as observed in the field).~~) and engineering plans were used to design drain and road.~~ One Neumann (constant flux) boundary condition was used on the top face for simulating precipitation. A constant~~ groundwater~~ head boundary condition (Dirichlet type) equal to the ground surface elevation (2m) was used on the lowest cells of the slope (x=76m on the Figure 5~~Figure 5~~a) allowing ~~the~~ groundwater to flow out of the model. Finally, a critical depth boundary condition which allows~~which forces the surface water to reach a~~allows surface water to flow out of the model domain ~~given elevation (2m in our case) to flow out of the model~~ was implemented on the top nodes located at x=76m. All~~ and a~~A~~ll~~ other faces are no-~~-~~flow boundary conditions.

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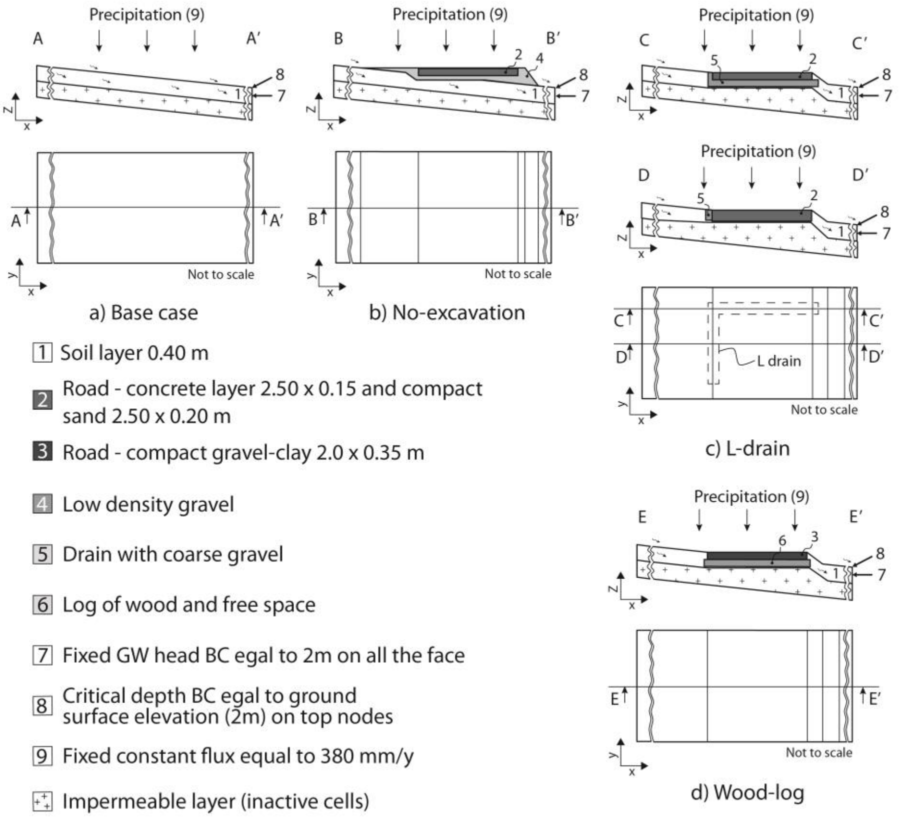

Figure 4 : a) Base case, b) No-excavation, c) L-drain and d) Wood-log structures conceptual models.

A~~To numerically solve the 3D flow equation, a~~A 3D- finite element ~~-~~mesh was developed (Figure 5~~Figure 5~~a). The mesh is 76m long in the X direction, 20m in the Y direction and the mesh thickness is 1.2m. The top elevation was fixed at 2m on the right side (x=76m) and varies from 9.6m to 24.8m on the left side (x=0) according to the slope of the model. The mesh was composed~~made up~~composed of 24 layers, 127,200 nodes and 118,440 rectangular prism elements. To guarantee numerical~~ensure an appropriate level of detail~~numerical stability, ~~several~~ mesh ~~discretization~~ refinements were implemented. The~~made~~imlemented~~. Therefore, t~~T~~he~~ element size varies between 2m and 0.1m horizontally (in the X and Y directions) and 0.09m and 0.06m vertically.

The base case model and the three other models representing different road types have the same boundary conditions and finite element meshes, however, modifications were made between coordinates 61<x<66 ~~to~~ for the implementation of the different road types. Figure 5~~Figure 5~~ depicts the differences between the base case model

(Figure 5~~Figure 5~~a and b) and models with roads (Figure 5~~Figure 5~~c, d, e and f). In ~~the case of~~ models ~~with~~ simulating a road, the mesh and the material properties ~~was~~were ~~deformed~~ ajusted~~and the properties were~~ adjusted~~changed~~. The fine spatial discretization of the mesh created between the coordinates 61<x<66 allows a more accurate representation of the simulated processes where high hydraulic gradients are expected (near roads and drains). ~~Additionally, the refinements allow an accurate representation of drains and the roads.~~

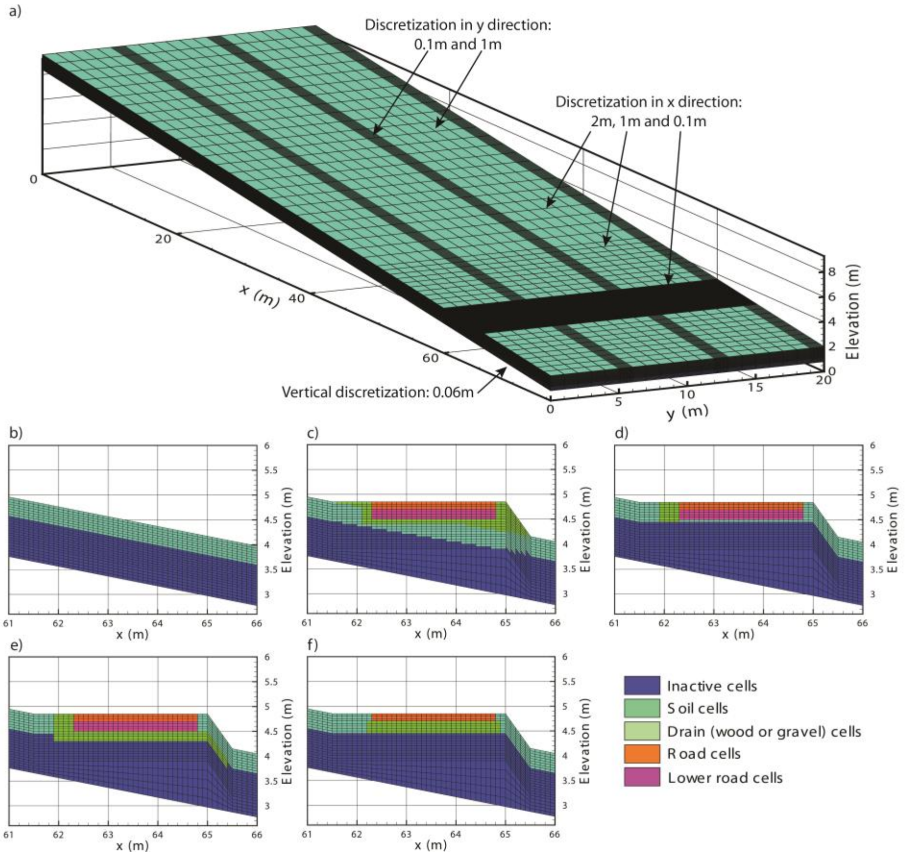

Figure 5 : Model development: a) Base case model, b) Base case model cross-section between 61m < x < 66m, c) No-excavation model between 61m < x < 66m, d) L-drain model between 61m < x < 66m, e) L-drain model between 61m < x < 66m along the transversal drain f) Wood-log model between 61m < x < 66m.

