Dear editor,

Please find in this document our answers.

We thank you for the time you devoted for our paper review.

The authors.

Reviewer 1

We thank you for your very positive comments.

Reviewer 2

We thank you for your time and the pertinent comments and questions. Please find below our answers and the modified manuscript.

The author give a thorough literature review on the subject of road construction and its impact on flow, erosion and vegetation. The reader is well introduced to the topic of research and the motivation of the study.

We thank the reviewer for the insightful comments.

However, background information on the three road structures developed in Switzerland is missing (lines 90-93). Have there been more structures developed than those presented? What are advantages and disadvantages? Are there economical and/or constructional constrains to the choice of road types? Readers might benefit from (short) answers to these questions in the introduction or conclusion, understanding better the motivation for investigating the different road types.

This suggestion is very useful and is integrated in the revision. We are not aware of any other structures. However, there are significant differences in the pricing for these road types. Unfortunatly we did not receive this information yet. This point will be added as soon as we have the information.

<u>Section 2</u>

<u>Section 2.2.1 + section 2.2.3:</u>

Section 2.2 should be reworked. The authors use a well-established subsurface surface- water simulation software HGS where process equations are well known and documented. The equations (general processes) are given in the text, but the more relevant aspects of parameter choices and boundary/initial conditions (problem specific) are not or hardly discussed. Subsection 2.2.1 resembles a repetition of the HGS manual (e.g. the sentence in l. 197 on rivers and lakes is redundant). I fully agree with stating the relevant processes and naming the equations and parameters involved, but what is the benefit of giving the mathematical equations? Have they been modified in the code for the numerical study? The authors might consider cutting out the equations and giving proper reference to the used forms.

Section 2.2.1 was completely reformulated as suggested. We have kept only the basic assumptions of HGS and gave references for a detailed HGS description, capabilities and application. The new subsection is presented below in 178 to 188.

Instead, the author should address all choices of model parameters. Give reference to Table 2. State the values of all input parameters (maybe additional table) and reason the choice and the source (measured values, educated guess, literature value etc.); e.g. explain the choice of the different Van-Genuchten parameters. Which are the most relevant parameters? Why is the sensitivity study chosen for the slope and K-values specifically? In total, the author should focus in this subsection on the core facts of the mathematics/physics behind and the relevant aspect for

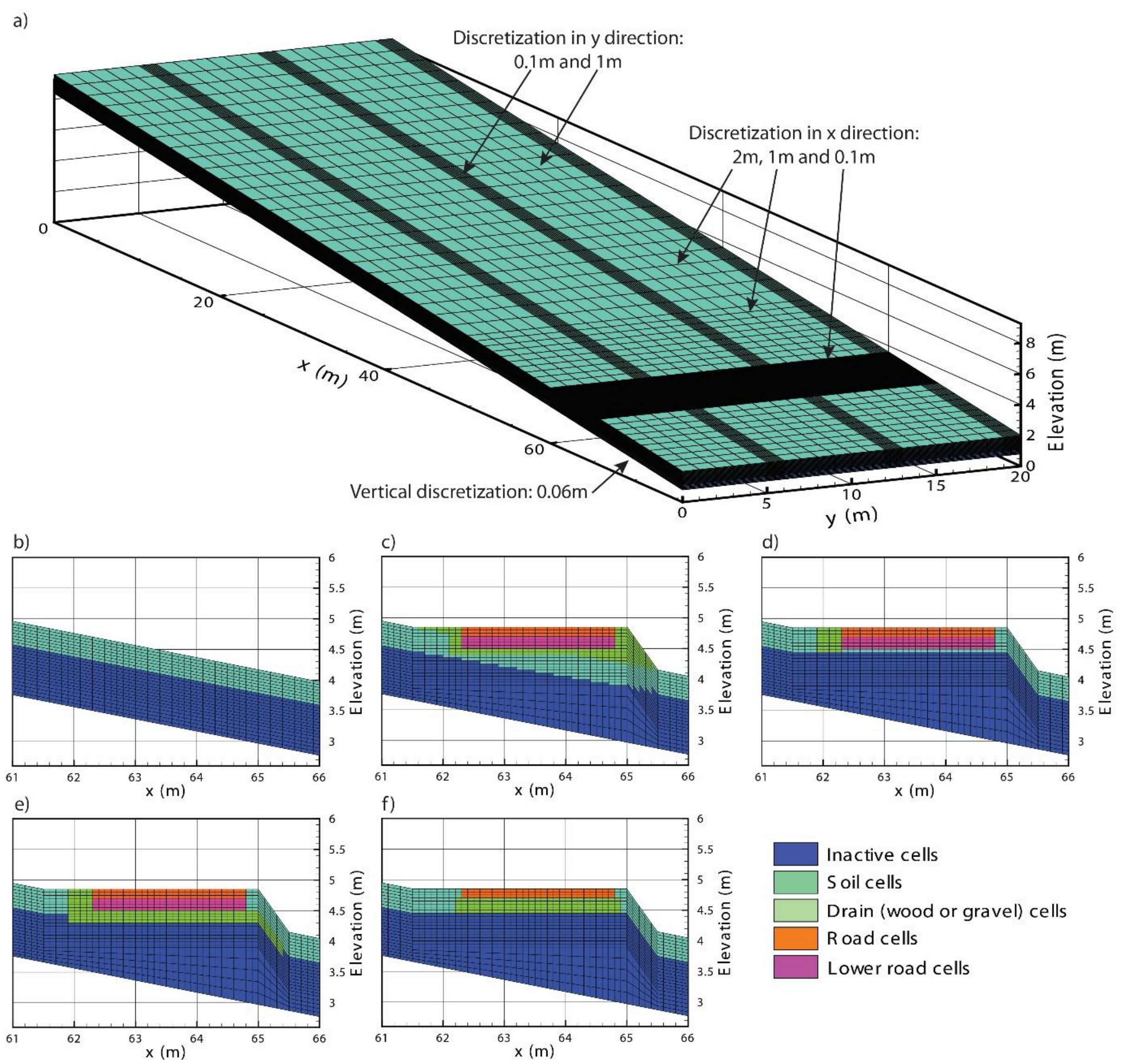
this specific case study. The authors should also give details on the choice of hydraulic conductivity values for the soil not only giving a reference (l. 235). The same for the values for the road drains (l.236) where there is not even a reference is given.

We agree with these comments and section 2.2.3 reworked (see line 202 to 232)

<u>Figure 5 + section 2.2.2</u>

The resolution of the mesh cross sections in Figure 5 is rather low. It does not allow to identify any mesh structure. Specify the refinements made in the mesh (l.217).

The size of Figure 5 was increased (see below). Now the discretization is well represented in figure 5b to 5f. Unfortunately, the size of the figure should be much bigger (about A3) to see clearly the mesh refinement… Therefore we added discretization details in figure 5a to inform the reader. You find the new figure in line 198.



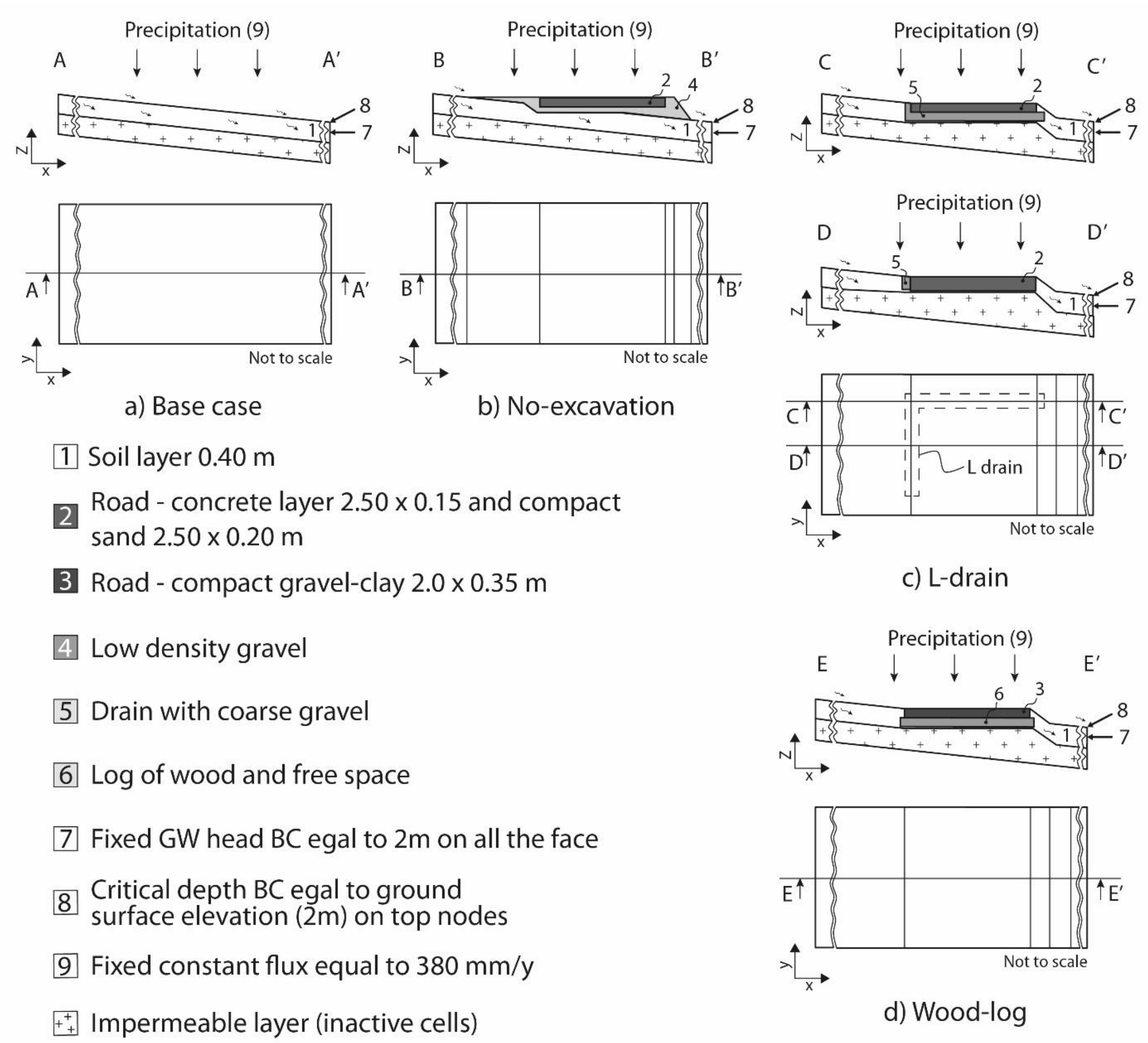
In figure 5c, are soil cells upstream connected with the soil cells below the road (not visible in figure with this resolution)?
Yes in figure5c soil cells are connected. With the modification of figure5, now the connection can be seen

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). Shouldn't there be soil cells below the road construction? This might significantly modify the simulation results.

When a road construction takes place, impermeable material is excavated upstream and filled downstream (see below). In order to implement this engineering structure in the model, inactive cells need to be present below the road. This conceptualization is therefore consistent with the construction of these road-types.

This is not in line with the conceptual model structures given in Fig. 4.

Yes, it is true it is not in line with the figure4. Therefore, we modified it as presented below. You find the modified figure in line 183



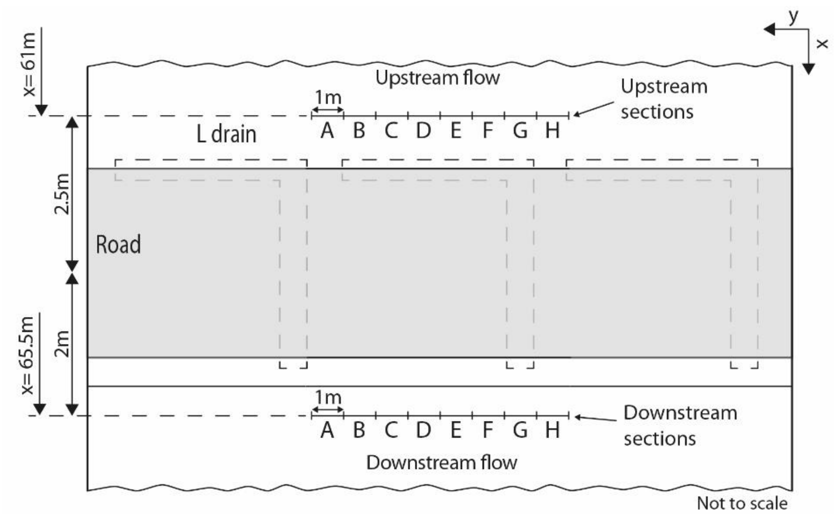
<u>Paragraph l.243-249</u>

The text does not really refer to the sensitivity study but are more part of the model setup and analysis.

We agree, the sensitivity analysis is a part of model setup and analysis. Therefore, we changed the name of this paragraph "model setup" (see line 202).

To my opinion the locations of the observation points (Figure 6) are crucial for the interpretation of the different scenarios (see statement later). The author should clarify the coordinates of the observation points, particularly the distance to the road structures.

We also agree, the location of the observation points (now sections) is crucial. We modified Figure 6 accordingly , and added the distance the observation points and the road (see line 233)



The same holds for the observation depth. Are the velocities taken at a specific depth or are they depth averaged? Please specify in the text and in Figure 6. I further recommend additional observation points. E.g. for comparison to flow velocities upstream, beneath the road structure and directly behind the road structure. Velocity profiles for the different road structures (and specific choices of parameter combinations) would be of interest.

Instead of extract velocities, it would be clearer to extract the subsurface flow rate through a section. Therefore we suggest extracting flow rate through 1m wide sections in the soil layer located upstream and downstream the road as presented in figure 6. Therefore all figures were modified (from velocities to flow rates).

I addition, the following results are presented:

1) Analysis of groundwater flow rates upslope the road (now figure 12 line 394 and presented below). In this way, the impact of the road in the upstream part of the fen is assessed.
2) Analysis of groundwater flow rates downslope the road at different distances to assess the extent of perturbation induced by the l-drain (now figure 10 line 389 and presented below). In this way, the water distribution downgradient of the L-shape structure is addressed.
3) Surface flow concentration caused by the L-drain (now figure 11 line 392 and presented below)

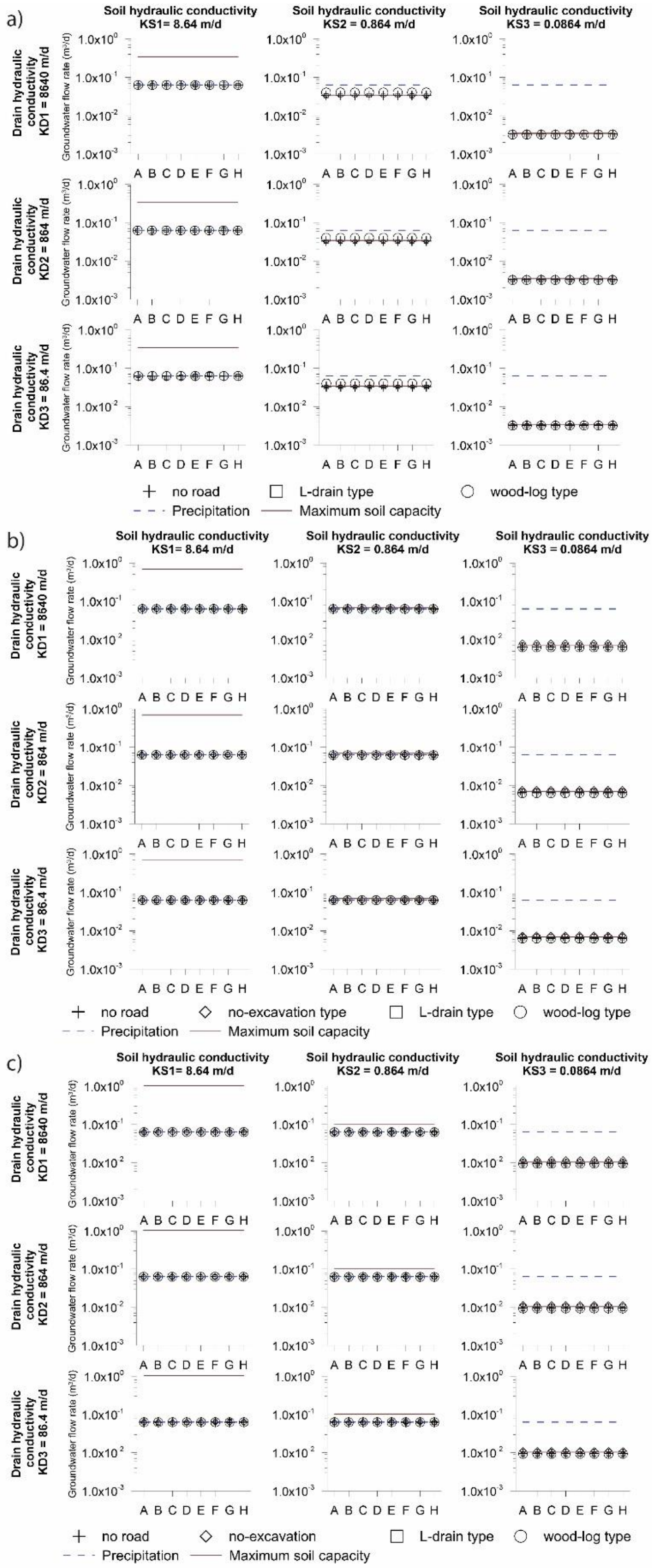


Figure 11: Simulated groundwater flow rates 2.5m upstream each road structures and each parameter combination with a slope of a) 10%, b) 20% and c) 30%.

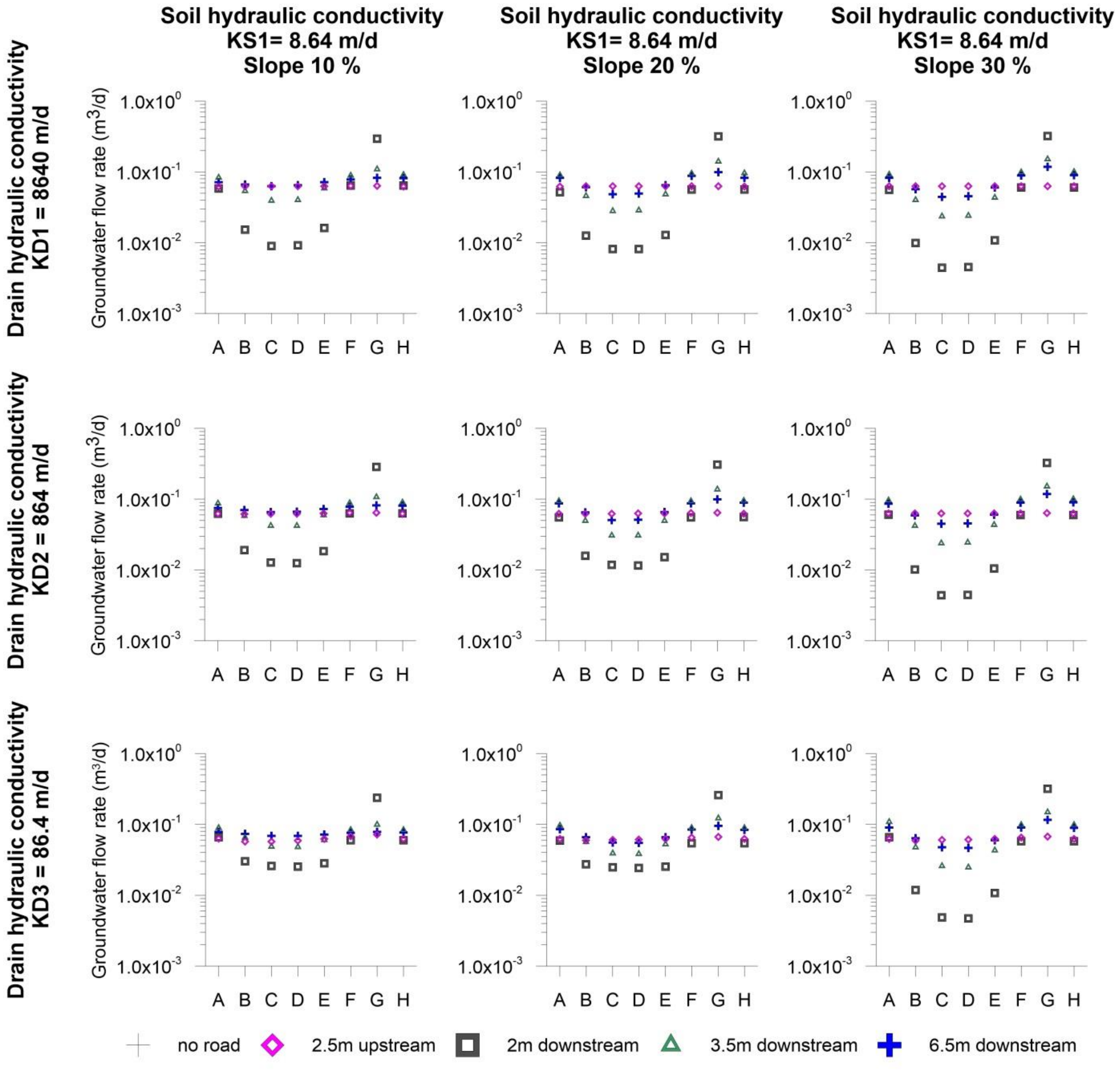


Figure 9 : Extent of perturbations due to the l-drain road type: Simulated groundwater v flow rates at G section at different distances the road.

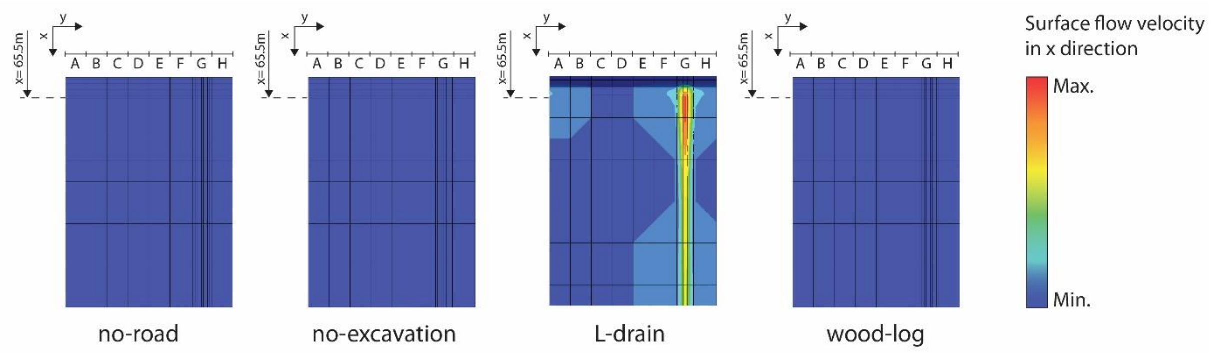


Figure 10: Simulated surface flow of the KS2-KD2 model and a slope of 20% for each road structure

Section 3

This section (mainly 3.2 line 271) was reworked to be less repetitive as you mention. In addition, a paragraph was added to assess the potential risk of gully erosion. To do that, the simulated groundwater flow rate will be compared with the maximum flux than can flow in the soil calculated with the Darcy law. If the road structure induces a groundwater flow higher than the soil capacity then gully may occur. For example in the surrounded plot in Figure 4, you see that L-drain induces a groundwater flow rate higher than the soil capacity and therefore may induce gully erosion.

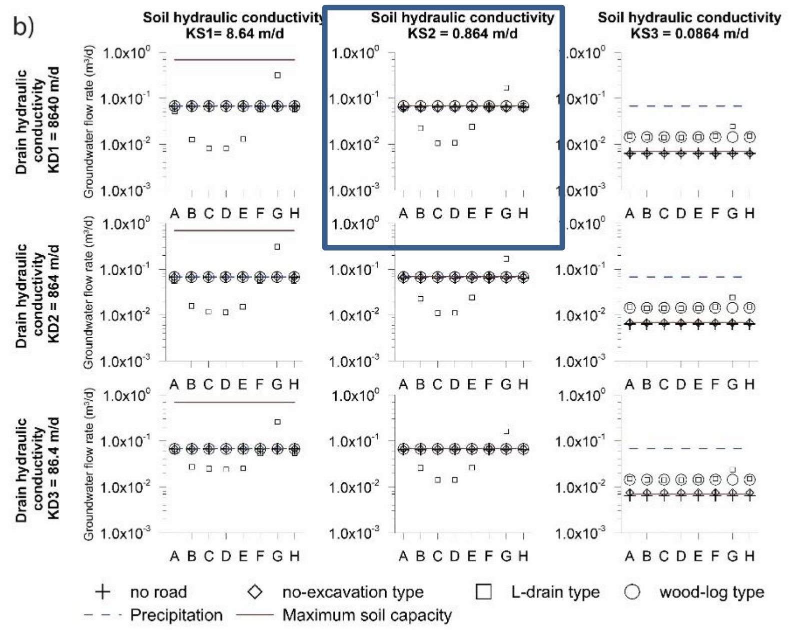


Figure 1 : Simulated groundwater flow rate 2 m downstream each road structures and each parameter combination with a slope 20%.

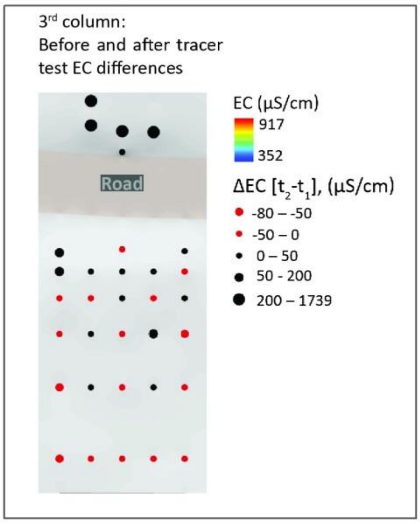
section 3.1 + Figure 7:

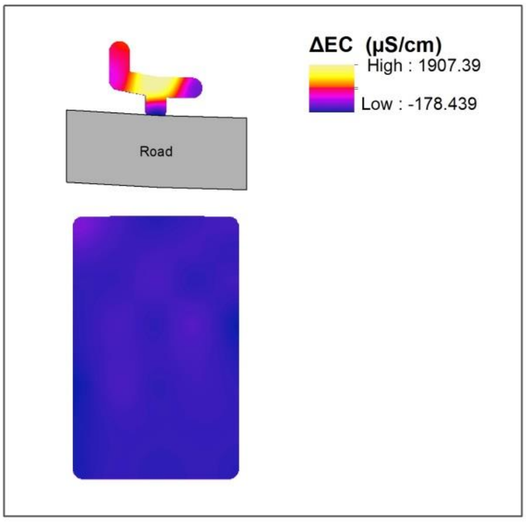
The resolution of the hydraulic head profiles should be adapted to the observed values in the first column for the sites SCH and STO, where the head profiles are not clearly observable in the current display form. The results for the EC contrasts (3rd column) are difficult to identify in the current form of presentation. I recommend a similar presentation as coloured pattern as in the 2nd column but preferably with a different colour scheme.

We try to modify the third column as you mention but in our opinion, it is not a better representation of results (see the figure below). What do you think ?

Current figure (STA)

Suggested modifications





For the resolution, do you mean the resolution of the picture or the intervals between level lines ?

Section 3.2:

This section requires significant revision. The text is partially repetitive. Whereas several key aspects of the model results are not discussed and at some points explanation are missing.

The section 3.2 was reworked (see line 271 to 372) and below your find our detailed answers to your relevant comments or questions.

paragraph l. 293 – 301:

The entire paragraph is repetitive and not to the point. Stick to the core message and argue with Darcy's law. I find the results for the flow velocities questionable. Or at least I see necessity for further analysis and discussion on the reported flow velocities. Lets focus on the reference case without road construction and undisturbed flow. There are almost the same flow velocities reported for the KS1 and KS2 (Figure 8) although the soil conductivities are one order of magnitude different. The effect amplifies for increasing slope (Figure 10). Making a coarse estimate with Darcy's law (assuming constant gradient, full saturation and neglecting the effect of recharge, which is of course a simplification): v = q=n = K=nr(h). With a porosity of n = 0:25, K = KS1 = 8:64 m/d and rh = 0:1 (slope of 10%), we find v = 3:456 m/d. This value is more than one order of magnitude higher then the highest reported velocity of 0.274. Is this related to the surface runoff? There seems to be a upper flow velocity threshold of around 0.269 (l.294, 303). Please explain and determine the general pattern for the flow dynamics.

In the base case and all others models, the precipitation is 380mm/year. It means that at x=65.5m in the model, the maximum flow rates with this precipitation rate is:

$$Q = 65.5\ (m)\ \times\ 380\ (mm/y)\ \times \frac{1}{1000}\ (m/mm)\ \times \frac{1}{365}\ (y/d)\ =\ 0.068 m3/d/m$$

The maximum flow rate according to the soil KS1 (8.64) and a slope of 10% is:

$$Q =\ q \times A = Ks \times \nabla H \times A = 8.6 \times 0.1 \times 0.4\ \times 1 = 0.345 m3/d$$

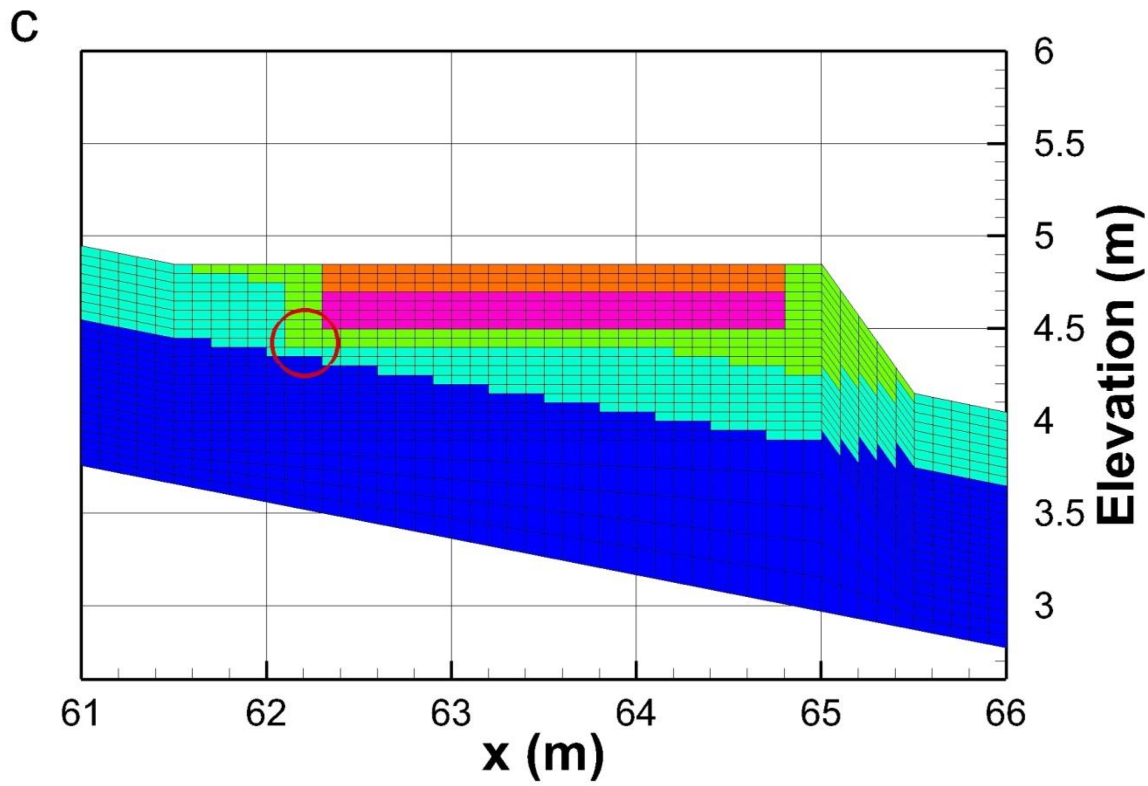
It means that the maximum flow rate in the soil may be more important than precipitation. It is however not always the case in the other models. In the new analysis of model results, we will compare the simulated flow rate vs. the maximum of flow rate of the soil to see if the simulate flow rate is close to the maximum of the soil. We will also compare the simulated flow rates and the maximum flow rates due to the precipitation (as previously calculated) to assess more in detail the concentration of the flux induced by road structures.

paragraph l. 302-313

The same as with the previous paragraph. Again an upper velocity threshold seems to be present. There seems also an apparent velocity threshold for the different drain conductivities (e.g. first column of figure 10). The explanation in l.309 – 313 is unsatisfying. Why are the results not comparable? I cannot see why flow velocities at the observation points should not be comparable for the grid adaption.

The threshold is due to precipitation rate which limits the flow rate in the subsurface.

In the figure below, you see the mesh of the no-excavation model. It was impossible to develop the model without a small extension of the road and drains in the soil layer because of the mesh geometry. This extension is surrounded in red in the figure. The extension induced artefact in results, but without any further implications for the upcoming analysis. Therefore we decided not to include these results. In 20% and 30% slope models, the slope is steep enough to develop the model without this extension.



__**paragraph l. 314-324:**__
Again repetitive, not to the point, missing explanations. What is meant with "observed in the same transect". It is unclear to what the sentence in l. 318-319 refers to. Explain what is meant with "the difference along the transect is smaller" (l. 320). The message of the last sentence (l. 322-324) is unclear.

“observed in the same transect" means observed along the transect formed by the observation section A, B, C, D, E, F, G and H. In other words, it means the simulated flow rates downslope the road __in a same model__.

"the difference along the transect is smaller" means that difference between G and C observation sections is smaller in a specific model than in another.

For the line 322-324, we wanted to say that the slope increases the differences between maximum and minimum simulated flow rates downslope the road.

This paragraph was reworked because it is not very clear as you mention. (see line 305 to 321)

paragraph l. 325-335
The paragraph seems to repeat the arguments just stated in the previous paragraph. Thereby the numbers given are not identical (l. 333 compared to l. 319-320). In l. 333-335, the authors mention the effect of infiltration of low-conductivity soil layers, but it is not clearly displayed. Can infiltration above/through the road structure occur?

This paragraph was removed because it was as you mention to repetitive.

Another possible explanation: observed velocities depend on the distance of the observation points from the road structure. For very low hydraulic conductivities the flow dynamics downstream of the road have already formed similar to those upstream of the road. For high conductivities and thus high flow velocities the distance between the road and the observation points is not big enough to establish the previous flow pattern. Therefore the author should investigate additional observation points and provide velocity profiles (in x-direction) for the different road structures.

We agree that a profile in x direction is useful to have a better understanding concerning the dynamics (see figure 9 line 386)

paragraph l. 336-347
The text is again repetitive, e.g. cut out sentence in l.339). The sentence in l. 345- 346) does not make sense. The preferential pathways are not small-scale processes, they are subject to the heterogeneity of hydraulic conductivity. This can be resolved by continuum scale models, but not if assuming a spatially homogeneous conductivity. Furthermore, “the exact hydraulic head in an individual mini-piezometer” is not a process. I cannot agree with the sentence in l. 346-347; simulation results using a spatially homogeneous conductivity are not an average across preferential flow paths.

This section was reworked to make it less repetitive and sentence l 345-346 will be clarified. We also agree that “hydraulic head” is not a process. “Processes” will be replaced by “observations”. Clearly, an average hydraulic conductivity cannot represent the dynamics in individual flow paths but may represent the average dynamics of multiple flow path and less conductive parts. We will reformulate the sentence accordingly.