2.2.3 ~~Model setup~~ Model application

The model application~~sensitivity analysis~~ consists of the variation of model properties. ~~and parameters in order to~~ assess their effect on~~understand how they control the~~ groundwater~~sloping fen dynamics.~~ The ~~sensitivities of the~~ following parameters were analyzed: fen slope, soil hydraulic conductivities and road drain hydraulic conductivities. These parameters were selected because according to the~~they govern the~~the Darcy’s law ~~(1)~~ they~~and consequently~~they control the groundwater flow dynamics. K is the hydraulic conductivity of the soil and the drain and ∇H the hydraulic gradient of~~gradient o~~o~~f~~ the fens which itselfitslef is~~will be~~ strongly influenced ~~controlled~~ by the topographical slope.

$$q = K * \nabla H \tag{1}$$

For each property varied in the sensitivity analysis, three different values were chosen (Table 2~~),~~): a low, ~~an~~ intermediate and ~~a~~ high value.~~values with the aim of covering the whole range of its observed values in sloping fens.~~ For the soil hydraulic conductivities (KS), values presented in Charman (2002)~~Charman (2002)~~ were used and ~~vary~~ varied between 8.64m/d and 0.0864m/d. This corresponds to a soil composed of gravely~~,~~ organic matter (as observed for example in St-Antonien site) or loamy organic matter (as observed for example in Schoeniseischwand site). ~~α and β~~ Van Genuchten parameters (α and β),)~~and the residual water content~~, as well as the residual water content, ~~were considered similar assuming~~were not varied.~~their capillary rises are comparable and does not play a critical role in a 40cm soil layer mainly saturated.~~ The road drains (KD) which are made ~~with~~ of coarse or very coarse gravel were~~and have~~were assigned a hydraulic conductivity ~~varying~~ between 8640m/d and 86.4m/d (Fetter 2001),~~)~~ ~~and~~, their van Genuchten parameters ~~are~~ corresponding to ~~those of~~ gravel. The slopes were fixed at 10%, 20% and 30%, as observed during the fieldwork. The~~Note that t~~T~~he~~ hydraulic conductivities of the wood-log (W-L) drain ~~hydraulic conductivities of the wood-log (W-L)~~ were assumed ten times more conductive and more porous than the gravel drain.~~because of its particular structure (wood logs).~~ The road concrete is almost impermeable and was thus conceptualized with a very low hydraulic conductivity,~~and~~ its van Genuchten parameters corresponding to ~~of~~a fine material. The road basement is constructed~~made with~~constructed using highly compacted fine material (sand and loam) and~~have a low~~~~feature~~and was thus implemented with a low hydraulic conductivity, the ~~and are assigned~~ van Genuchten parameters ~~of~~ corresponding to fine material. Finally, the implemented soil and road surface flow properties correspond to a wetland and urban cover (Li et al., 2008)~~(Li et al., 2008)~~.

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Table 2 : Subsurface and surface flow parameters.

Subsurface flow properties

	Hydraulic conductivity	**Porosity**	**Van Genuchten α**	**Van Genuchten β**	**Residual water content**
Units	**K [md^{-1}]**	**θ [-]**	**α [m^{-1}]**	**β [-]**	**Swr [-]**
Soil - KS1	8.64	0.25	4	1.41	0.04
Soil - KS2	0.864	0.25	4	1.41	0.04
Soil - KS3	0.0864	0.25	4	1.41	0.04

Drains - KD1	8640	0.25	29.4	3.281	0.04
Drains - KD2	864	0.25	29.4	3.281	0.04
Drains - KD3	86.4	0.25	29.4	3.281	0.04
Drains - WL - KD1	86400	0.7	29.4	3.281	0.04
Drains - WL - KD2	8640	0.7	29.4	3.281	0.04
Drains - WL - KD3	864	0.7	29.4	3.281	0.04
Road concrete	0.0000864	0.05	1.581	1.416	0.04
Road basement	0.00864	0.25	4	1.416	0.04

Surface flow properties

	Coupling length	**Manning's roughness coefficient**		**Rill storage height**	**Obstruction height**
Units	**l_c [m]**	**n_x [$m^{-1/3}s$]**	**n_y [$m^{-1/3}s$]**	**D_t [m]**	**O_t [m]**
Soil	1. x 10^{-2}	0.03	0.03	0.005	0.005
Road	1. x 10^{-2}	0.018	0.018	0.001	0.001

In order to simulate each parameter combination, a total of 90 models were developed (27 models for each road structures and 9 models for natural conditions). Models are run for 10’000 days (about 27 years) with a constant flux equal to 380mm/y on the top representing the rainfall to reach a steady state. ~~This precipitation allows for the saturation of the downslope part of the model.~~ Subsequently, subsurface flow rates in the soil layer were extracted at each section with an area of 0.4m^2 (1m wide times the soil thickness) presented in Figure 6~~Figure 6~~. Changes in subsurface flow rates indicate a perturbation of flow dynamics and therefore, a comparison of flow ratesrates~~velocities~~ between each model was made to present the effect of each road structure and sloping fen properties on the dynamics.