Technical corrections:

l. 129: subsurface flows perpendicular -> subsurface flow is perpendicular
Yes, we corrected "subsurface flows perpendicular" by "subsurface is perpendicular". The corrected sentence is: …another important criterion for the selection of the study areas was that subsurface flow is perpendicular to the road (line 113)

l. 176: The mathematical representation of the nabla-operator is not fully correct. Please put the partial derivatives in brackets to symbolize its vector character.

These lines were removed.

l. 176: modify formulation "with the outside of the simulation domain"

These lines were removed

l. 306 if the hydraulic conductivity -> if the hydraulic soil conductivity

Yes you are correct, it is clearer if we add "soil".

l. 319: correct "from to 0.017"

Yes it is a mistake. We removed the useless "to".

l. 367: rephrase to "both sides of the road where hydraulically connected for all investigated road structures"

Yes, we corrected, the sentence is "The tracer tests showed that both sides of the road where hydraulically connected for all investigated road structures."

check references (particularly appearance and positions of doi's) as well as ref in l. 411

We checked the reference (Deroze 1998), the doi is unusual but it is correct.

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 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 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. Roads designed with an L-drain collecting water upslope and releasing it in a concentrated manner downslope constitute the largest perturbations. The other investigated road structures were found to have less impact. The developed methodologies and results are useful for the planning of future road projects.

1 Introduction

Wetlands can play a significant role in flood control (Baker, 2009;Zollner, 2003;Reckendorfer, 2013), mitigate climate change impacts (Cognard Plancq et al., 2004;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). 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.

The link between hydrological changes and sediment dynamics has been studied in various contexts. 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. (2005a);Descroix et al. (2008);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) 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 outlets of lateral road drains. Based on fieldwork and a subsequent statistical analysis, they concluded that the main causes for gully development are 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.

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) 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 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) 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) 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) 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.

Road construction can also impact the development of vegetation (Chimner, 2016). Von Sengbusch (2015) investigated the changes in 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 subsurface flow and therefore prevents the upslope water to flow to the bog. According to 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.

Based on these previous studies and basic principles of subsurface flow, a simple conceptual model describing the influence of roads on the flow system can be drawn (Figure 1). Roads are generally built with materials of low hydraulic conductive and therefore 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 (Figure 1a) as overlandflow. If a road is constructed, it constitutes a hydrogeological barrier (Figure 1b) and consequently affects 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.

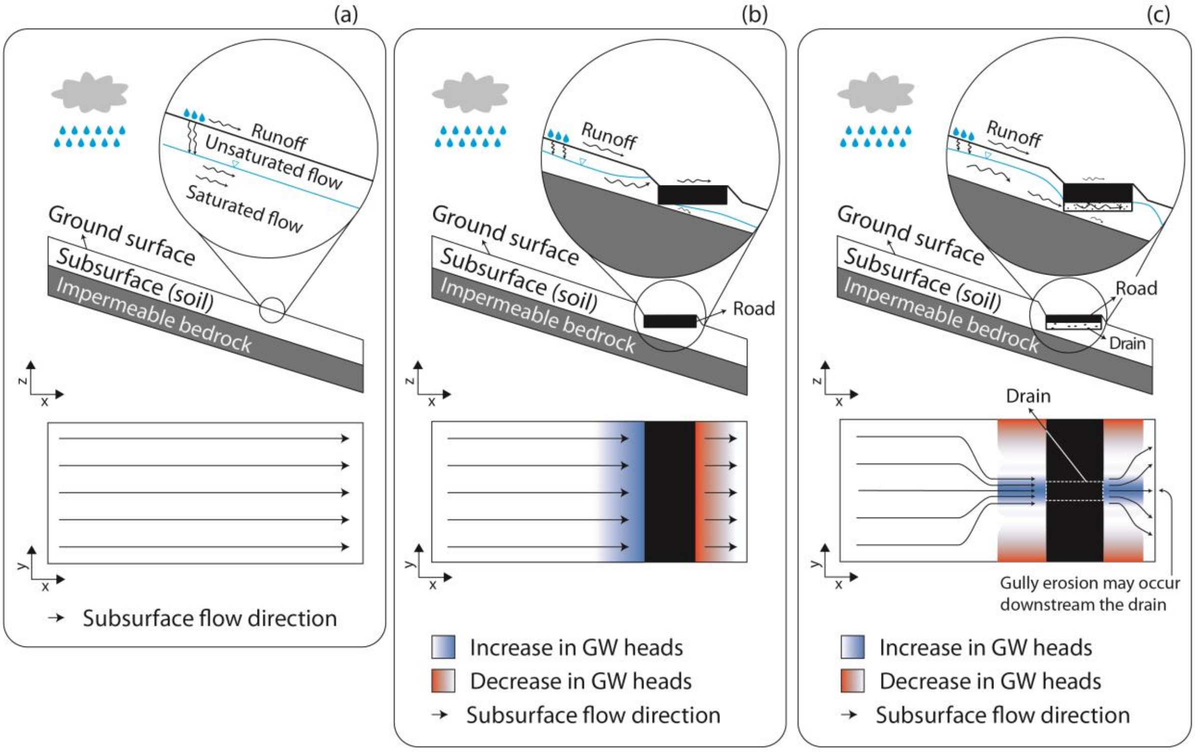

Figure 1 Conceptual subsurface dynamics in sloping fens: a) natural conditions, b) with road without a drain and c) with a road and a drain.

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 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. 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 2a) aims at preserving soil continuity under the road. It consists of a 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 2b) aims at collecting subsurface water 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.
- The *wood-log* structure (Figure 2c) 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.

The aim of this study is to investigate, document and assess the hydrogeological impact of various road structures and their effects on fen water dynamics. 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, however, they cannot provide 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 main advantage of the modelling approach is the possibility to generate a multitude of different models with various characteristics such as different road structures, slopes or fen hydraulic conductivity and to test their impacts on the flow dynamics. These model results can help in the planning of new roads.

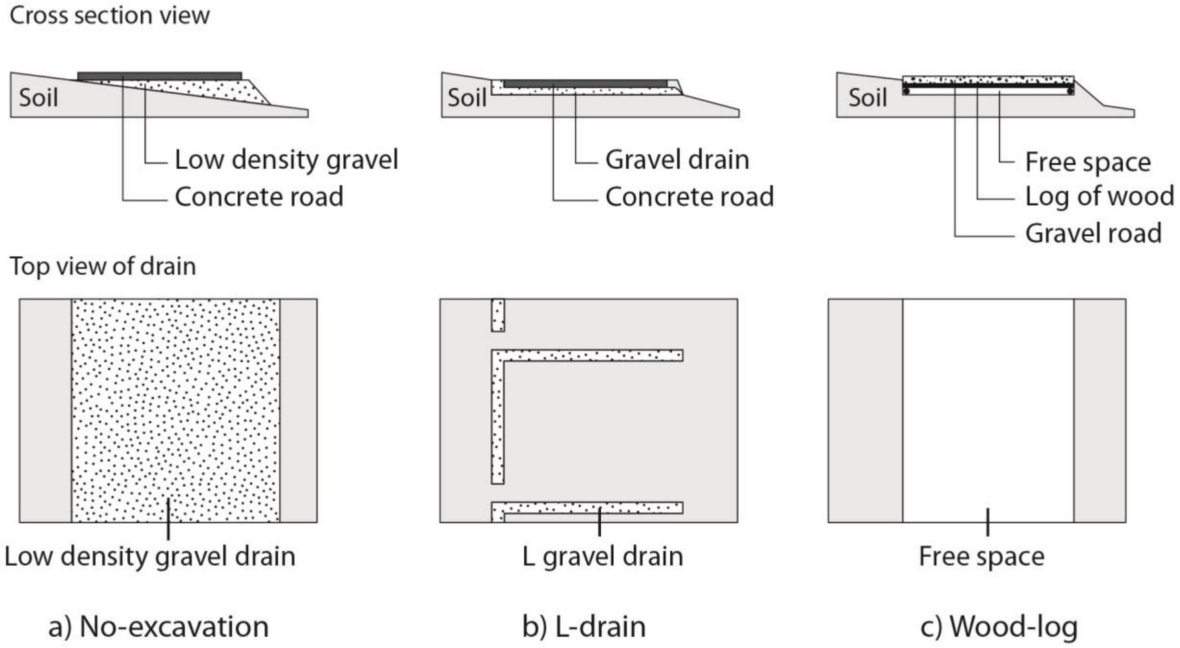

Figure 2 : Conceptual road structures, a) No-excavation road structure, b) L-drain road structure and c) Wood-log road structure.

2 Methods

2.1 Study areas and fieldwork

Four sloping fen areas located in alpine or peri-alpine regions of Switzerland (Table 1) 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 structures, tracer tests were carried out. As illustrated schematically in Figure 3, the upslope 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 corresponds to an 8 x 20m rectangle that includes a 2.5 to 3.5m wide road segment. A network of approximately 30 mini-piezometers on both sides of the road (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. Then, the area (60m^2) upslope of the road (upslope injection area of Figure 3) was irrigated with the salt solution using the two sprinklers. The electrical conductivity (EC) of soil water was manually measured using a 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 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.

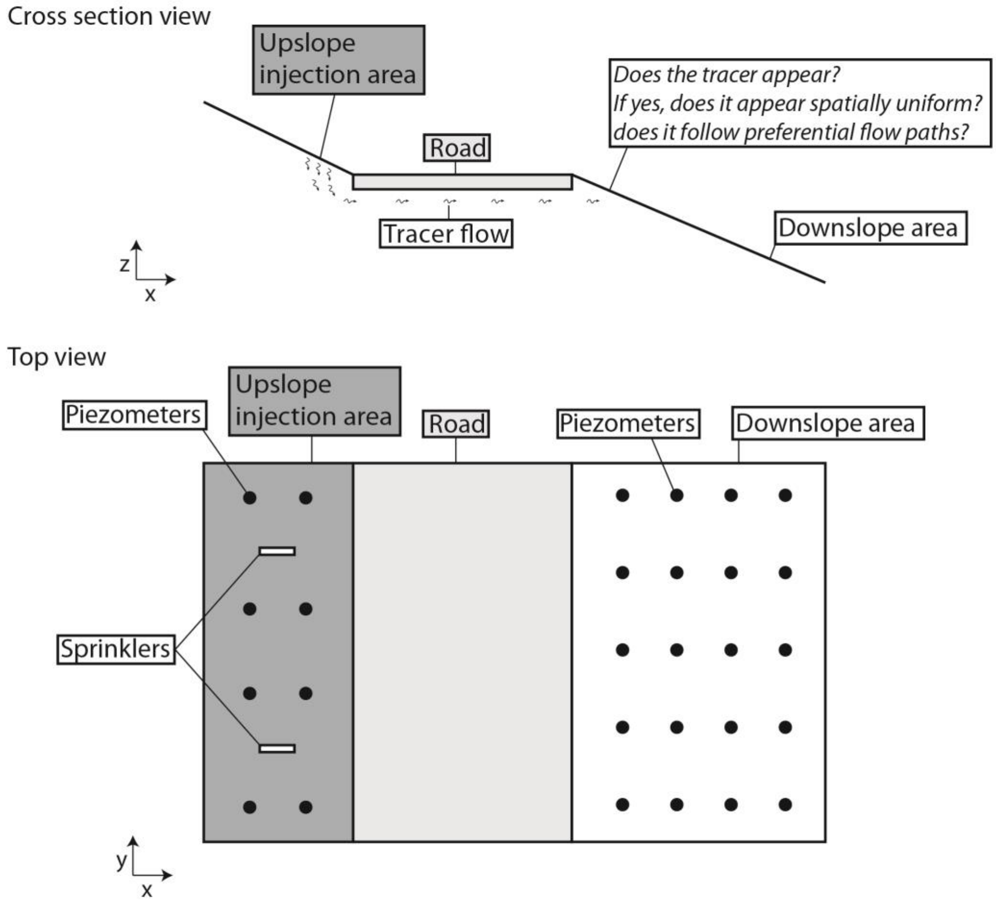

Figure 3 : Schematic view of the fieldwork areas.

2.2 Numerical modelling

To quantify the impact of the roads on the flow dynamics in sloping fens in a generalized way, the 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, 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). 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 not saturated, HGS employs the Van Genuchten (1980) functions to relate pressure head to saturation and relative hydraulic conductivity. Simultaneously, HGS also solves the 2D depth average 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 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. 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 illustrates the conceptual model of each case. 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 only supplied by precipitation. The upstream boundary is the catchment boundary (water divide) and the 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 5a) allowing the groundwater to flow out of the model. Finally, a critical depth boundary condition which forces the surface water to reach a given elevation (2m in our case) to flow out of the model was implemented on the top nodes located at x=76m and all other faces are no flow boundary conditions.

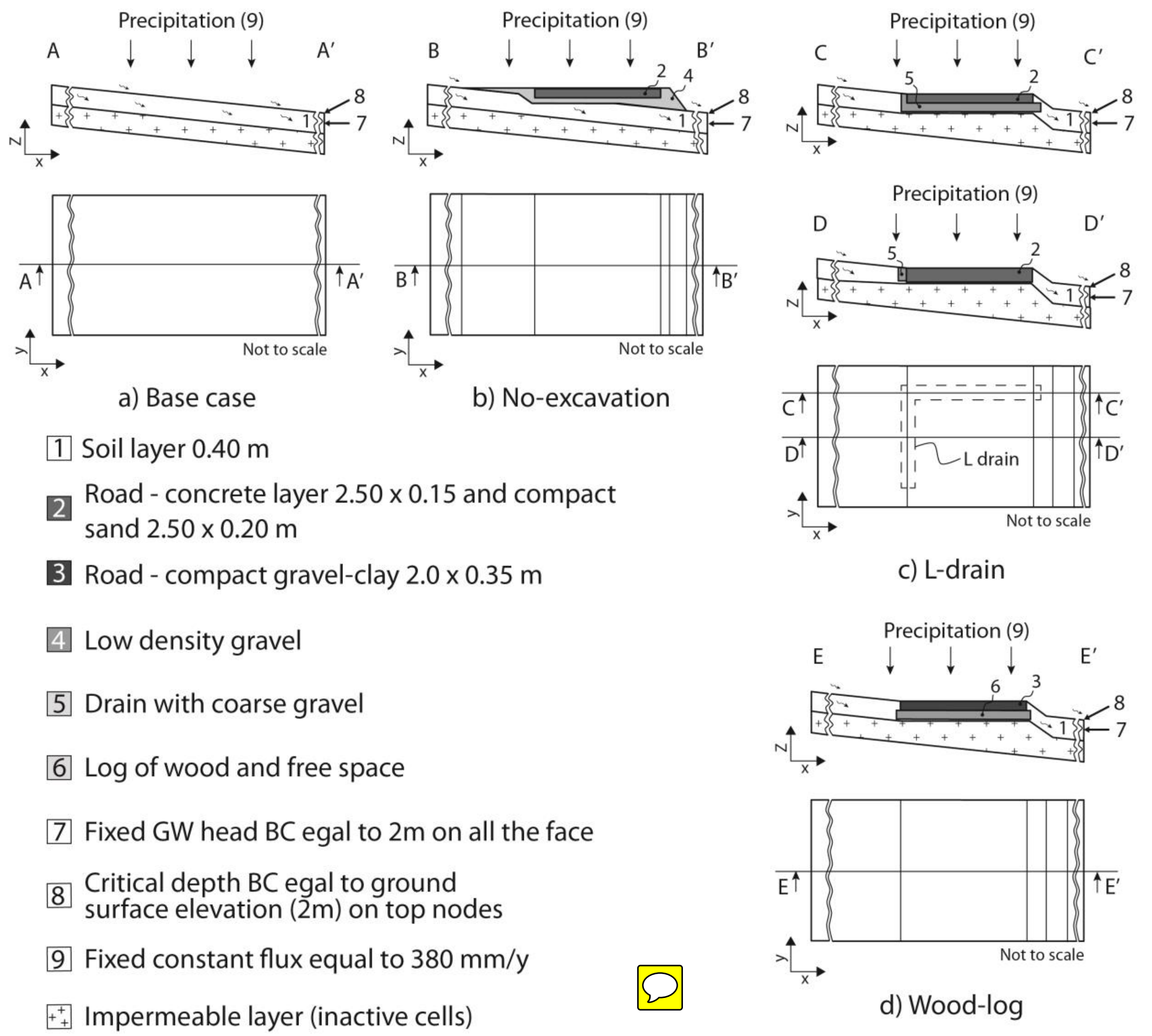

Figure 4 : a) Base case, b) No-excavation, c) L-drain and d) Wood-log structures conceptual models.

To numerically solve the 3D flow equation, a 3D mesh was developed (Figure 5a). 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 made up of 24 layers, 127,200 nodes and 118,440 rectangular prism elements. To ensure an appropriate level of detail, several mesh discretization refinements were made. Therefore, the 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 implement the different road types. Figure 5 depicts the differences between the base case model (Figure 5a and b) and models with roads (Figure 5c, d, e and f). In the case of models with a road, the mesh was deformed and the properties were 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.