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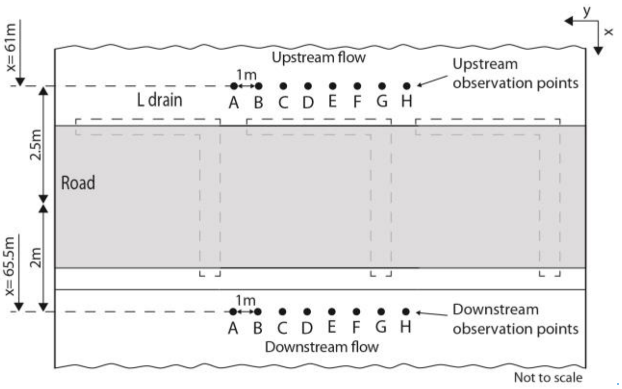

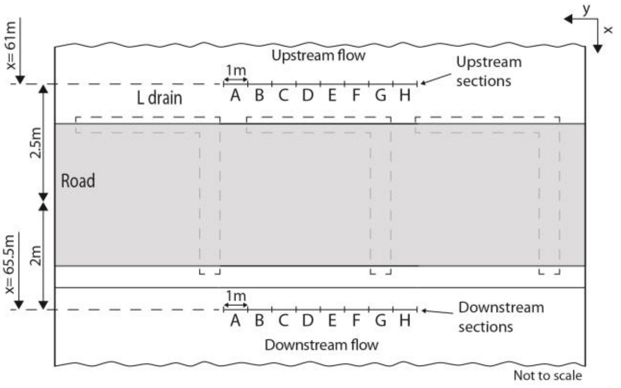

Figure 6 : Location of observation ~~points~~ sections in the models.

3 Results and Discussion

3.1 Fieldwork

Based on the observations, all sites show a continuous saturated zone before the experiment, both upslope~~upstream~~ and downslope~~downstream~~ of the road, the hydraulic gradients being ~~mostly~~ similar to the terrain slope (Figure 7~~Figure 7~~, 1st column). In contrast, the EC maps established prior to the tracer test show a spatial variability of one to several meters (Figure 7~~Figure 7~~, 2nd column.). Within each plot, EC varies from 482 to 629µS/cm. At the SCH site, the highest values are located downslope~~downstream~~ of the L-drain outlet which could indicate that the EC increases as water is flowing through the drain (e.g. through the dissolution of the construction material). Given that this initial distribution of EC is not uniform, the comparison of EC after the sprinkling experiment has to be made in a relative manner (Figure 7~~Figure 7~~, 3rd column).

The heterogeneity of the hydraulic conductivity of the soil is apparent from the tracer tests ~~results~~ (Figure 7~~Figure 7~~, 3rd column: EC 24 hours after injection). At all four sites, the front of the saline solution is not uniform because of the ~~but follows the~~ heterogeneity of the soil hydraulic conductivity. Nevertheless, the~~road structures~~the road structures or the drains may create~~play the role of aconstitute~~create preferential flow paths. This ~~that~~This is clearly occurring~~particularly obvious~~clearly occuring at the SCH site where the front follows two preferential flow paths. One related to the L-drain (right path) and the other on the left, unrelated to the L-drain, suggesting that the latter drains only a part of the water and the other part follows a natural, preferential flow path. At the HMD site, the saline solution is far more concentrated on the left side of the plot, yet apparently not as a result of the road's structure. Rather, the soil appears more permeable on the left side of the plot, both upslope and downslope of the road. Finally, the decrease in EC observed 24 hours after injection at some locations might result from the following: (1) the tracer injection induces, by "piston effect", the displacement of a small volume of local water with a lower EC; (2) the tracer injection was preceded by a period of irrigation without tracer. This~~, which~~ could have diluted the pre-irrigation soil solution.

In each case, the irrigation experiments demonstrate the continuity of subsurface flow under the road for all structures. For the no-excavation and wood-log type, the perturbation of the flow field seems to be controlled by the natural heterogeneity of the soil and flow paths, and not by the road itself. Conversely, the field data strongly suggest that the L-drain constitutes an important preferential pathway and consequently subsurface flow is increasingly concentrated. ~~In terms of wetland conservation, t~~ This flow convergence ~~is a serious threat (~~can cause gully erosion. ~~, local drying up of the soil). Despite these strong indications, it is clear that with the field data alone no conclusive analysis can be made as no data before the construction of the road are available. Fieldwork allows for site-specific conclusions, but more general conclusions which are not specific to a site are impossible. Therefore, numerical modelling was used to fill this gap.~~

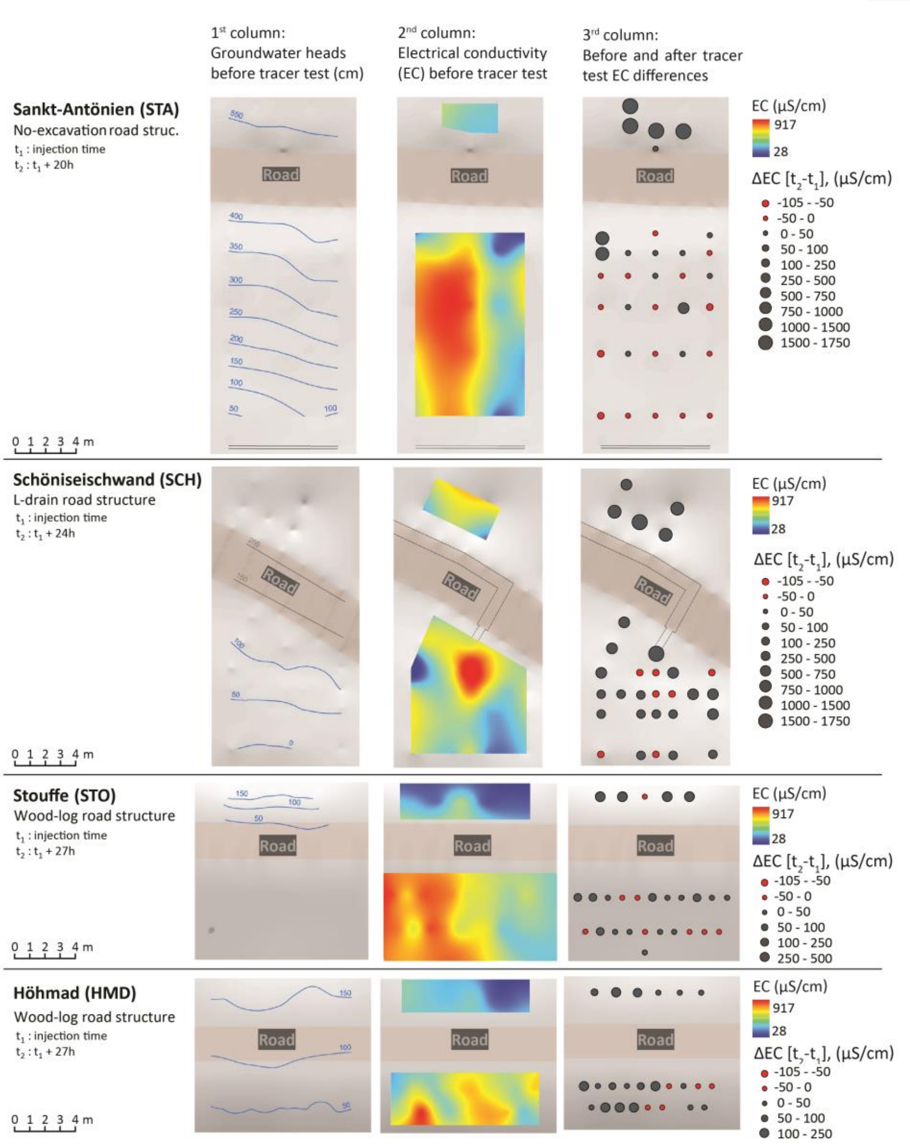

Figure 7 : Fieldwork results at the four field sites: 1st column) Measured groundwater heads before tracer test, 2nd column) ~~Measured~~ measured EC before tracer test and 3rd before and after tracer test differences in EC. The hydraulic heads downslope the road in the Stouffe site is about 25cm and upslope the road in the Schöniseischwand is about 225cm (between two isolines) and are not presented in the figure