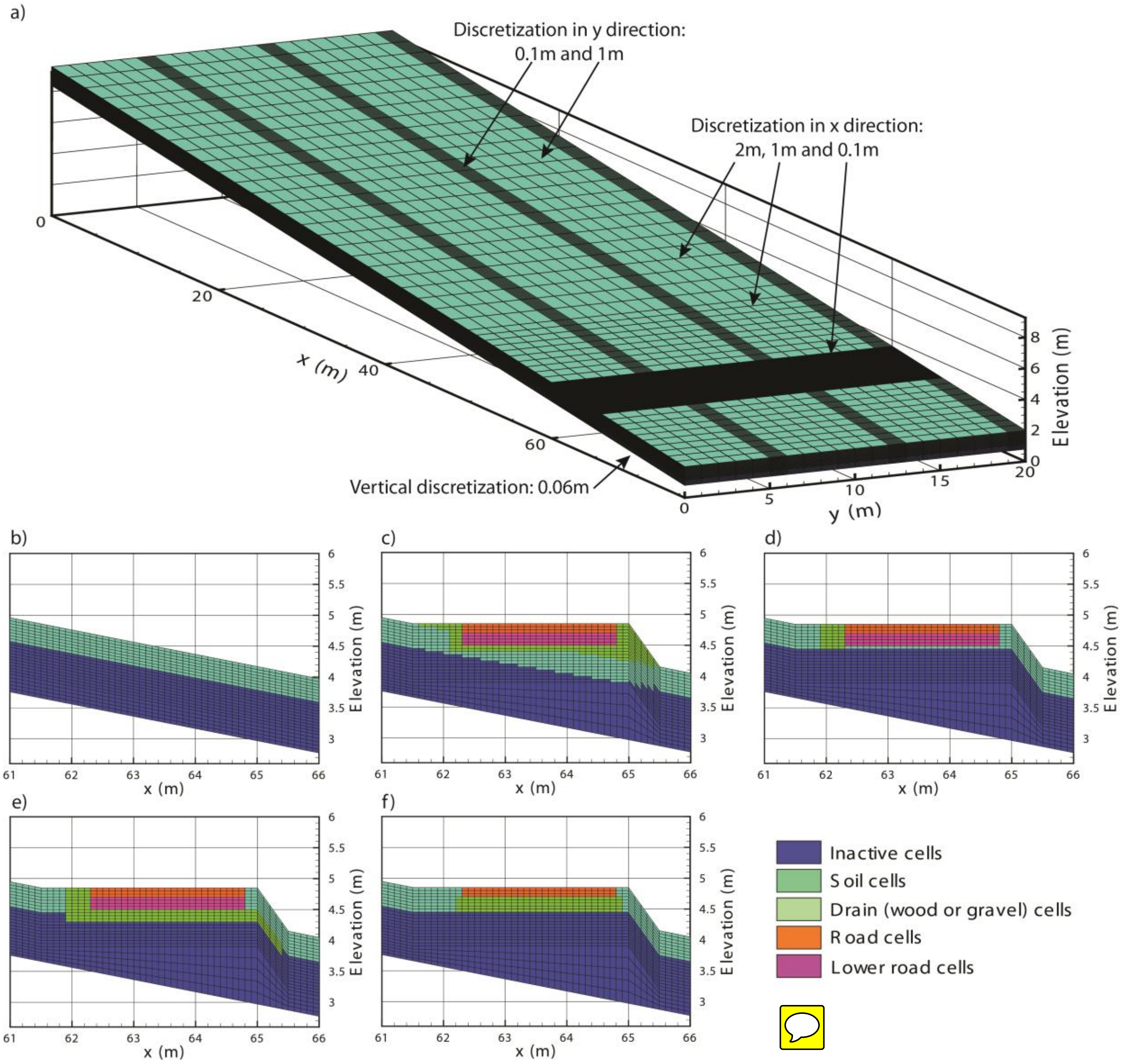

Figure 5 : Model development: a) Base case model, b) Base case model cross-section between 61m < x < 66m, c) No-excavation model between 61m < x < 66m, d) L-drain model between 61m < x < 66m, e) L-drain model between 61m < x < 66m along the transversal drain f) Wood-log model between 61m < x < 66m.

2.2.3 Model setup

The sensitivity analysis consists of the variation of model properties and parameters in order to understand how they control the 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 they govern the Darcy law (1) and consequently the groundwater dynamics. K is the hydraulic conductivity of the soil and the drain and ∇H the gradient of the fens controlled by the slope.

$$q = K * \nabla H \qquad (1)$$

For each property, three different values were chosen (Table 2), a low, an intermediate and a high 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) were used and vary 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 and the residual water content were considered similar assuming 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 coarse or very coarse gravel and have a hydraulic conductivity varying between 8640m/d and 86.4m/d (Fetter 2001) and their van Genuchten parameters are those of gravel. The slopes were fixed at 10%, 20% and 30% as observed during the fieldwork. Note that the drain hydraulic conductivities of the wood-log (W-L) were assumed ten times more conductive and more porous than gravel drain because of its particular structure (wood logs). The road concrete is almost impermeable with a very low hydraulic conductivity and its van Genuchten parameters of fine material. The road basement made with highly compacted fine material (sand and loam) feature a low hydraulic conductivity and are assigned van Genuchten parameters corresponding to fine material. Finally, the implemented soil and road surface flow properties correspond to a wetland and urban cover (Li et al., 2008).

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	$1. \times 10^{-2}$	0.03	0.03	0.005	0.005
Road	$1. \times 10^{-2}$	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. Flow-rates at any given location represent the cumulative vertical flow. Their spatial assessment allows to assess to what extent the roads perturb the system, and further allows to assess the erosion risk associated with the induced preferential flow. Therefore, a comparison of flow rates between each model was made to present the effect of each road structure and sloping fen properties on the dynamics.

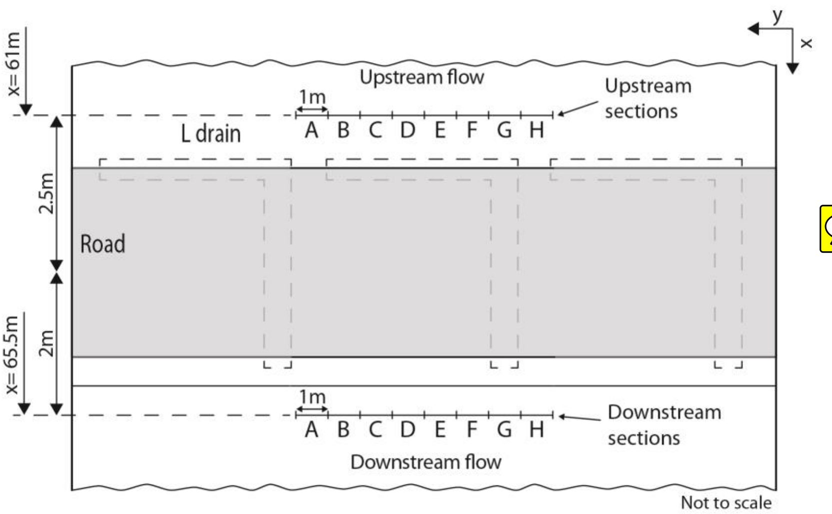

Figure 6 : Location of observation sections in the models.

3 Results and Discussion

3.1 Fieldwork

Based on the observations, all sites show a continuous saturated zone before the experiment, both upstream and downstream of the road, the hydraulic gradients being similar to the terrain slope (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, 2nd column.). Within each plot, EC varies from 482 to 629µS/cm. At the SCH site, the highest values are located 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, 3rd column).

The heterogeneity of the hydraulic conductivity of the soil is apparent from the tracer tests (Figure 7, 3rd column: EC 24 hours after injection). At all four sites, the front of the saline solution is not uniform but follows the heterogeneity of the soil hydraulic conductivity. Nevertheless, road structures may create preferential flow path that is particularly obvious 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, 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, this flow convergence is a serious threat (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.

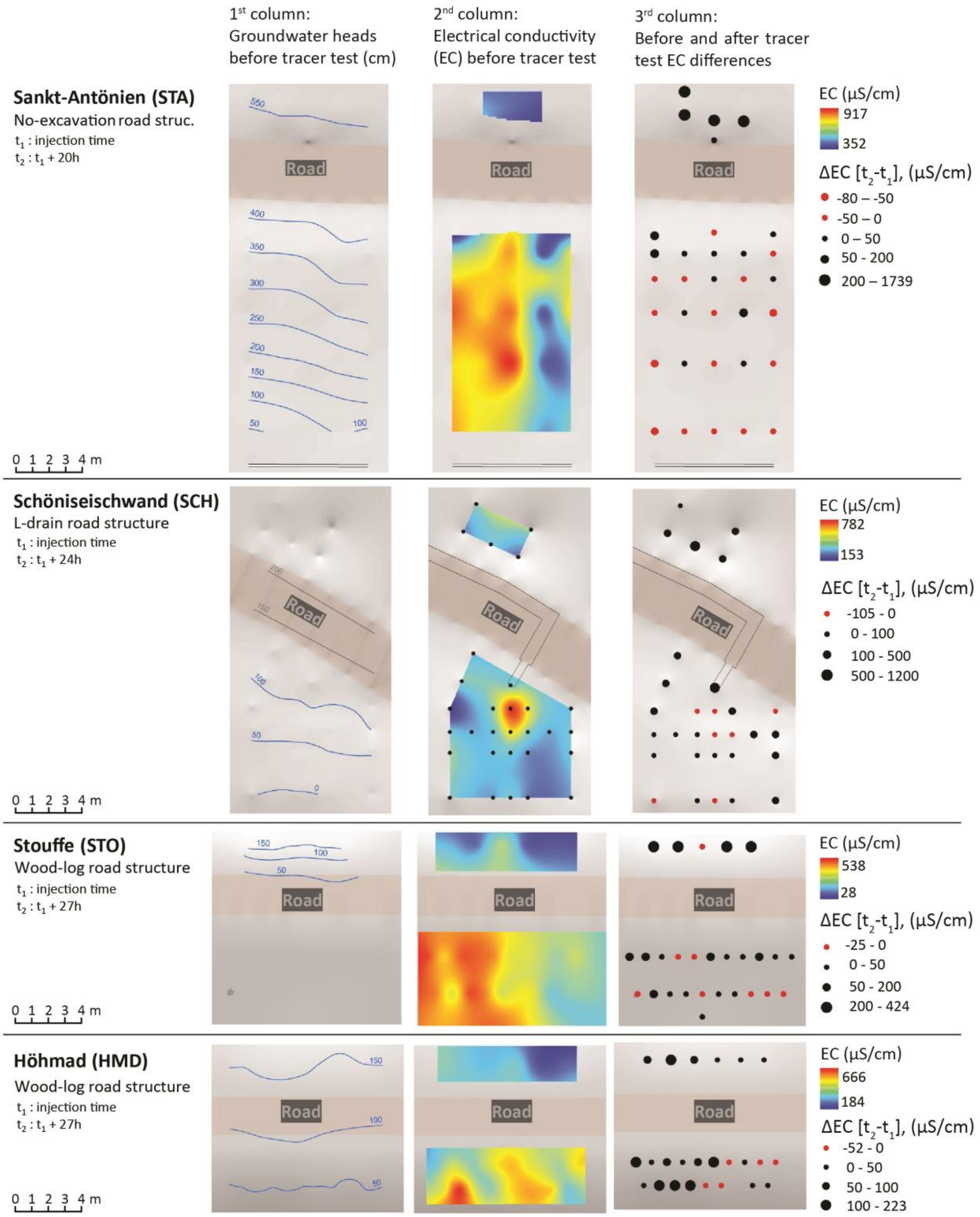

Figure 7 : Fieldwork results at the four field sites: 1st column) Spline interpolated measured groundwater heads before tracer test , 2nd column) Measured EC before tracer test and 3rd before and after tracer test differences in EC.

3.2 Modelling

Figure 8a shows the results of the models with a slope of 10%, Figure 8b with a slope of 20% and Figure 8b 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 Law (1) and the flow rate induced by the precipitation are also presented for the interpretation of the results. In 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 rates vary from 0.003 (m^3/d) to 0.069 (m^3/d) for 10% slope, 0.006 (m^3/d) to 0.069 (m^3/d) for 20% slope and to 0.009 (m^3/d) to 0.069 (m^3/d) for 30% slope. The groundwater flow rate decreases gradually depending on the hydraulic conductivities (KS) of the soil layer. For any slope, where hydraulic conductivities are high (KS1), groundwater flow rates are higher compared to the case where hydraulic conductivities are low (KS3). The primary observation is that groundwater flow rates are mainly controlled by the hydraulic conductivities and therefore the slope plays a minor role. Differences between the maximum and minimum hydraulic conductivity are two orders of magnitude, whereas changes between slopes multiply by 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%. 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 KS2 and KS3 models, surface flow occurs and conversely the soil is able to infiltrate the precipitation in KS1 models.

In the no-excavation and wood-log type models, the effect of road structures is quite similar. The groundwater flows vary from 0.01 (m^3/d) to 0.069 (m^3/d) for 10% slope, 0.01 (m^3/d) to 0.069 (m^3/d) for 20% slope and to 0.010 (m^3/d) to 0.069 (m^3/d) for 30% slope. Compared to the base case model, results show that the no-excavation and wood-log type structures have a minimal impact. The only marked difference is that groundwater flow rates are slightly higher if the soil hydraulic conductivities are low (KS3) for each slope in the wood-log type model. This can, to a certain extent, be explained by the fact that the hydraulic conductivity of the base of the road (consisting of wood-logs) is higher than the hydraulic conductivity of the soil and therefore facilitate the infiltration. Conversely, in the base case model, less water is infiltrated but more runoff occurs. However, the process is limited, because at 3.5 m downstream the road (x=67m), the simulated flow rates of the model KS3- KD1 and a slope of 20% for the wood-log and no-road model are equal (Figure 9). 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 is markedly different from the other road structures. The groundwater flows vary significantly in the observation sections. The maximum flows are always obtained in the observation section G just downstream the drain outlet and can be 10 times higher than in the base case. Conversely, minimum flows are obtained in C and D observation sections in which flow rate may be 10 times lower. Significant differences in groundwater flow are also observed in the same transect (i.e. the transect formed by the observation section A, B, C, D, E, F, G and H within the same model). The maximum differences are observed if 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 flow rates are slightly higher than the base case model. Finally, it can be seen that slope accentuates groundwater flow rate differences along the transect. Therefore, an increase of groundwater flow differences in the same model is observed for the 10% and 30% slope scenarios. The impact of L-drain may be further explored by extracting groundwater flows lower than 3.5m to assess the extent of perturbations. Figure 10 shows additional simulated groundwater flows for the most critical cases (i.e. KS1 with a slope of 10%, 20% and 30%) downstream the road at 3.5m and 6.5m respectively and 2.5m upstream. It can be seen that at 3.5m the groundwater flows already regain their upstream conditions. At 6.5m downstream the road, all observation sections are very close the upstream flows except in section G where flows are still slightly higher.

The model results can be used to predict the risk of gully erosion and. 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, the maximum flow rate capacity of the soil is small in caparison with precipitation. For all model scenarios except for KS1, the soil capacity is lower than the precipitation amount which is already set pretty low in the model. This means that runoff already occurs in sloping fens. However, the runoff may be accentuated by subsurface perturbation caused by the L-drain structures. To illustrate this process, the simulated surface flow velocities of each road structure downstream the road for the model KS2-KD2 and slope of 20% are presented in Figure 11. In this case, maximum flow rate capacity of the soil is approximately equal to precipitation, therefore runoff should not occur. However, it can be seen some runoff in the L-drain model which is the consequence of the subsurface flow concentration. In this configuration, the soil infiltration capacity is too small and consequently, the groundwater emerges and flows on the surface. Although the formation of gullies depends 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. A simple recommendation can be made to avoid this runoff concentration.

1. 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.
2. 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

Finally, the impact of road structure on the upstream road dynamics may be also assessed. Figure 12 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 flow across the road.

The impact of the L-drain road structure which concentrates groundwater flow is clearly identified in the numerical approach and is consistent with the field observations. For other road structures also, numerical models are consistent with fieldwork results by showing relatively undisturbed groundwater flow downslope the road. The 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, a numerical model is always a simplified reproduction of reality. The main model assumption is that hydraulic conductivity of the soil is homogeneous. Groundwater flow in fens can occur along preferential pathways. Therefore, the models are not able to reproduce small-scale observations, i.e. the exact hydraulic head in an individual mini-piezometer. Models results have to be interpreted as an average across multiple preferential flow paths.

Further investigations should be carried out to identify groundwater 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 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.

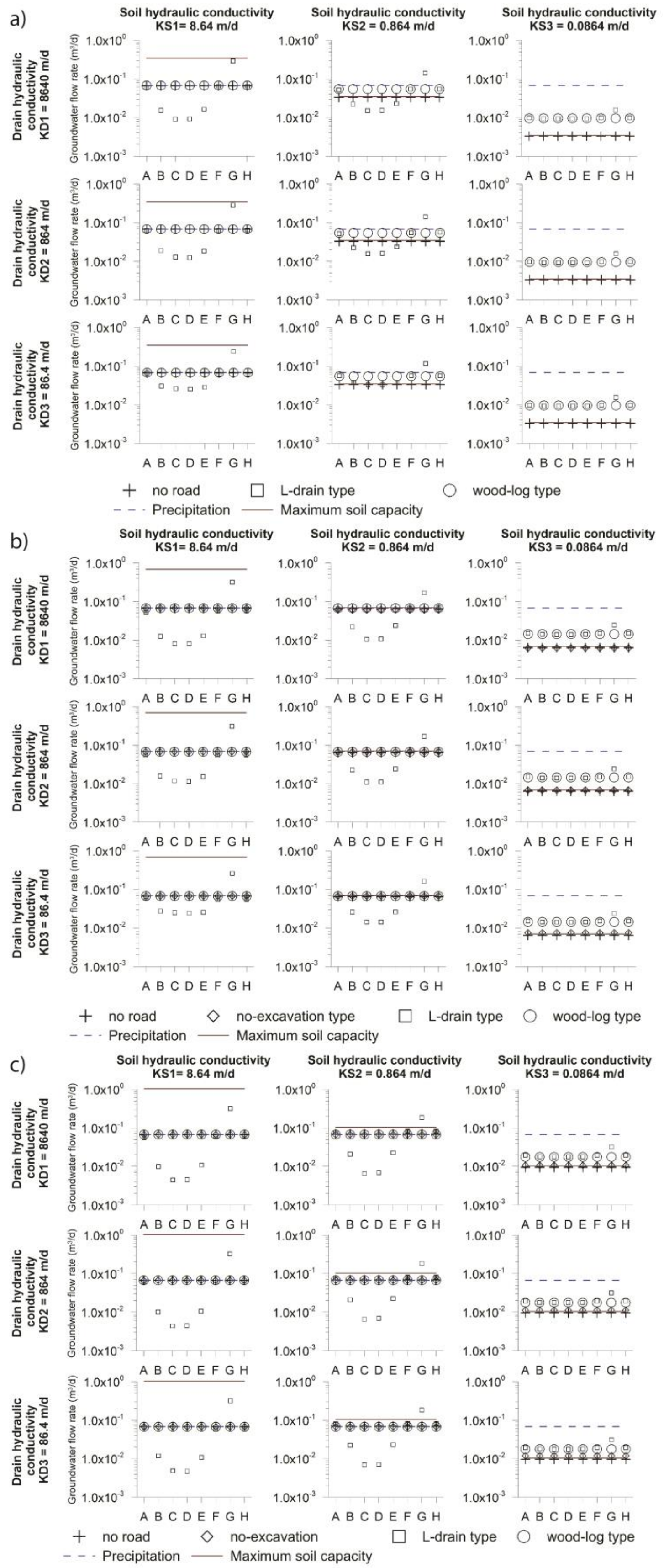

Figure 8 : Simulated groundwater flow rates 2m downstream each road structures and each parameter combination with a slope of a) 10%, b) 20% and c) 30%.