3.2 Modelling

~~The presentation of models results is divided into three parts; the first one focus on the lower part of the fen downstream the road, the second on the upper part of the fen upstream the road and finally, all model results are discussed.~~ Figure 8~~Figure 8~~a shows the results of the models with a slope of 10%, Figure 8~~Figure 8~~b with a slope of 20% and Figure 8~~Figure 8~~b with a slope of 30%. In each dot chart, the groundwater flow rates (always in m^3/d) are plotted with crosses for the base case model, diamonds for the no-excavation type, squares for the L-drain type and circles for the wood-log type. In addition, the maximum flow rate capacity of the soil calculated with ~~the~~ Darcy's LawL~~law~~ (1) and the flow rate induced by the precipitation are also presented for the interpretation of the results. In the following paragraphs, the base case (natural conditions) results are presented and discussed, followed by the simulations of the road structures.

In the base case model, groundwater flow ratesrates~~velocities~~ vary from 0.003 (m^3/d) to 0.069 (m^3/d) for a 10% slope, 0.006 (m^3/d) to 0.069 (m^3/d) for a 20% slope and ~~to~~ from 0.009 (m^3/d) to 0.069 (m^3/d) for a 30% slope. The groundwater flow rate decreases following ~~gradually depending~~following a decreasedecrese of ~~on~~ the hydraulic conductivities (KS) of the soil layer. The~~For any slope, where hydraulic conductivities are high (KS1), groundwater~~ flow ratesrates~~velocities are higher compared to the case where hydraulic conductivities are low (KS3). The primary observation is that groundwater~~ flow rates~~velocities~~ are mainly controlled by the hydraulic conductivities, ~~and therefore~~ the slope plays a ~~minor~~ less important role. This is expected, as the ratios~~D~~differences~~ratios of ~~between~~ the maximum and minimum hydraulic conductivity are two orders of magnitude, while~~whereas changes between~~while slopes were multiplied~~multiply~~ied by a factor of ~~tow~~ two (for a slope of 20%) or three (for a slope of 30%).~~%) the groundwater flow.~~ Therefore, ~~the~~ groundwater flow is increased by a factor 3 between the model KS3 with a slope of 10% and model KS3 with a slope of 30%. Concerning~~Finally, it can be seen that the maximum flow rate of the soil is reached and lower than precipitation in all cases except if the hydraulic conductivity is high (KS1). This means that for~~Concerning the formation of surface flow the~~some~~the following observation ~~interesting observations~~ can be made. For all KS2 and KS3 models, surface flow occurs while~~and conversely the soil is able to infiltrate the precipitation in~~while the infiltration capacity of the KS1 models is never exceeded~~,~~ and thus no surface flow occurs.

In the no-excavation and wood-log type models, the influence~~effect~~influence on flowrates caused by the presence of the ~~of~~ road structures is quite similar. Groundwater~~The g~~G~~roundwater~~ flows vary from 0.01 (m^3/d) to

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0.069 (m^3/d) for a 10% slope, 0.01 (m^3/d) to 0.069 (m^3/d) for a 20% slope and to 0.010 (m^3/d) to 0.069 (m^3/d) for a 30% slope. Compared to the base case model, results show that the no-excavation and wood-log type structures have a minimal impact on flow perturbationpertubration. The only marked difference is that groundwater flow ratesrates~~velocities~~ are slightly higher if the soil hydraulic conductivities are low (KS3). This is due to~~for each slope in the wood-log type model. This can, to a certain extent, be explained by the fact that because~~ because the hydraulic conductivity of the base of the road (consisting of wood-logs) ~~is~~ higher than the hydraulic conductivity of the soil which ~~and therefore~~ facilitates ~~the~~ infiltration. Conversely, in the base case model, less water is infiltrated but more surface runoff occurs. ~~For the no-excavation model with a slope of 10%, results are not presented for technical reasons. For this specific geometry and topography, a different structure of the mesh had to be generated which did not allow for a direct visual comparison with the other models.~~ In the 20% and 30% slope models, the results of the no-excavation model are similar to the base case model.

In the L-drain ~~type~~ model, the effect of the road is markedly different from the other road structures. The groundwater flows vary significantly in the observation sections.~~points~~sections~~.~~ The maximum flows are always obtained in the observation ~~point~~ section G (see Figure 6 for the location of the sections) just downslope~~downstream~~ of the drain outlet and can be 10 times higher than compared~~in the~~compared to the base case. Conversely, minimum flows are obtained in observation sections C and D ~~observation points sections~~ in which flow rates canrates~~velocity may~~can be 10 times lower. Significant differences in groundwater flow are also observed in the same transect (within the same model).~~)~~ To condense this information, the ratios between maximum and minimum flow rate are calculated for the L-drain structures (numbersNumbers at the bottom right of the panels in Figure 8~~Figure 8~~). The maximum differences are observed for~~if the~~for the cases where the hydraulic conductivity of soil (KS) and drain (KD) are high and ~~may~~ vary from 0.025 (m^3/d) to 0.150 (m^3/d). Conversely, when KS and/or KD are low, the differences along the transect are smaller. ~~The L-drain structures also facilitate water infiltration in soil with a low permeability (KS3) where groundwater velocities are slightly higher than the base case model.~~ Finally, the ~~it can be seen that~~ slope accentuates groundwater flow raterate~~velocity~~ differences along the transect. Therefore, an increase of groundwater flow differences ~~in the same model~~ is observed for the 10% and 30% slope scenarios, within the same model. The impact of the L-drain may be further explored by extracting groundwater flows lower than 2m downslope the road 2~~3.5m~~ to assess the extent of perturbations. Figure 9~~Figure 9~~ shows ~~additional~~ simulated groundwater flows for the most critical cases (i.e. KS1 with a slope of 10%, 20% and 30%) downslope~~downstream~~ the road at 3.5m and 6.5m respectively and 2.5m upslope. At~~upstream. It can be seen that a~~A~~t~~ 3.5m the groundwater flows already regain their upslope~~upstream~~

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Mis en forme : Anglais (Royaume-Uni) conditions. At 6.5m downslope~~downstream~~ the road, all observation ~~points~~ sections are very close to the upslope~~upstream~~ flows except in section~~observation point~~section G where flows are still slightly higher.