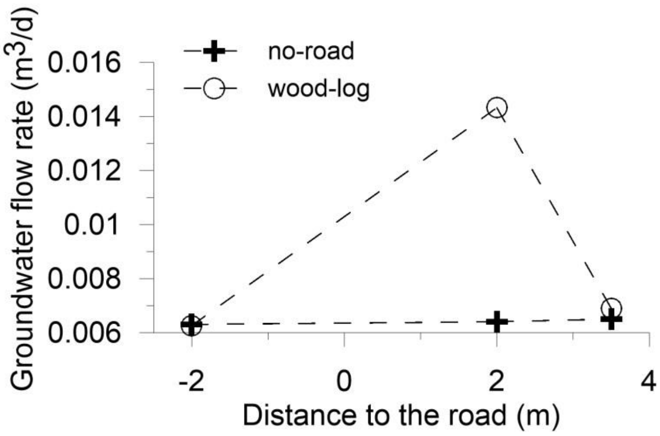

Figure 9 : Simulated groundwater flow rates along x direction for the KS3-KD1 models with the wood-log structure and without road.

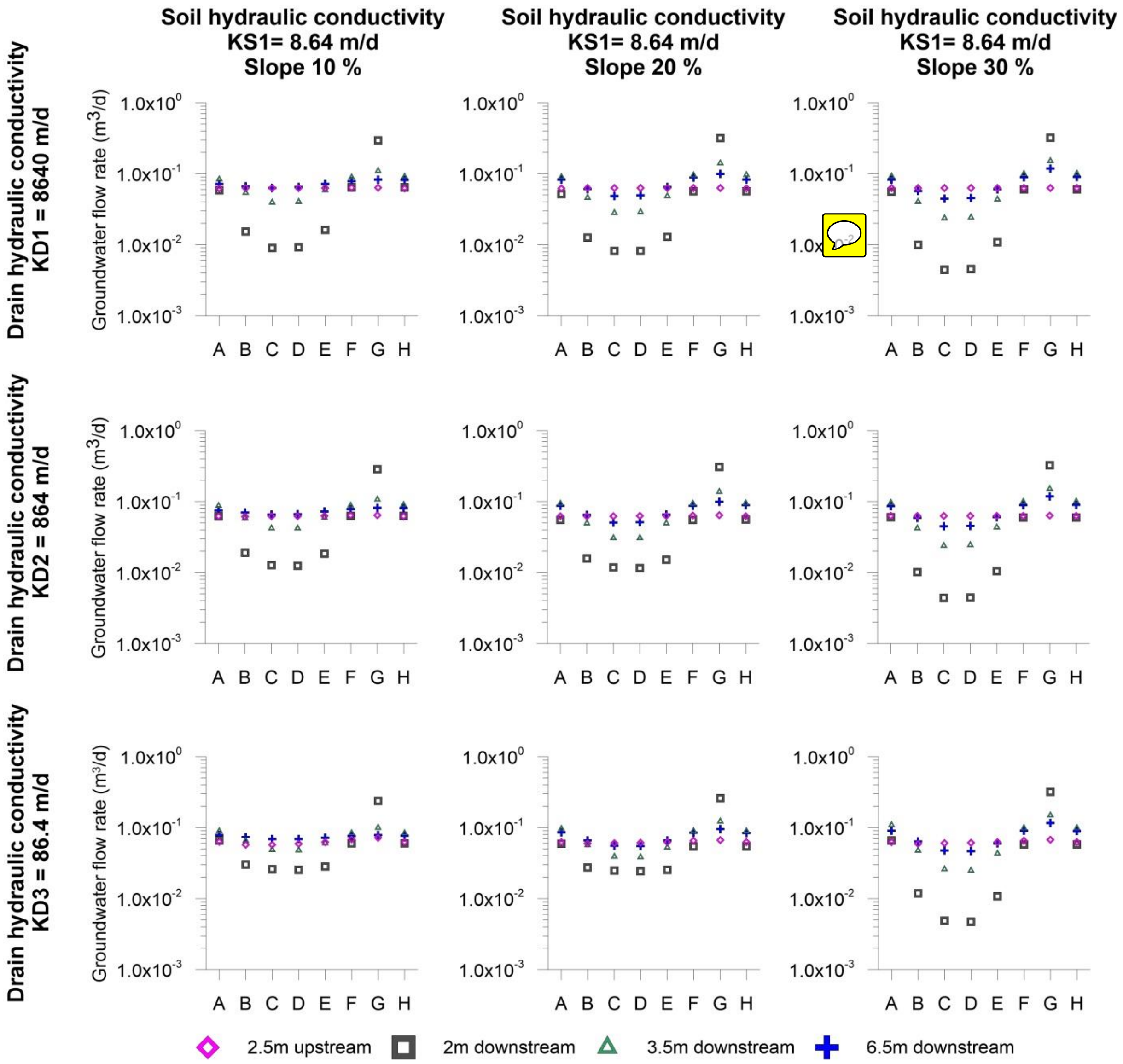

Figure 10 : Extent of perturbations due to the l-drain road type: Simulated groundwater v flow rates at G section at different distances the road.

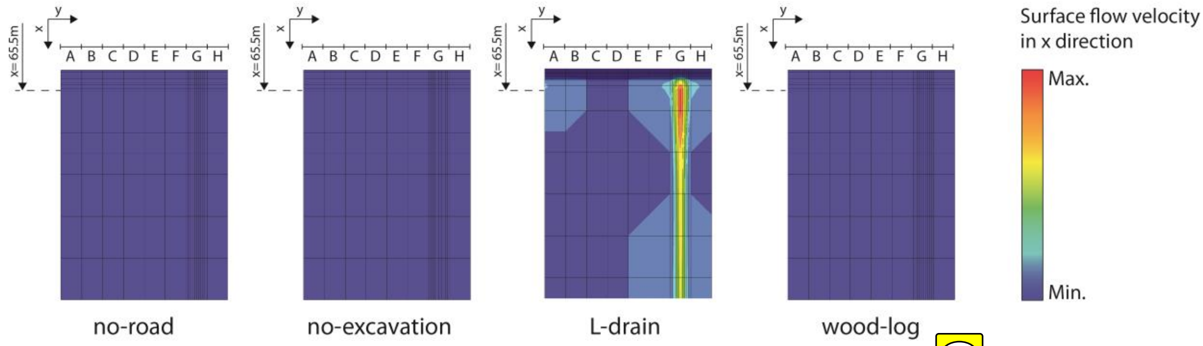

Figure 11 : Simulated surface flow of the KS2-KD2 model and a slope of 20% for each road structure

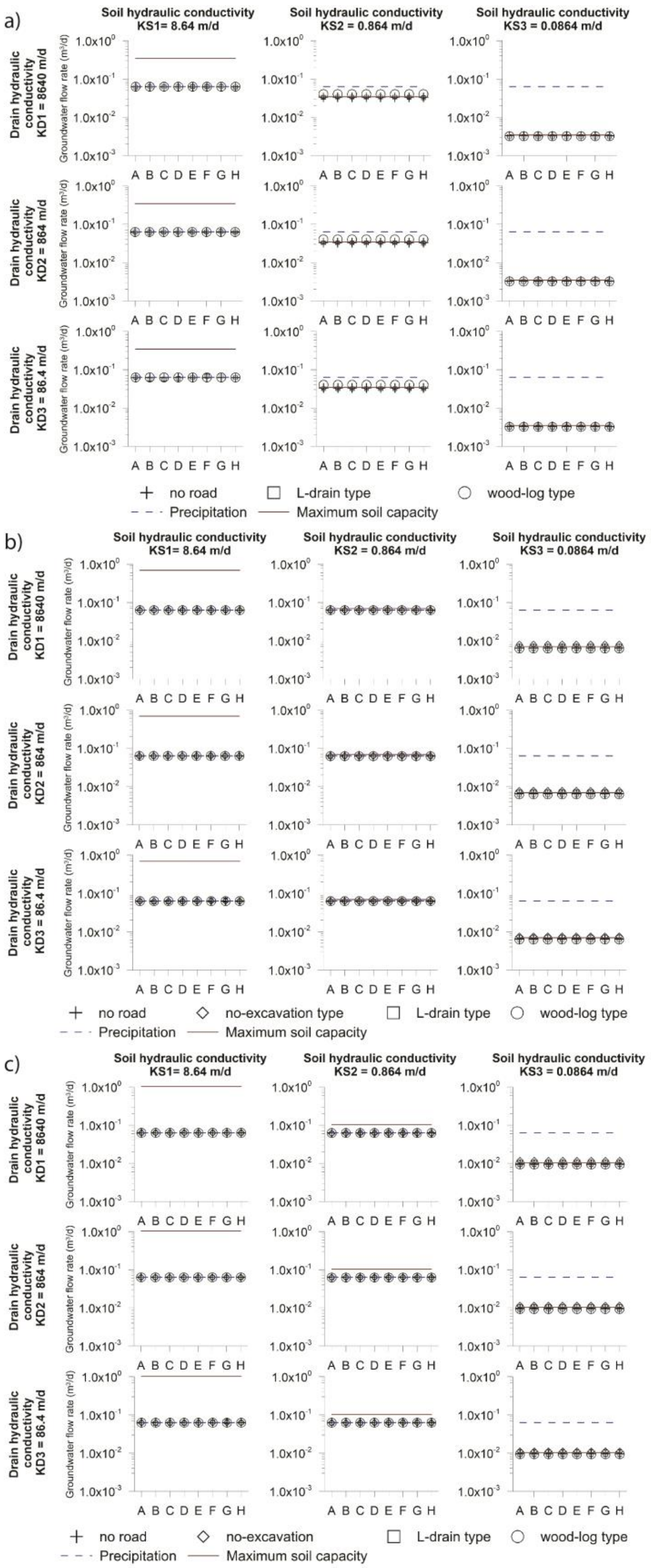

Figure 12 : Simulated groundwater flow rates 2.5m upstream each road structures and each parameter combination with a slope of a) 10%, b) 20% and c) 30%.

4 Conclusions

This study 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-based tracer tests and numerical models simulating groundwater flow for the different road structures.

It is the first time that the performance of these road-structures has 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 preferential flow paths in the soil. The presence of a transversal drain (L-drain) beneath the road constitutes a preferential flow path, however, which is of much greater importance than the naturally occurring preferential pathways. This was also confirmed by the models. Groundwater flow rates 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.

5 Acknowledgements

This research was funded by the Swiss Federal Office for the Environment (FOEN) and supported by Swiss Federal Office for Agriculture (FOAG). The authors are grateful to Benoit Magnin, Peter Staubli Andreas Stalder, Anton Stübi and Ueli Salvisberger for their collaborations. We thank the three anonymous reviewers and the editor for their constructive comments.

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Reviewer 3

We thank you for your time and relevant comments and questions. Please find below our answers and the modified manuscript.

Your answer sounds quite promising and I am curious about reading the revision. If you would extent your story according to the listed points, I see potential for an improvement of your manuscript.

Thank you for the comment.

However, I still not really see the connection of the tracer test and modelling. I agree that a quantitative coupling (e.g. comparison of simulated and observed concentrations) will be very challenging caused by parameter heterogeneities, which are difficult to capture. Also, I can somehow agree to the argument that you want to provide a general modelling framework. However, this leaves me with the question: Why you Discussion paper incorporate the tracer test at all? How does it support your synthetic model? Besides showing natural heterogeneities, you just prove that a L-drain constitutes a preferential flow path. Isn't that a bit too trivial?

In our experience it never hurts to have field experiments backing up a modelling approach—actually quite the opposite. Even if it might appear trivial at a first glance we believe there is always value in the field data. Apart from this general consideration, we don't think it is a trivial as mentioned by the reviewer. Below some examples (which we will elaborate in the revised manuscript):

- It is also not all clear how important the natural heterogeneities and preferential pathways are in comparison with the drain.
- The price differences of these engineering structures is significant. Given that the models always need to simplify a system it is in our experience unwise to base decision purely on modelling approaches--- the most convincing approach is a combination of both with a demonstration that the planned systems work as planned, and then the models can help to identify how the proposed system will affect flow under different conditions.
- It could also be that the engineering structure is not well implemented or its execution has not been communicated correctly. This is in fact a very common problem. It is not at all trivial to implement these engineering structures in wetland, as the construction machines cannot leave the road, access is difficult and there are legal considerations ect. With the field tests we show that these structures can be built and functions as planned.

Finally, we want to highlight that this paper is directed not only towards the scientific community, but also stakeholder and the engineering firms who implement these structures. It it therefore particularly important to demonstrate that model can reproduced the general behaviour observed in the field.

Moreover, regarding the term novelty, we seem to have a slightly different opinion. For me novelty should be more than the application of an existing model to just a new case. Sure, not all HESS papers present an entirely new model or method, but they should present at least a creative solution or new combination of methods. I encourage you to strongly revise your manuscript by adding some new ideas regarding e.g. drying up of fens or gully erosion (could be also something else). Basically, you should dig a bit deeper, but I am optimistic that you are able to do it.

In term of novelty we added a range of points as suggested by the reviewer. We agree that more results can be extracted from the modelling approach. It is the first time this topic is treated, and we also want to highlight that physically based models such as the ones we use are not that commonly used. Finally, we want to highlight that HESS also encourages the submission of applied research, as highlighted in the description of the journal:

"*HESS encourages and supports fundamental and applied research that advances the understanding of hydrological systems, their role in providing water for ecosystems and society, and the role of the water cycle in the functioning of the Earth system.* "

In addition, section 3 was deeply reworked (see line 295 to 396) and new subsections were added in which we assess the potential risk of gully erosion. To achieve this, the simulated groundwater flow rate are compared with the maximum flux than can flow in the soil calculated with the Darcy law. If the road structure induces a groundwater flow higher than the soil capacity then gully may occur. For example in the surrounded plot in Figure 1 below, you see that L-drain induces a groundwater flow rate higher than the soil capacity and therefore may induce gully erosion. We can also show the consequences of this groundwater concentration by using simulated surface flow illustrated in figure 2. It can be seen that the groundwater flow concentration causes an increase in surface flow and consequently induce gully erosion.

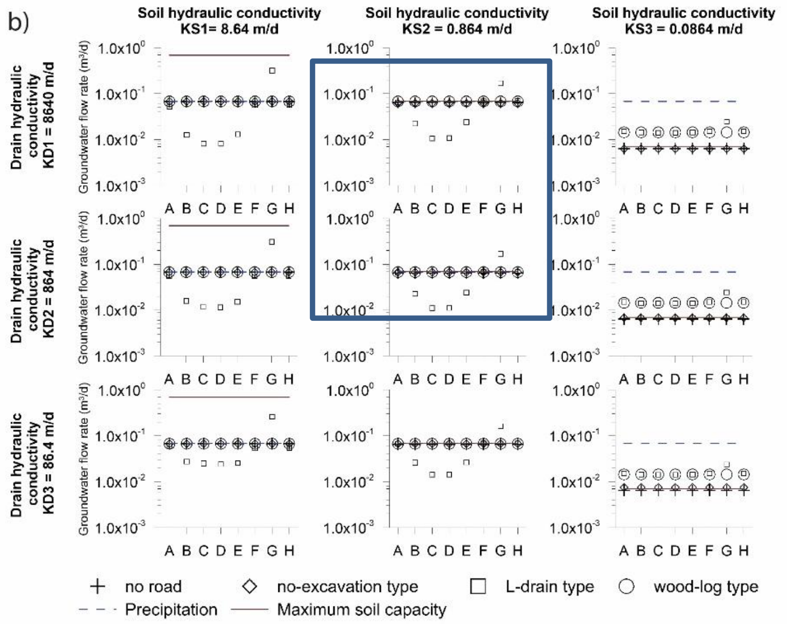


Figure 1 : Simulated groundwater velocities 2 m downstream each road structures and each parameter combination with a slope 20%.

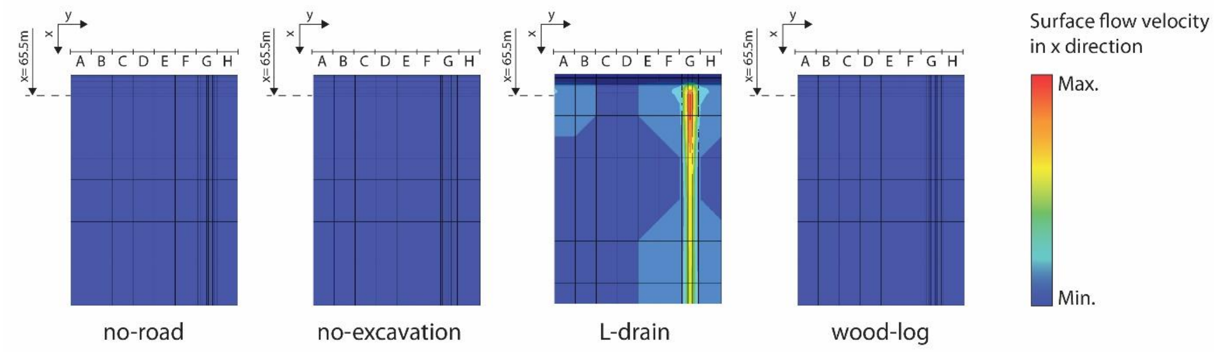


Figure 2 : Simulated surface flow of the KS2-KD2 model and a slope of 20% for each road structure

Finally, the simulation results are presented at different distance of the road to have a better assessment of the road impact. We are also able to identify areas in which the soil layer is not fully saturated or on the contrary areas in which runoff occurs. See an example in the figure 3.