~~Finally, the impact of road structure on the upstream road dynamics may be also assessed. Figure 10 shows the same information as Figure 8 but at 2.5m upstream. It can be seen that for all models, upstream flows are similar to the base case model. This means that all structures allow the groundwater to cross the road.~~

~~3.3 Modelling results discussion~~

~~Results show that the no-excavation structure has the least impact on the groundwater velocities and the wood-log structure has a limited impact on groundwater dynamics. The only difference with the base case (no road at all) model is that the groundwater velocities observed are slightly higher where the hydraulic conductivity of the soil layer is low (KS3). This is caused by the wood-log drain which facilitates water infiltration in a low-conductive soil layer. Finally, the L-drain structure impacted significantly the groundwater dynamics. Significant differences are observed in each scenario, mainly due to the L-shape drain. Downstream of the drain outlet (observation point G), groundwater velocities are higher than other observation points along the transect, regardless of the slope and the drain hydraulic conductivity. Maximum differences may reach two orders of magnitude from 0.0346 (m/d) to 1.296 (m/d) in the same transect. Only the soil hydraulic conductivity reduces differences in groundwater velocity along the transect and the slightly higher groundwater velocity in comparison with the base case model indicates that gravel drain also facilitates water infiltration in low-conductivity soil layer.~~

In addition to the assessment of perturbation through roads, the model~~T~~the ~~M~~m~~odel~~ results can be used to evaluate~~predict~~evaluate the risk of gully erosion.~~ and allows us to make recommendation to avoid them~~. ~~Gully erosion may occur when changes in surface flow dynamics induce runoff concentration (Nyssen et al., 2002;Valentin et al., 2005b).~~ As presented in Figure 8~~Figure 8~~, the maximum flow rate capacity of the soil is small in comparison to c~~a~~omparison ~~with~~to ~~the~~ precipitation. For all model scenarios except for KS1, the soil capacity is lower than the precipitation and~~amount which is already set pretty low in the model. This means~~and thus surface~~that~~surface runoff ~~already~~ occurs in the models and is likely to occuroccur~~e~~ naturally.~~ in sloping fens~~. However, ~~the~~ surface runoff may be triggered~~accentuated~~triggered ~~by subsurface perturbation caused~~ by the presence of ~~the~~ L-drain structures. To illustrate this process, the simulated surface flow velocities of each road structure downslopedownstream the road for the model KS2-KD2 and slope of 20% are presented in Figure 10~~Figure 10~~. In this case, the maximum flow rate capacity of the soil is approximatelyapproximately~~ively~~ equal to precipitation, therefore runoff should not occur. However, this~~it can be seen some runoff in the~~this is not the case

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Mis en forme : Vérifier l'orthographe et la grammaire for the L-drain~~ model~~. The occurrence of surface runoff~~ which is~~ is the consequence of the subsurface flow concentration. In this configuration, the ~~soil ~~infiltration capacity of the soil is too small to accommodate the concentrated flow collected upslope, thusupstream, ~~and consequently, the~~thus groundwater emerges ~~and flows on the surface~~and surface flow is triggered.~~,~~. This constitutes an increaseincreas~~inge~~ ~~the ~~of the risk for gully erosion. In addition, the perturbation on the roads upslopeuphill of the road was assessed. ~~Although the formation of gullies depends of a lot of other factors (Valentin et al., 2005b), such as soil type or the rain intensity, the model showed that downstream L-drain structure may cause runoff concentration which is an important factor.~~

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~~A simple recommendation can be made to avoid this runoff concentration.~~

~~If the maximum flow rate capacity of the soil is smaller than the flow rate induced by precipitation, the installation of an L-drain structure should not be considered.may lead to surface runoff.~~

~~If the maximum flow rate capacity of the soil is larger than the flow rate induced by precipitation, an L-drain may be considered only if the concentred flow calculated by multiplying the drainage area by the precipitation is smaller than maximum flow rate capacity of the soil~~

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Finally, the impact of road structure on the upslopeupstream road dynamics was~~may~~were be also assessed (Figure not shown))~~. Figure 11Figure 11 shows the same information as Figure 8Figure 8 but at~~ 2.5m upslope. Upslopeup~~stream~~hill. ~~It can be seen that for all models, u~~Up~~stream~~hill flows are similar to the base case model, thus the influence of the road is, not unexpectedly, marginal for all road types. .~~.~~ ~~This means that all structures allow the groundwater to crossflow across the road.~~

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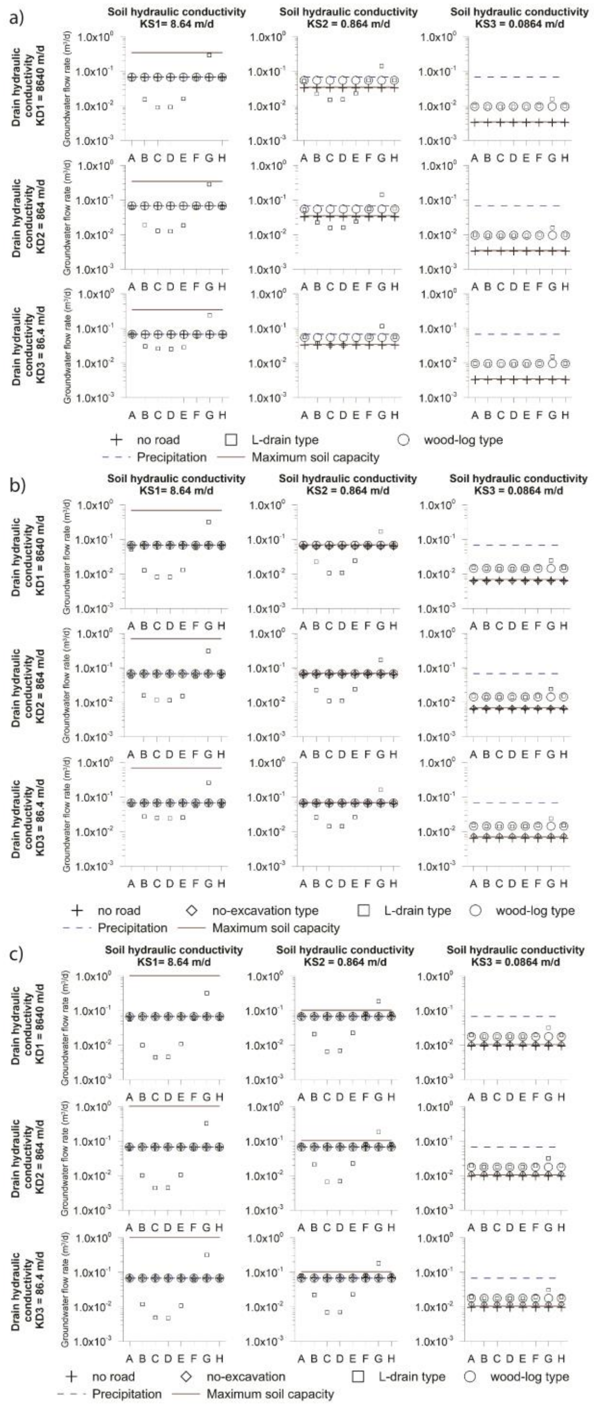
~~The~~ significant ~~impact of the L-drain road structure which concentrates groundwater flow is clearly established~~~~identified in the numerical approach and is consistent with the field observations. For~~ the ~~other road structures also~~too, the ~~numerical models are consistent with fieldwork results by showing a relatively undisturbed groundwater flow downslope the road. The use of numerical models allowed for a quantitative estimation of the flow perturbation induced by each road structure and model results were consistent with the field observations. In addition, t~~T~~he~~ development of models with various combinations of parameters ~~also ~~allowed for exploring a larger parameter space than using field work only. For instance, the fact that the impact of an L-drain structure on the water dynamics is less marked if the hydraulic conductivity of soil is low would have been impossible to identify by using fieldwork only. However