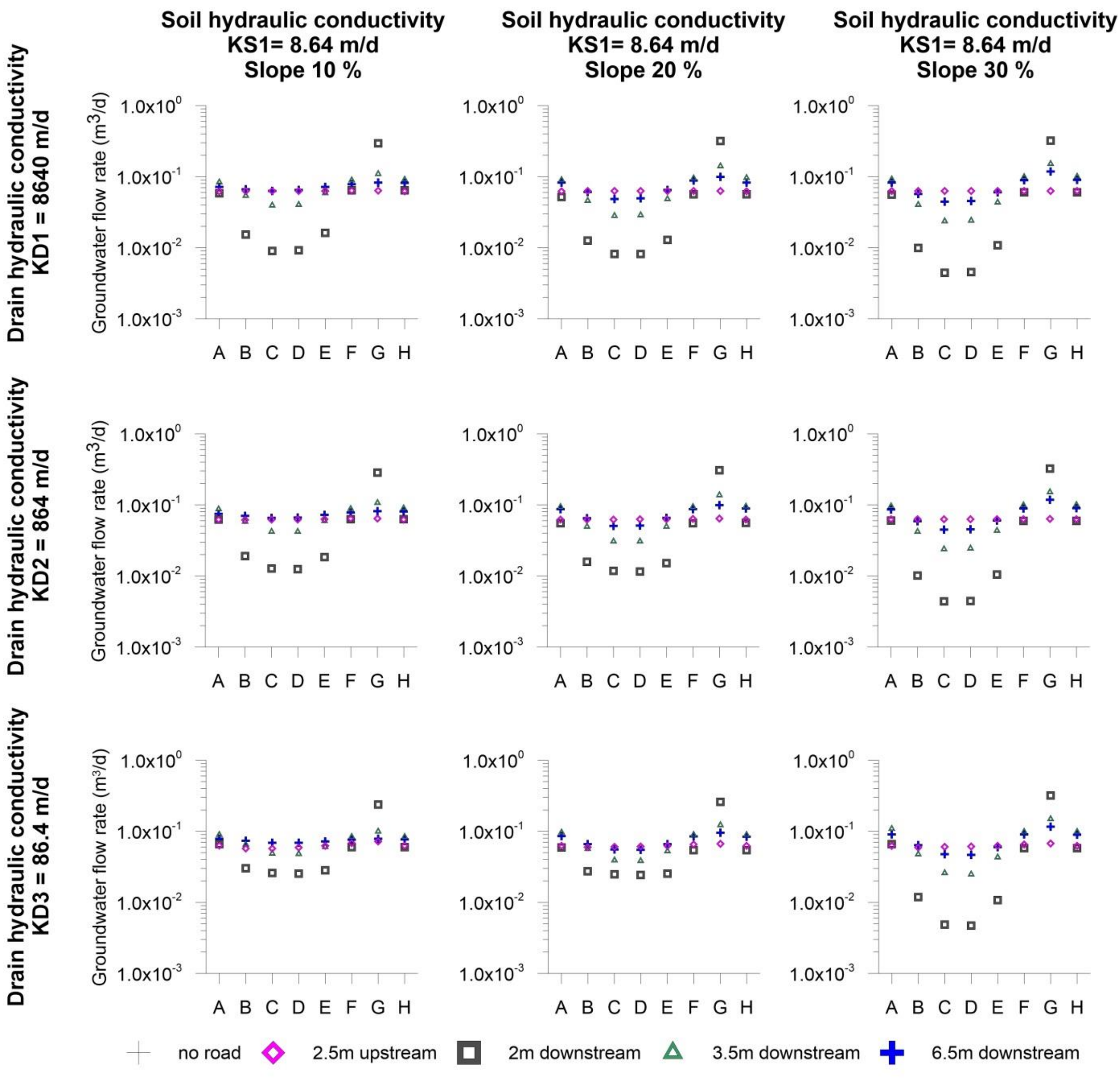


Figure 3: Extent of perturbations due to the l-drain road type: Simulated groundwater flow rates at different distances of the road.

Minor comments

General: Sometimes you are using spaces between numbers and operators and sometimes not. Please, check the guidelines of the journal.

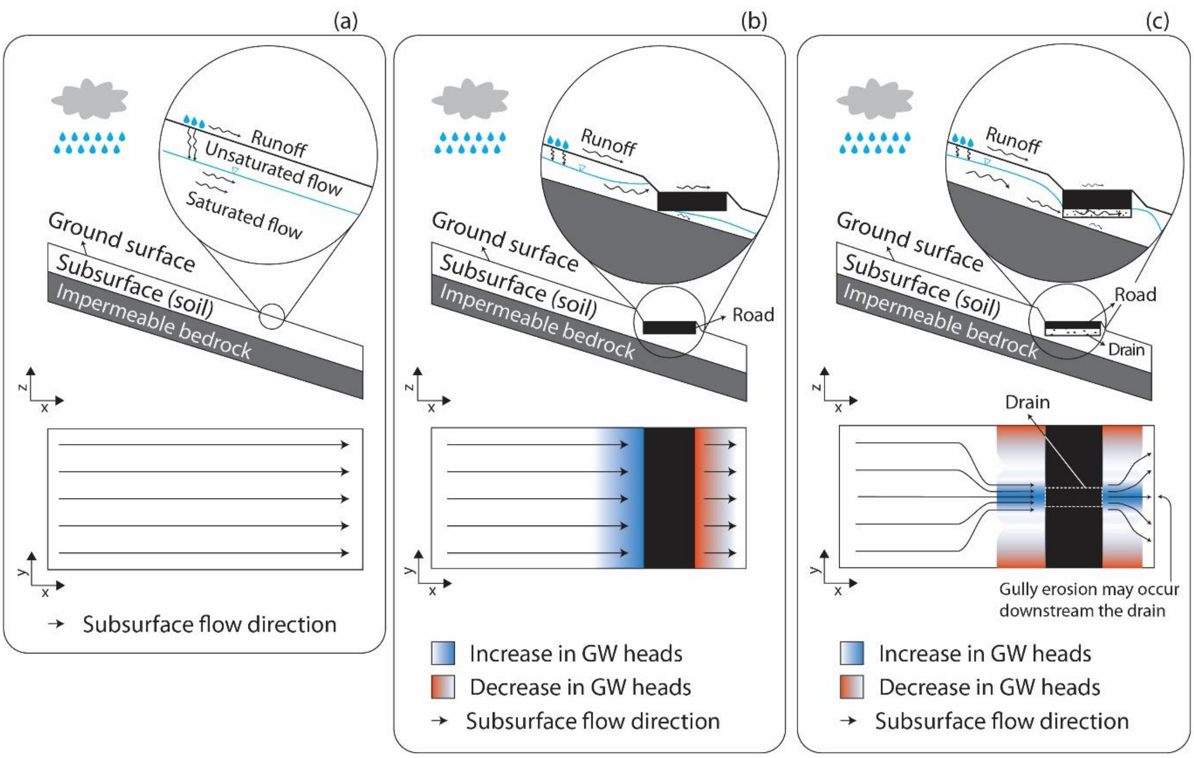
Spaces between numbers and units were removed as described in the guideline

Line 59: Capital "V" for Von Sengbusch. It's the start of a new sentence.

Capital V was corrected.

Figure 1: The cross-sectional view suggests that the water could easily pass underneath the road. However, in the text you mentioned that the top soil is very thin so that the road blocks the water flow to a large extent (also indicated by the lower figure). Isn't the figure a bit misleading? I would just increase a bit the size of the road and additionally sketch the impermeable bedrock.

The size of the road in the figure 1 was increased and impermeable bedrock was added. In this way, the reader will directly understand that the groundwater is blocked upstream the road (see line 55)



Line 126: "similar" or "comparable" instead of "same" would be a more suitable word in this regard.

"same" was replaced by "similar".

Line 131: I would add “bed” to “road bed structures”

“Bed” was added, now the sentence is: To evaluate the hydraulic connection provided by the road bed structures, tracer tests were carried out (see line 114).

Line 156: I wouldn’t use the term “indirectly indicates”. I would write something like “clearly shows”. At least, I would skip “indirectly”.

The term “indirectly indicates” was removed and replaced by “clearly shows”. Now the sentence is: An increase in EC in piezometers located in the downslope area indicates that the injected salt water flowed from the upslope area to the downslope area below the road and clearly shows a hydraulic connection.

Line 157: Here, it is the other way around. Instead of writing “this indicates that there is no connection”, I would be more careful by writing “this indicates a strongly hampered hydraulic connection”.

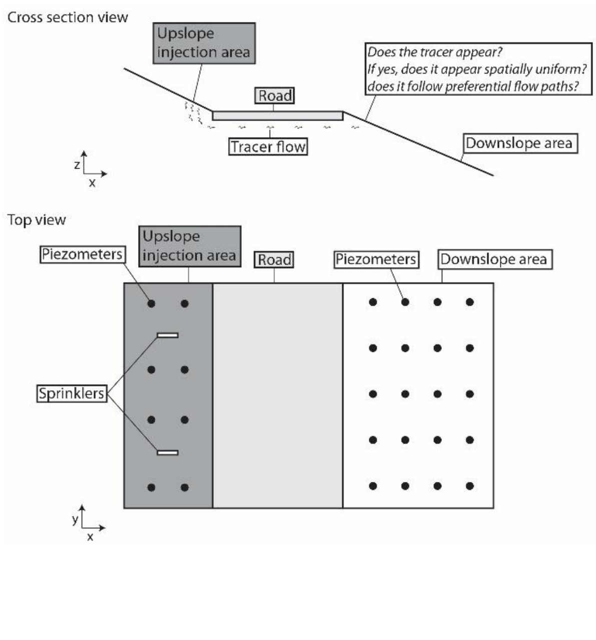
Yes it is more finely described if we use “strongly hampered” instead of “no connection”. We also removed “finally a decrease in EC is not expected”. After correction, the whole sentence is: Conversely, if no changes in EC are observed in piezometers, this indicates a strongly hampered hydraulic connection below the road.

Line 158: I would delete “and finally a decrease in EC is not expected”. (It is just too obvious.)

“and finally a decrease in EC is not expected” is deleted.

Figure 3: For me, the cross sectional view is a bit superficial, but I guess this is a matter of taste: Still, the spaces before the question marks should be deleted. Moreover, I would just write “Piezometer” instead of “Mini-piezometer”.

The figure 3 was modified according to your comments. (see line 143)



Line 163: What does "variable saturated" means? Sometimes saturated, sometimes unsaturated or variable hydraulic parameters? This should be explained more specific (I guess it is a terminology from HGS.)

Variably saturated means that change in saturation of the soil is simulated. However, is not important to mention that here. To be clearer, we changed "variably saturated subsurface water flow" by "subsurface water flow". The corrected sentence is: First, a 3D base case model representing surface and subsurface water flow in a sloping fen was elaborated. (see line 146)

Line 166: I would replace "produce a sensitivity analysis and explore their sensitivities in" just by "analyse their impact on". Calling it sensitivity analysis is not really wrong, but for my taste not well fitting.

In our opinion, it is a sensitivity analysis however, we can change. The suggested sentence is:

For each model, various slopes, organic soil and road drain hydraulic conductivities were implemented to produce a sensitivity analysis and analyse their impact on the sloping fen flow dynamics (see line 148)

Section 2.2.1: I would strongly shorten this section, as it is not really a part of your story. If somebody is interested in the mathematics behind your model, he/she would read the original publication of HGS. I would write a couple of lines mentioning the basic assumptions and methods, but no equations. In case you really want to keep them, I have some minor suggestions:

Indeed, the section may be reduced (reviewer 2 made the same comment). We keep only the main assumptions and method. (see line 154)

(i) You should give the equations in the same order as referred to in the text, i.e. 1st Richard, 2nd Saint Venant, 3rd Darcy. Or just mention the diffusion a bit later in your text; (ii) Eq 1 and Eq 2 are modified versions of the Richards and Darcy. This should be mentioned. (iii) Line 176: No need to explain "Nabla". It's the common notation; (iv)Line 178: Commonly, "Uppercase Theta" is used for water content and not for porosity;(v) Line 180: I would add "saturated". K is the "saturated" hydraulic conductivity:(Multiplying with kr results in the actual hydraulic conductivity.)

These lines were removed.

Line 207f: "was used on the right face" – left and right are just a matter orientation. Maybe you better write something like: The lowest cells of the slope constitute a constant head boundary condition.

Yes, it is better to use "the lowest cells of the slope" than "one the right face". The sentence now reads: 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 **Erreur ! Source du renvoi introuvable.**a) allowing the groundwater to flow out of the model. (see line 176).

Line 218: Missing space between “2” and “m”.

According to the guideline, we should not use a space between a number and an abbreviation of a unit. Therefore, we removed all spaces in the manuscript.

Line 234: Generally, I prefer the use of SI units, i.e. m/s instead of m/d.

As hydrogeologist, we also prefer m/s instead of m/d, however, the manuscript is not only hydrogeologist but for other environmental sciences such as biology. In our opinion, m/d provides greater clarity.

Line 256f: What do you mean by “length scale of one to several meters”. Is this a common expression?

“length scale of one to several meters” is not a common expression but a mistake. We removed “length scale”. Now the sentence is: In contrast, the EC maps established prior to the tracer test show a spatial variability of one to several meters (line 238)

Line 257: “629uS/am” – What is this? I guess 629 _S/cm

Yes it is 629µS/am. We corrected. (line 240)

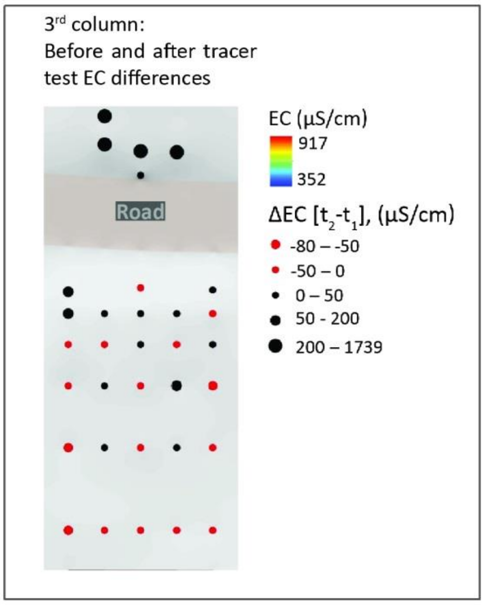
Line 279: “local drying up of the soil)” – If you consider this as a problem, it would be quite easy to further investigate it with your numerical model. This would allow answering the question: how large is the affected area and to which extent it dries out?

Yes, you are absolutely right. Therefore, a new figure (figure 10 line 365) was created in which we can see the extent of perturbations induced be the l-drain structure.

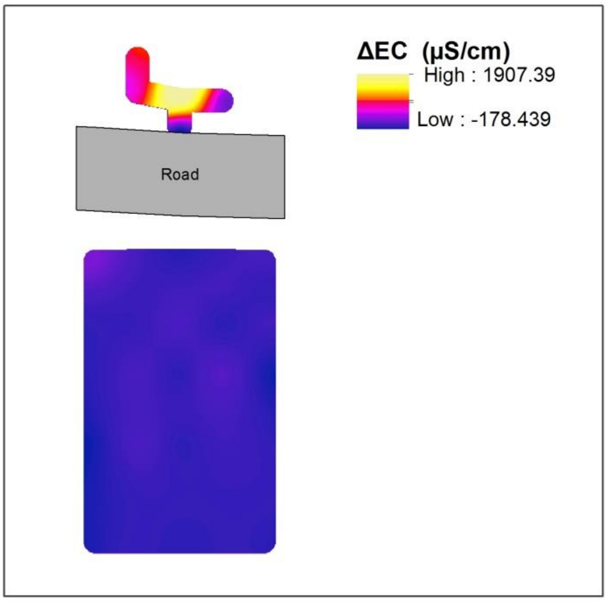
Figure 7: In column 2 and 3 you are showing EC values. I am wondering why you are using totally different graphical representations. Moreover, if you are interpolating (I am not a big fan of interpolation, if it is not really necessary: : :), you should state which method you are using. What kind of background map you are using? Does it tell us something?

The spline interpolation was used for the 2nd column (we added this information in the legend of the figure). We used a different representation bcause it is not very clear if we use the interpolation in the 3rd column (see figure below). The backgroung does not tell something.

Current figure (STA)



Interpolated results



Line 288-292: For me, these lines are superficial. I would just delete them.

We wanted to help the reader by describing each step of the result interpretation. If you think it is superficial, we can remove them.

Line 293-301: This is very trivial and doesn't need any explanation. It can be directly derived from the Darcy equation (at least for the base case model).

Yes it is trivial it can be directly derived from the Darcy equation. However, it seems important to describe the base case insofar as the base case is used to compare other results.

Line 316f: Are you sure that "may be" is the right expression here?

Do you prefer "can be"? We modified the "may be" by can be".

Figure 8-10: It is not very comfortable to analyse the differences between the different slopes. Can't you just put all figures together using a slope specific colour?

Yes it is true. We grouped together the three slopes.

Line 451: Is the year 2005 correct? I guess you want to refer to the manual, or? The one, I found, is from 2010.

Yes it was the former version. However, we should use the new reference: Aquanty: HydroGeoSphere, a three-dimensional numerical model describing fully- integrated subsurface and surface flow and solute transport. Waterloo, ON, Canada., 2017.

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 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 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. Roads designed with an L-drain collecting water upslope and releasing it in a concentrated manner downslope constitute the largest perturbations. The other investigated road structures were found to have less impact. The developed methodologies and results are useful for the planning of future road projects.

1 Introduction

Wetlands can play a significant role in flood control (Baker, 2009;Zollner, 2003;Reckendorfer, 2013), mitigate climate change impacts (Cognard Plancq et al., 2004;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). 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.

The link between hydrological changes and sediment dynamics has been studied in various contexts. 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. (2005a);Descroix et al. (2008);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) 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 outlets of lateral road drains. Based on fieldwork and a subsequent statistical analysis, they concluded that the main causes for gully development are 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.

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) 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 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) 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) 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) 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.

Road construction can also impact the development of vegetation (Chimner, 2016). Von Sengbusch (2015) investigated the changes in 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 subsurface flow and therefore prevents the upslope water to flow to the bog. According to 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.

Based on these previous studies and basic principles of subsurface flow, a simple conceptual model describing the influence of roads on the flow system can be drawn (Figure 1). Roads are generally built with materials of low hydraulic conductive and therefore 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 (Figure 1a) as overlandflow. If a road is constructed, it constitutes a hydrogeological barrier (Figure 1b) and consequently affects 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.

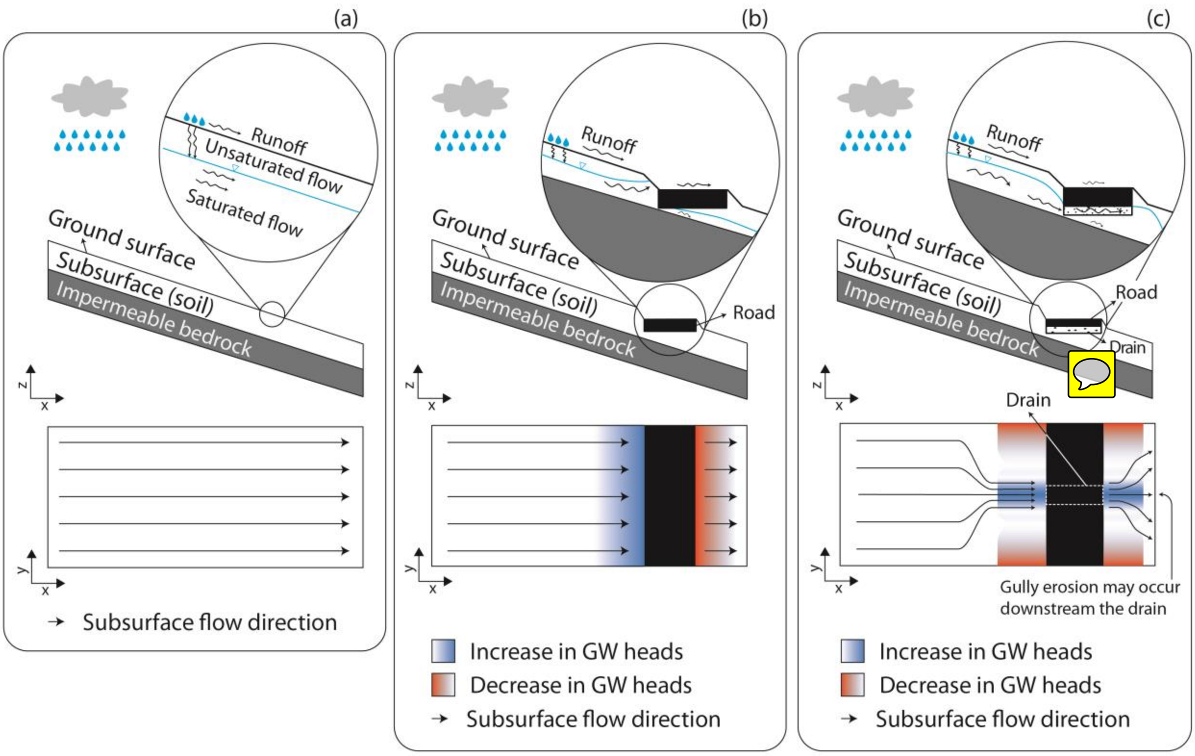

Figure 1 Conceptual subsurface dynamics in sloping fens: a) natural conditions, b) with road without a drain and c) with a road and a drain.

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 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. 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 2a) aims at preserving soil continuity under the road. It consists of a 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 2b) aims at collecting subsurface water 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.
- The *wood-log* structure (Figure 2c) 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.

The aim of this study is to investigate, document and assess the hydrogeological impact of various road structures and their effects on fen water dynamics. 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, however, they cannot provide 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 main advantage of the modelling approach is the possibility to generate a multitude of different models with various characteristics such as different road structures, slopes or fen hydraulic conductivity and to test their impacts on the flow dynamics. These model results can help in the planning of new roads.

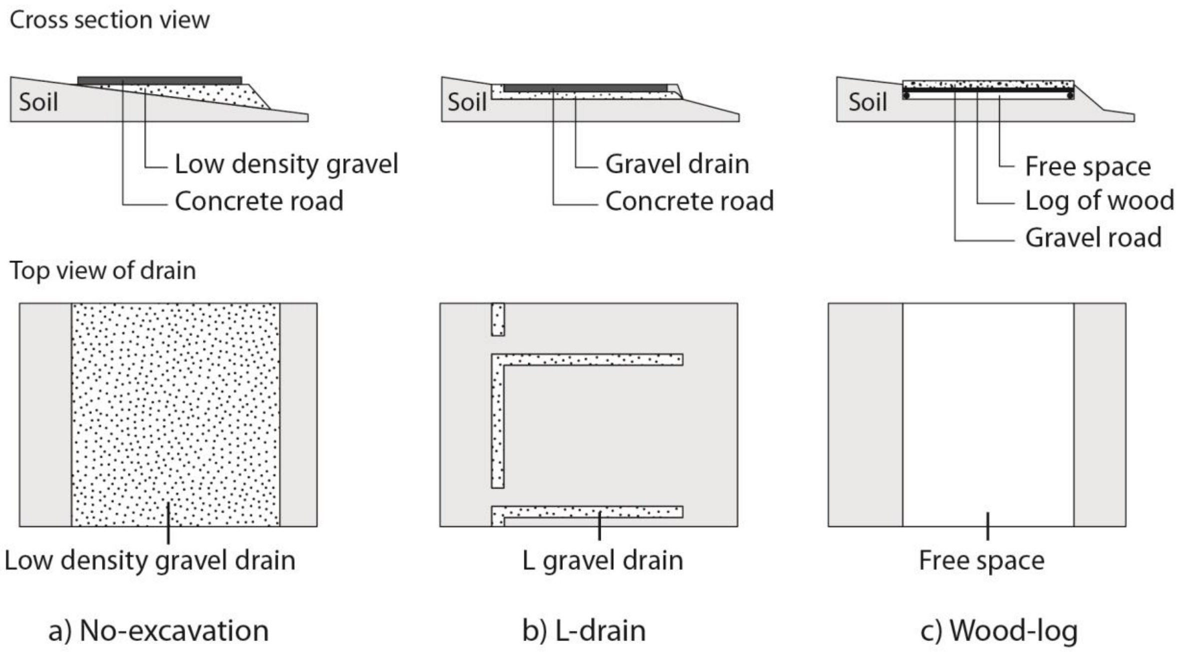

Figure 2 : Conceptual road structures, a) No-excavation road structure, b) L-drain road structure and c) Wood-log road structure.

2 Methods

2.1 Study areas and fieldwork

Four sloping fen areas located in alpine or peri-alpine regions of Switzerland (Table 1) 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 structures, tracer tests were carried out. As illustrated schematically in Figure 3, the upslope 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 corresponds to an 8 x 20m rectangle that includes a 2.5 to 3.5m wide road segment. A network of approximately 30 mini-piezometers on both sides of the road (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. Then, the area (60m^2) upslope of the road (upslope injection area of Figure 3) was irrigated with the salt solution using the two sprinklers. The electrical conductivity (EC) of soil water was manually measured using a 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 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.

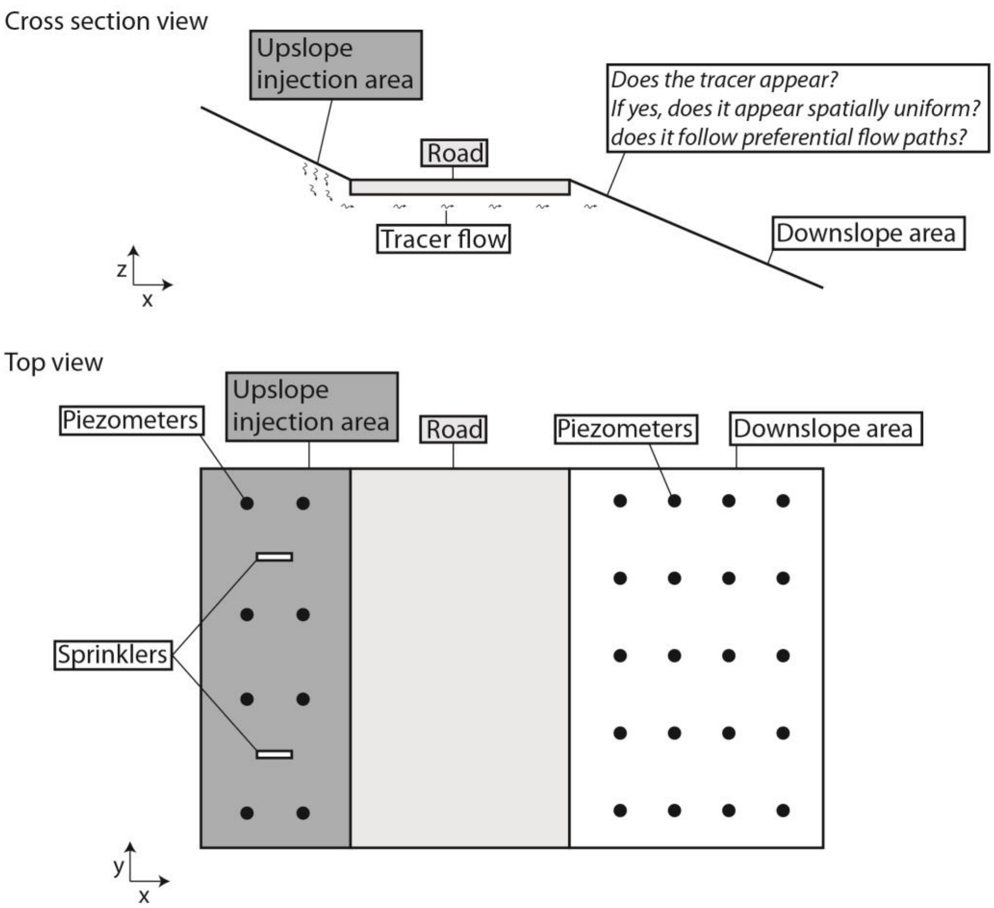

Figure 3 : Schematic view of the fieldwork areas.

2.2 Numerical modelling

To quantify the impact of the roads on the flow dynamics in sloping fens in a generalized way, the 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, 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). 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 not saturated, HGS employs the Van Genuchten (1980) functions to relate pressure head to saturation and relative hydraulic conductivity. Simultaneously, HGS also solves the 2D depth average 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 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. 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 illustrates the conceptual model of each case. 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 only supplied by precipitation. The upstream boundary is the catchment boundary (water divide) and the 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 5a) allowing the groundwater to flow out of the model. Finally, a critical depth boundary condition which forces the surface water to reach a given elevation (2m in our case) to flow out of the model was implemented on the top nodes located at x=76m and all other faces are no flow boundary conditions.

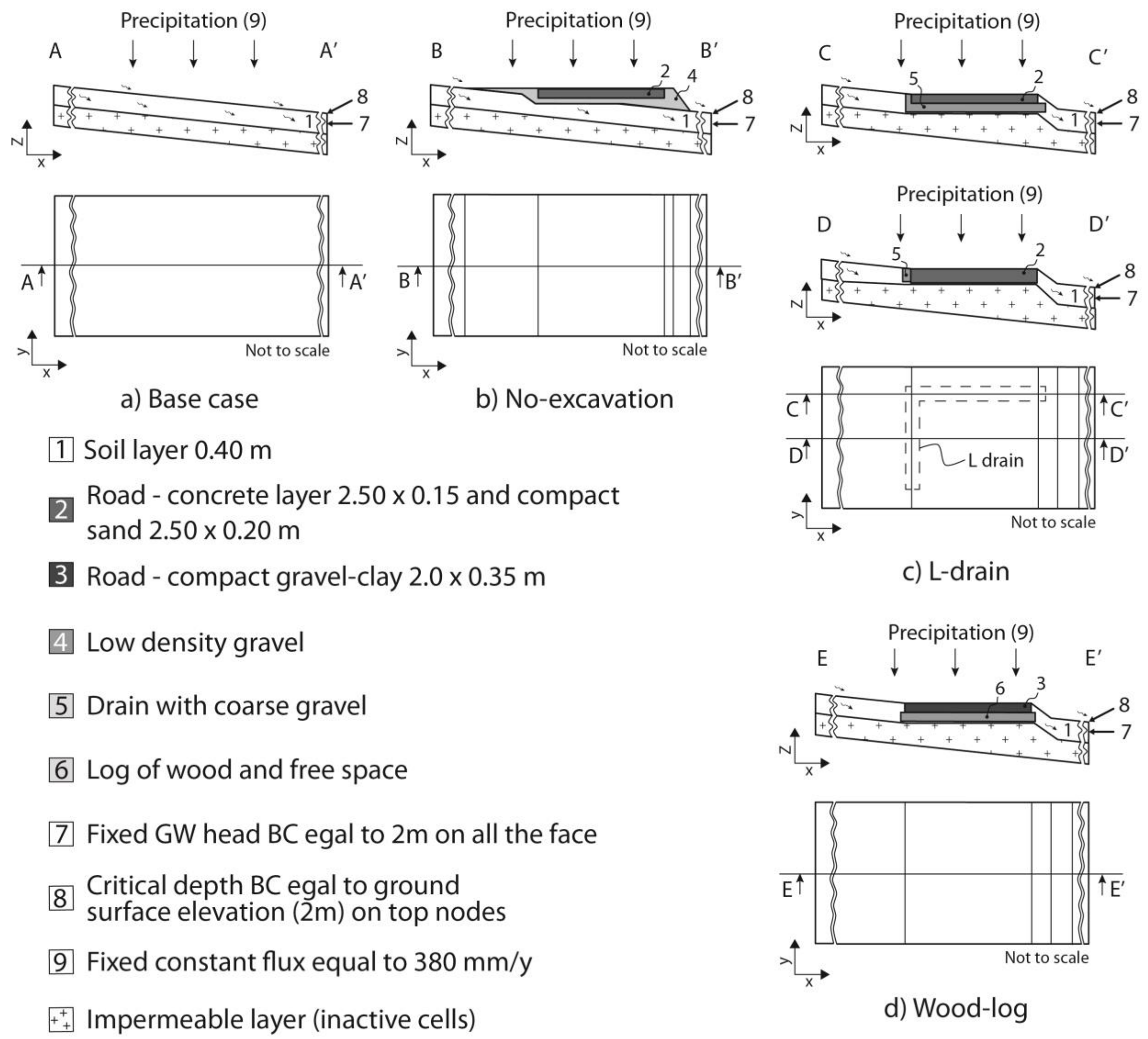

Figure 4 : a) Base case, b) No-excavation, c) L-drain and d) Wood-log structures conceptual models.

To numerically solve the 3D flow equation, a 3D mesh was developed (Figure 5a). 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 made up of 24 layers, 127,200 nodes and 118,440 rectangular prism elements. To ensure an appropriate level of detail, several mesh discretization refinements were made. Therefore, the 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 implement the different road types. Figure 5 depicts the differences between the base case model (Figure 5a and b) and models with roads (Figure 5c, d, e and f). In the case of models with a road, the mesh was deformed and the properties were 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.