~~The main~~However, a numerical model is always a simplified reproduction of ~~the~~ reality. The ~~simplification of the~~The main model ~~simplification~~ assumption is that the~~the assumption~~ that~~of a homogeneous~~ hydraulic conductivity of the soil is homogeneous. HoweverHowever~~Groundwater flow in fens can occur along preferential pathways. T~~, t~~herefore, the~~ models are not ~~able~~ intended to reproduce small-scale observations~~processes~~observations, i.e. the exact hydraulic head in a~~an individual~~a ~~mini~~ piezometer, but instead can be used to explore the influence of the road structures under different soil conditions (overall hydraulic conductivity) and slopes. ~~.~~ Given that no horizontal redistribution of the flow downslopedownstream can be simulated,- for this the consideration of heterogeneity would be required, consequently- ~~,~~ the models thus constitute a worst-case scenario. The models ~~Models results have to be interpreted as an average across multiple preferential flow paths. Nevertheless, t~~The models ~~nevertheless~~ allow for a relative ranking of the potential impact and clearly show the increased risk for surface water flow generation and thus gully erosion. Clearly, the L-drain shows the largest impact. The two other road structures are thus the preferred choice.

~~Further investigations should be carried out to identify groundwater velocity~~ flow ~~threshold values above which a risk of for instance gully erosion is present. This is especially important for L-drain structures where the increase of flow velocities is higher than for the other structures. Finally, the impact on sloping fen vegetation related to perturbations of the groundwater flow should be further investigated. In this way, road construction could be better planned.~~


a)
Soil hydraulic conductivity KS1= 8.64 m/d
Soil hydraulic conductivity KS2 = 0.864 m/d
Soil hydraulic conductivity KS3 = 0.0864 m/d
Drain hydraulic conductivity KD1 = 8640 m/d
Drain hydraulic conductivity KD2 = 864 m/d
Drain hydraulic conductivity KD3 = 86.4 m/d
Groundwater flow rate (m³/d)
1.0x10⁰
1.0x10⁻¹
1.0x10⁻²
1.0x10⁻³
A B C D E F G H
+ no road
□ L-drain type
○ wood-log type
- - - Precipitation
—— Maximum soil capacity
b)
Soil hydraulic conductivity KS1= 8.64 m/d
Soil hydraulic conductivity KS2 = 0.864 m/d
Soil hydraulic conductivity KS3 = 0.0864 m/d
Drain hydraulic conductivity KD1 = 8640 m/d
Drain hydraulic conductivity KD2 = 864 m/d
Drain hydraulic conductivity KD3 = 86.4 m/d
Groundwater flow rate (m³/d)
A B C D E F G H
+ no road
◇ no-excavation type
□ L-drain type
○ wood-log type
- - - Precipitation
—— Maximum soil capacity
c)
Soil hydraulic conductivity KS1= 8.64 m/d
Soil hydraulic conductivity KS2 = 0.864 m/d
Soil hydraulic conductivity KS3 = 0.0864 m/d
Drain hydraulic conductivity KD1 = 8640 m/d
Drain hydraulic conductivity KD2 = 864 m/d
Drain hydraulic conductivity KD3 = 86.4 m/d
Groundwater flow rate (m³/d)
A B C D E F G H
+ no road
◇ no-excavation
□ L-drain type
○ wood-log type
- - - Precipitation
—— Maximum soil capacity

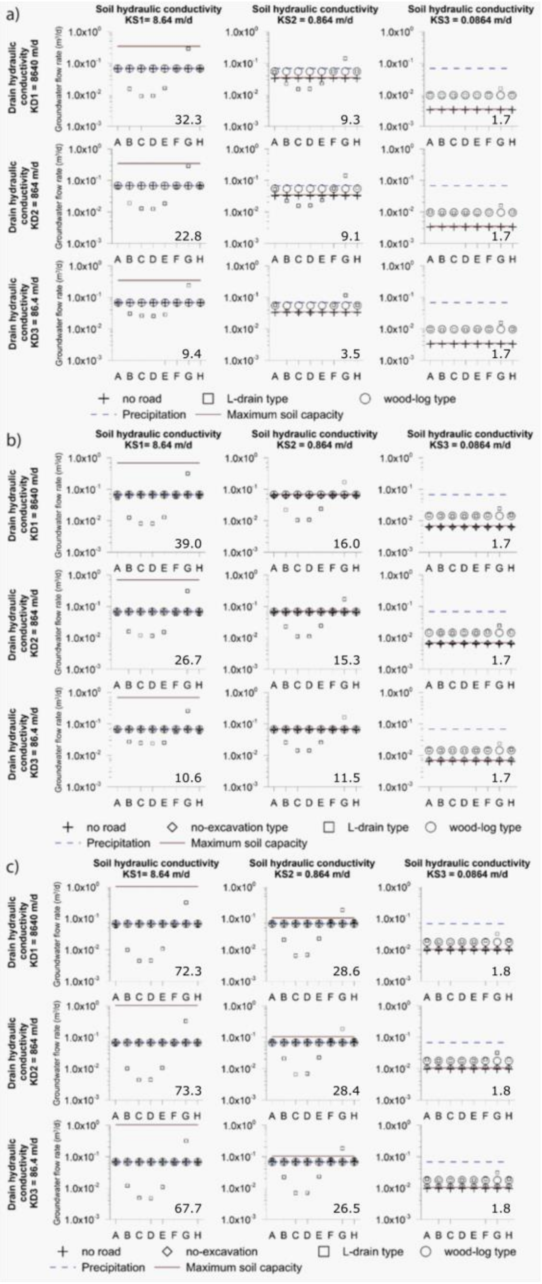


Figure 8 : Simulated groundwater flow ratesrates~~velocities~~ 2m downslope ~~downstream~~ each road structure~~structur~~e~~es~~ and each parameter combination with a slope of a) 10%, b) 20% and c) 30%. Numbers at the bottom right of each panel are the ratio between maximum and minimum groundwater flow within the LL~~l~~-drain transect

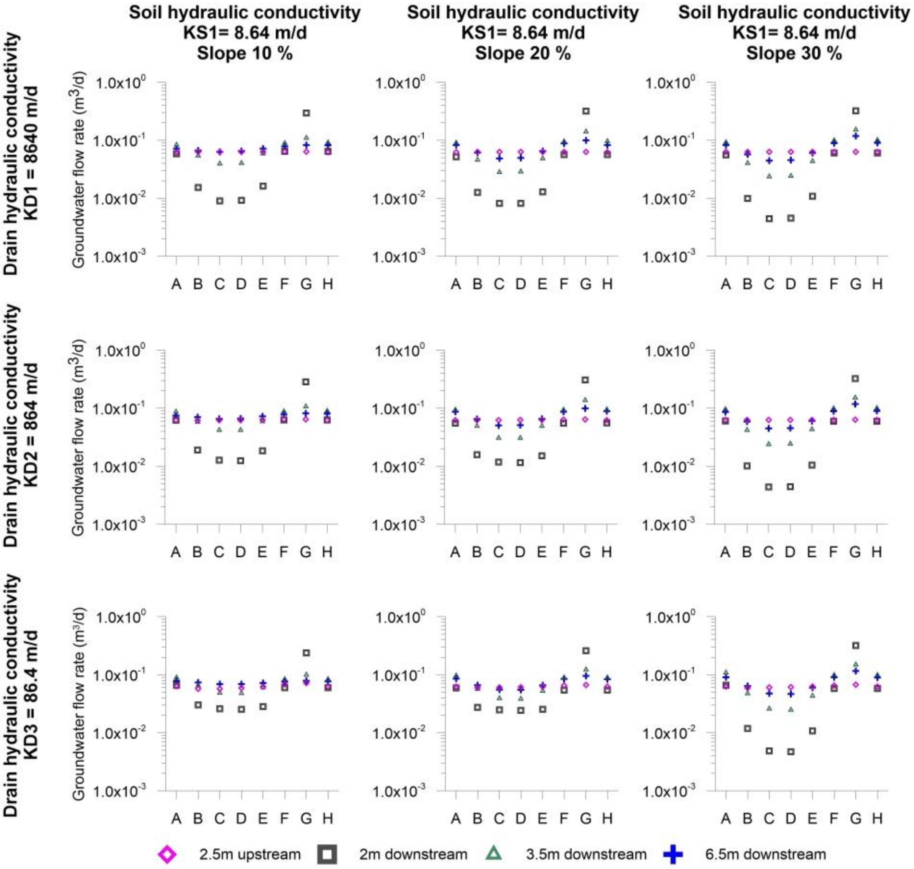


Figure 9 : Extent of perturbations due to the L~~l~~L-drain road type: Simulated groundwater ~~v~~ flow ratesrates~~elocities at G point section G at for~~ different distances the road.

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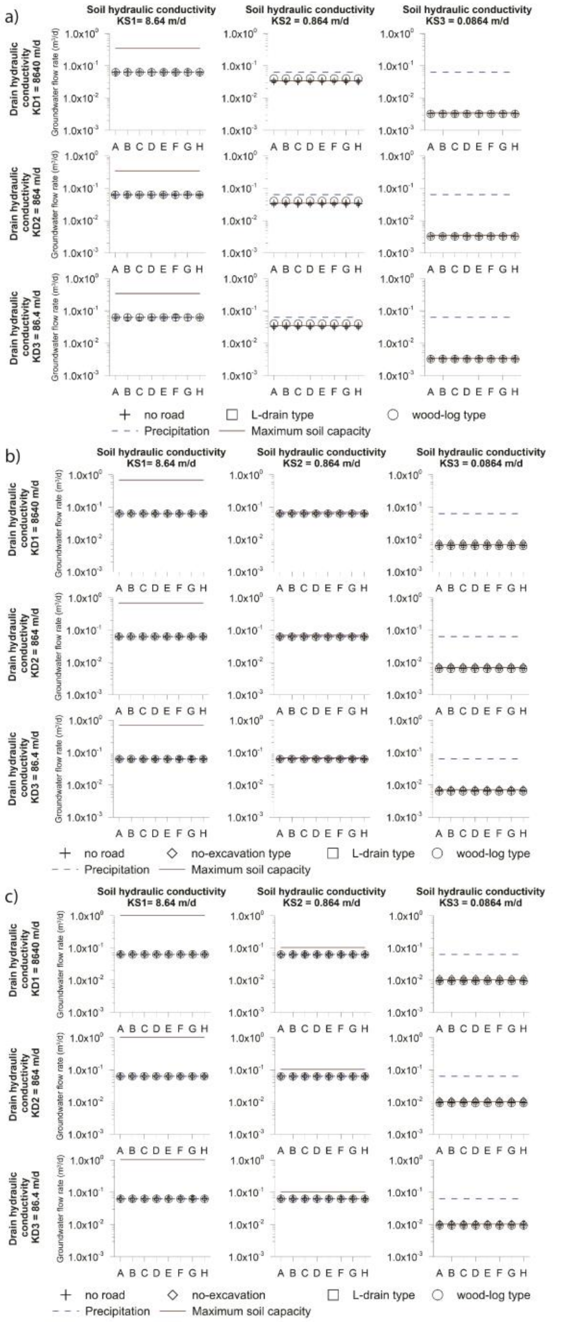
a)
b)
c)
Soil hydraulic conductivity KS1= 8.64 m/d
Soil hydraulic conductivity KS2 = 0.864 m/d
Soil hydraulic conductivity KS3 = 0.0864 m/d
Drain hydraulic conductivity KD1 = 8640 m/d
Drain hydraulic conductivity KD2 = 864 m/d
Drain hydraulic conductivity KD3 = 86.4 m/d
Groundwater flow rate (m³/d)
1.0x10⁰
1.0x10⁻¹
1.0x10⁻²
1.0x10⁻³
A B C D E F G H
+ no road
◇ no-excavation type
◇ no-excavation
□ L-drain type
○ wood-log type
- - - Precipitation
—— Maximum soil capacity

~~Figure 10 : Simulated groundwater velocities 2.5m upstream each road structures and each parameter combination with a slope of a) 10%, b) 20% and c) 30%.~~

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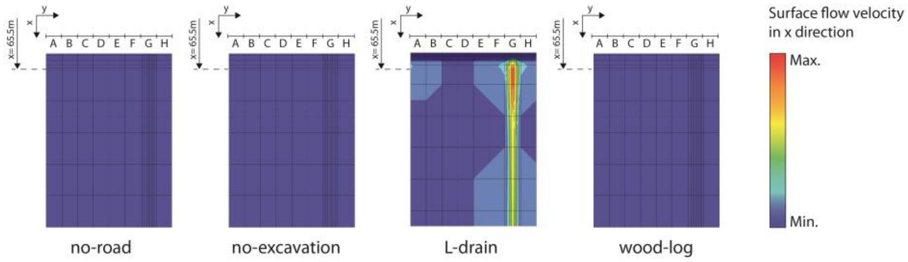
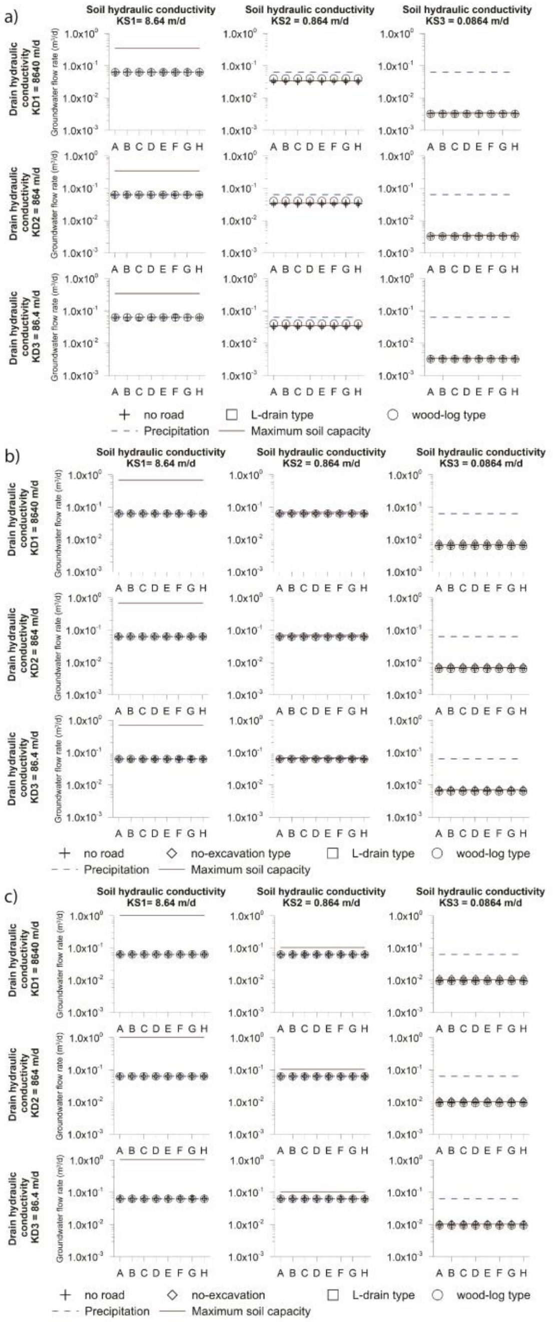


Figure 10 : Simulated surface flow of the KS2-KD2 model and a slope of 20% for each road structure. The results clearly indicate the increased risk caused by the L-drain of triggering surface runoff and thus potentially gully-erosion and the drying out of sections of the wetland


a)
Soil hydraulic conductivity KS1= 8.64 m/d
Soil hydraulic conductivity KS2 = 0.864 m/d
Soil hydraulic conductivity KS3 = 0.0864 m/d
Drain hydraulic conductivity KD1 = 8640 m/d
Drain hydraulic conductivity KD2 = 864 m/d
Drain hydraulic conductivity KD3 = 86.4 m/d
Groundwater flow rate (m³/d)
1.0x10⁰
1.0x10⁻¹
1.0x10⁻²
1.0x10⁻³
A B C D E F G H
no road
L-drain type
wood-log type
Precipitation
Maximum soil capacity
b)
no road
no-excavation type
L-drain type
wood-log type
Precipitation
Maximum soil capacity
c)
no road
no-excavation
L-drain type
wood-log type
Precipitation
Maximum soil capacity

~~Figure : Simulated groundwater flow rates 2.5m upstream each road structures and each parameter combination with a slope of a) 10%, b) 20% and c) 30%.~~

Mis en forme : Français (Canada)

4 Conclusions

This study assessed~~presented an assessment of~~assessed three road structures regarding their perturbations of the natural groundwater flow. Two of these road structures were specifically developed to reduce the negative impacts of the road. The study is based on two complementary approaches; field~~a~~field-based tracer test~~s in the field~~ and numerical models simulating groundwater flow for the different road structures. The combination of fieldwork and the development of numerical models was fundamental to achieve the goal of this study. The tracer test allowed for a better understanding of groundwater flow throughout road structures and allowed for evaluating their effectiveness at a given location. However, the tracer tests are time-consuming and only a few field sites are available. The numerical approach, on the other hand, allows for exploring any combination of slope, hydraulic properties or road structure, thus providing a more comprehensive approach. ~~In our study, the trends between the numerical and field approaches were consistent.~~The significant impact of the L-drain road structure is clearly established in the numerical approach and is consistent with the field observations. For the other road structures too, the numerical models are consistent with fieldwork results by showing relatively undisturbed groundwater flow downslope the road.

It is the first time that the performance of these road-structures ha~~s~~s been investigated in the field. The tracer tests showed that both sides of the road where hydraulically connected for all investigated road structures. Groundwater flow was heterogeneous suggesting the occurrence of natural preferential flow paths in the soil. The presence of a transversal drain (L-drain) beneath the road ~~constitutes~~ suggests that an L-drain constitutes a preferential flow path~~, however, which is~~ of much greater importance than the naturally occurring preferential pathways. The field results further suggest that the wood-log and no-excavation structures as less impactful that the L-drain. The~~ This was also confirmed by the models~~The simulation results are consistent with the assessment of the relative impact of the different road-types . Groundwater flow rates~~Velocities~~ 10 times larger than in the natural case were obtained in the numerical simulations. ~~This is not further astonishing as the drains were specifically designed for this purpose.~~ The two other road structures (wood-log and no-excavation) do not perturb the flow field to the extent of the L-drain. To minimize the perturbation of flow fields, the wood-log and no-excavation structures are recommended.

~~The combination of fieldwork and the development of numerical models was fundamental to achieve the goal of this study. The tracer test allowed for a better understanding of groundwater flow throughout road structures and allowed for evaluating their effectiveness at a given location. However, the tracer tests are time-consuming and only a few field sites are available. The numerical approach, on the other hand, allows for exploring any combination of slope, hydraulic properties or road structure, thus providing a more comprehensive approach. In our study, the trends between the numerical and field approaches were consistent.~~

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