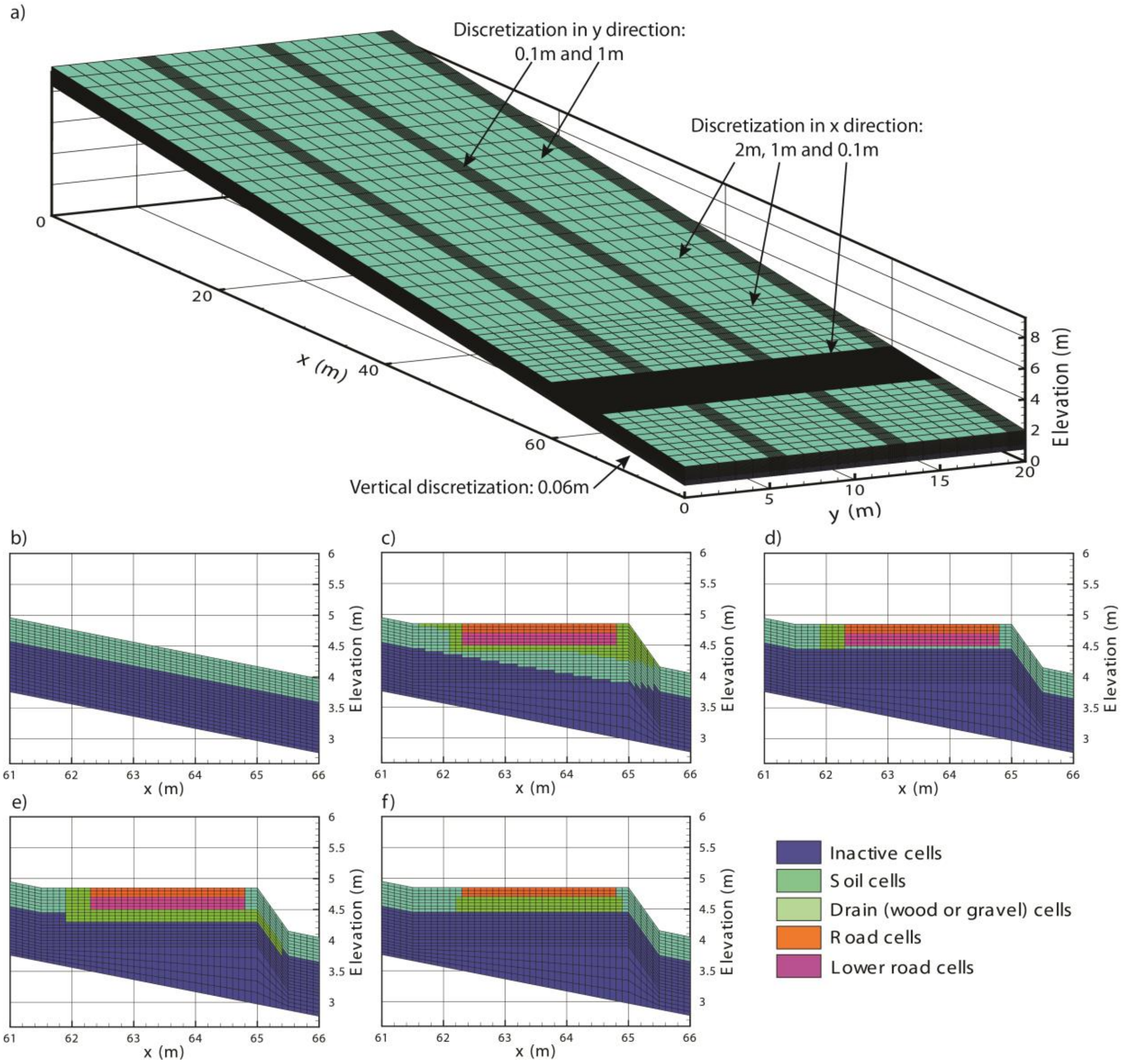

Figure 5 : Model development: a) Base case model, b) Base case model cross-section between 61m < x < 66m, c) No-excavation model between 61m < x < 66m, d) L-drain model between 61m < x < 66m, e) L-drain model between 61m < x < 66m along the transversal drain f) Wood-log model between 61m < x < 66m.

2.2.3 Model setup

The sensitivity analysis consists of the variation of model properties and parameters in order to understand how they control the 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 they govern the Darcy law (1) and consequently the groundwater dynamics. K is the hydraulic conductivity of the soil and the drain and ∇H the gradient of the fens controlled by the slope.

$$q = K * \nabla H \qquad (1)$$

For each property, three different values were chosen (Table 2), a low, an intermediate and a high 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) were used and vary 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 and the residual water content were considered similar assuming 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 coarse or very coarse gravel and have a hydraulic conductivity varying between 8640m/d and 86.4m/d (Fetter 2001) and their van Genuchten parameters are those of gravel. The slopes were fixed at 10%, 20% and 30% as observed during the fieldwork. Note that the drain hydraulic conductivities of the wood-log (W-L) were assumed ten times more conductive and more porous than gravel drain because of its particular structure (wood logs). The road concrete is almost impermeable with a very low hydraulic conductivity and its van Genuchten parameters of fine material. The road basement made with highly compacted fine material (sand and loam) feature a low hydraulic conductivity and are assigned van Genuchten parameters corresponding to fine material. Finally, the implemented soil and road surface flow properties correspond to a wetland and urban cover (Li et al., 2008).

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. Flow-rates at any given location represent the cumulative vertical flow. Their spatial assessment allows to assess to what extent the roads perturb the system, and further allows to assess the erosion risk associated with the induced preferential flow. Therefore, a comparison of flow rates between each model was made to present the effect of each road structure and sloping fen properties on the dynamics.

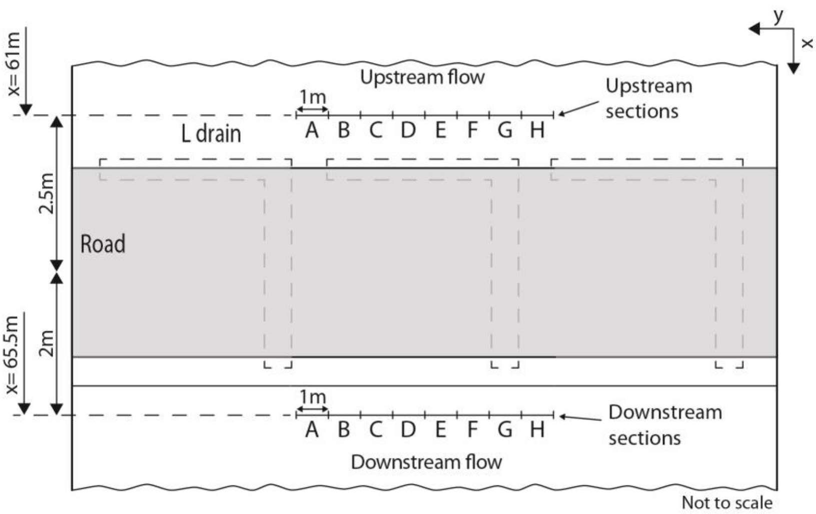

Figure 6 : Location of observation sections in the models.

3 Results and Discussion

3.1 Fieldwork

Based on the observations, all sites show a continuous saturated zone before the experiment, both upstream and downstream of the road, the hydraulic gradients being similar to the terrain slope (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, 2nd column.). Within each plot, EC varies from 482 to 629µS/cm. At the SCH site, the highest values are located 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, 3rd column).

The heterogeneity of the hydraulic conductivity of the soil is apparent from the tracer tests (Figure 7, 3rd column: EC 24 hours after injection). At all four sites, the front of the saline solution is not uniform but follows the heterogeneity of the soil hydraulic conductivity. Nevertheless, road structures may create preferential flow path that is particularly obvious 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, 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, this flow convergence is a serious threat (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.

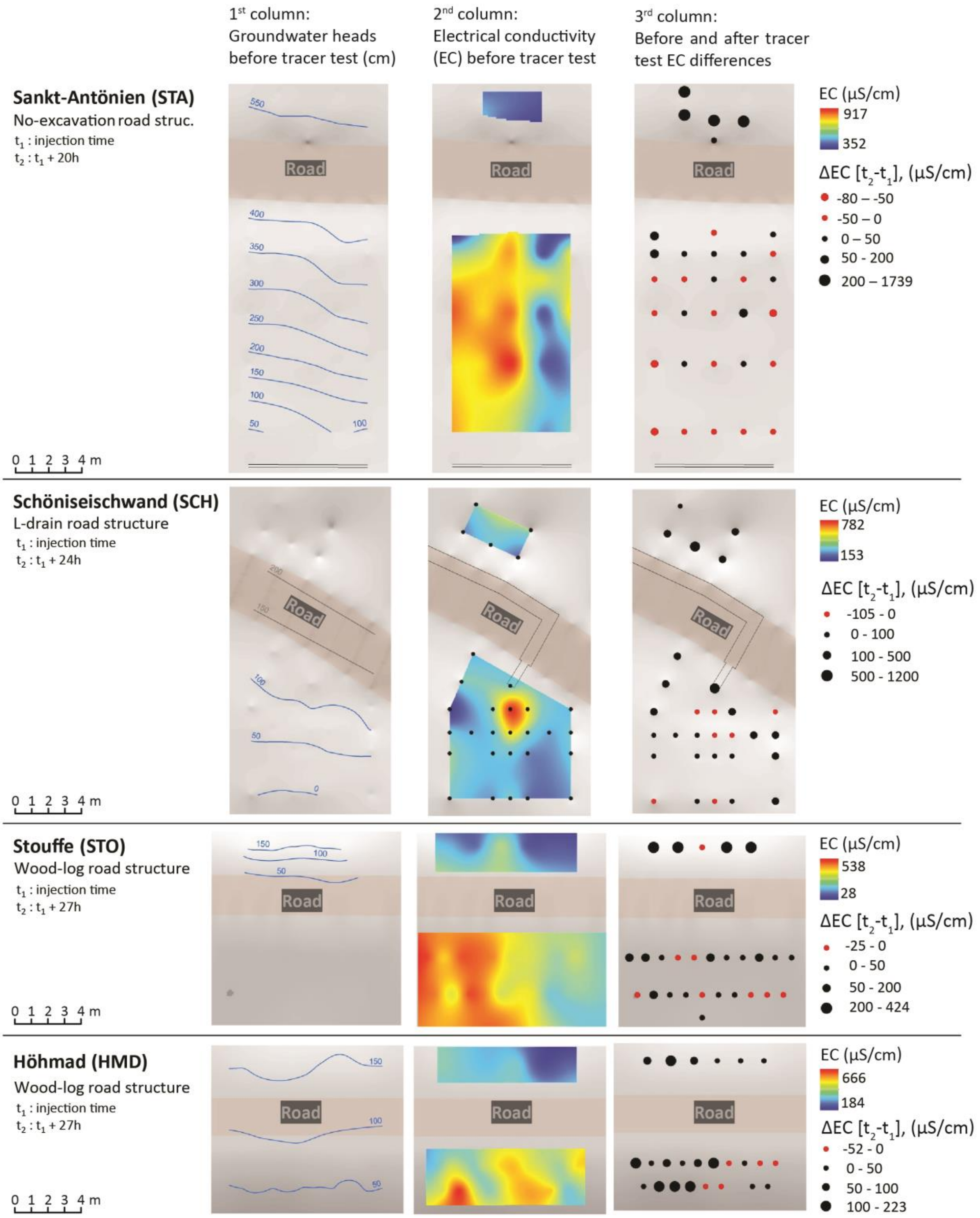

Figure 7 : Fieldwork results at the four field sites: 1st column) Spline interpolated measured groundwater heads before tracer test , 2nd column) Measured EC before tracer test and 3rd before and after tracer test differences in EC.

3.2 Modelling

Figure 8a shows the results of the models with a slope of 10%, Figure 8b with a slope of 20% and Figure 8b 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 Law (1) and the flow rate induced by the precipitation are also presented for the interpretation of the results. In 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 rates vary from 0.003 (m^3/d) to 0.069 (m^3/d) for 10% slope, 0.006 (m^3/d) to 0.069 (m^3/d) for 20% slope and to 0.009 (m^3/d) to 0.069 (m^3/d) for 30% slope. The groundwater flow rate decreases gradually depending on the hydraulic conductivities (KS) of the soil layer. For any slope, where hydraulic conductivities are high (KS1), groundwater flow rates are higher compared to the case where hydraulic conductivities are low (KS3). The primary observation is that groundwater flow rates are mainly controlled by the hydraulic conductivities and therefore the slope plays a minor role. Differences between the maximum and minimum hydraulic conductivity are two orders of magnitude, whereas changes between slopes multiply by 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%. 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 KS2 and KS3 models, surface flow occurs and conversely the soil is able to infiltrate the precipitation in KS1 models.

In the no-excavation and wood-log type models, the effect of road structures is quite similar. The groundwater flows vary from 0.01 (m^3/d) to 0.069 (m^3/d) for 10% slope, 0.01 (m^3/d) to 0.069 (m^3/d) for 20% slope and to 0.010 (m^3/d) to 0.069 (m^3/d) for 30% slope. Compared to the base case model, results show that the no-excavation and wood-log type structures have a minimal impact. The only marked difference is that groundwater flow rates are slightly higher if the soil hydraulic conductivities are low (KS3) for each slope in the wood-log type model. This can, to a certain extent, be explained by the fact that the hydraulic conductivity of the base of the road (consisting of wood-logs) is higher than the hydraulic conductivity of the soil and therefore facilitate the infiltration. Conversely, in the base case model, less water is infiltrated but more runoff occurs. However, the process is limited, because at 3.5 m downstream the road (x=67m), the simulated flow rates of the model KS3- KD1 and a slope of 20% for the wood-log and no-road model are equal (Figure 9). 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 is markedly different from the other road structures. The groundwater flows vary significantly in the observation sections. The maximum flows are always obtained in the observation section G just downstream the drain outlet and can be 10 times higher than in the base case. Conversely, minimum flows are obtained in C and D observation sections in which flow rate may be 10 times lower. Significant differences in groundwater flow are also observed in the same transect (i.e. the transect formed by the observation section A, B, C, D, E, F, G and H within the same model). The maximum differences are observed if 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 flow rates are slightly higher than the base case model. Finally, it can be seen that slope accentuates groundwater flow rate differences along the transect. Therefore, an increase of groundwater flow differences in the same model is observed for the 10% and 30% slope scenarios. The impact of L-drain may be further explored by extracting groundwater flows lower than 3.5m to assess the extent of perturbations. Figure 10 shows additional simulated groundwater flows for the most critical cases (i.e. KS1 with a slope of 10%, 20% and 30%) downstream the road at 3.5m and 6.5m respectively and 2.5m upstream. It can be seen that at 3.5m the groundwater flows already regain their upstream conditions. At 6.5m downstream the road, all observation sections are very close the upstream flows except in section G where flows are still slightly higher.

The model results can be used to predict the risk of gully erosion and. 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, the maximum flow rate capacity of the soil is small in caparison with precipitation. For all model scenarios except for KS1, the soil capacity is lower than the precipitation amount which is already set pretty low in the model. This means that runoff already occurs in sloping fens. However, the runoff may be accentuated by subsurface perturbation caused by the L-drain structures. To illustrate this process, the simulated surface flow velocities of each road structure downstream the road for the model KS2-KD2 and slope of 20% are presented in Figure 11. In this case, maximum flow rate capacity of the soil is approximately equal to precipitation, therefore runoff should not occur. However, it can be seen some runoff in the L-drain model which is the consequence of the subsurface flow concentration. In this configuration, the soil infiltration capacity is too small and consequently, the groundwater emerges and flows on the surface. Although the formation of gullies depends 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. A simple recommendation can be made to avoid this runoff concentration.

1. 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.
2. 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

Finally, the impact of road structure on the upstream road dynamics may be also assessed. Figure 12 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 flow across the road.

The impact of the L-drain road structure which concentrates groundwater flow is clearly identified in the numerical approach and is consistent with the field observations. For other road structures also, numerical models are consistent with fieldwork results by showing relatively undisturbed groundwater flow downslope the road. The 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, a numerical model is always a simplified reproduction of reality. The main model assumption is that hydraulic conductivity of the soil is homogeneous. Groundwater flow in fens can occur along preferential pathways. Therefore, the models are not able to reproduce small-scale observations, i.e. the exact hydraulic head in an individual mini-piezometer. Models results have to be interpreted as an average across multiple preferential flow paths.

Further investigations should be carried out to identify groundwater 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 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.

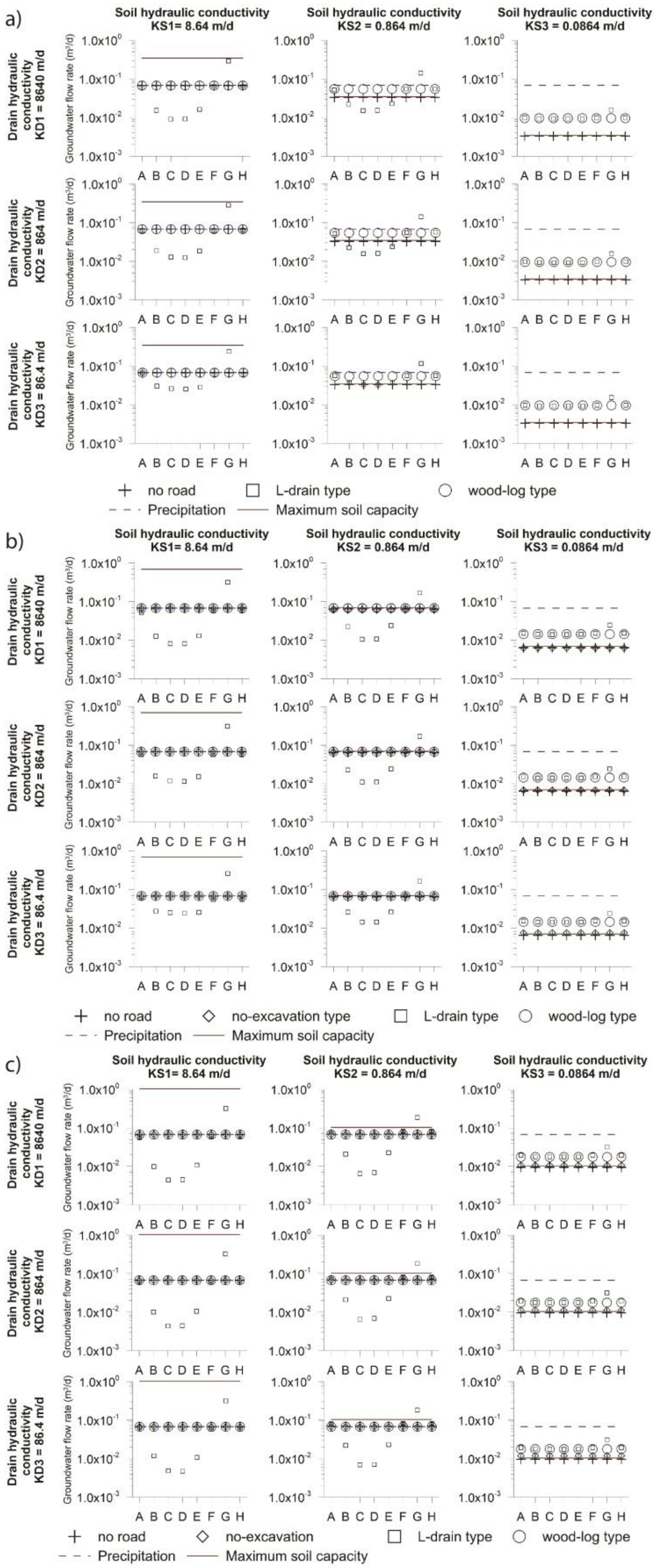

Figure 8 : Simulated groundwater flow rates 2m downstream each road structures and each parameter combination with a slope of a) 10%, b) 20% and c) 30%.

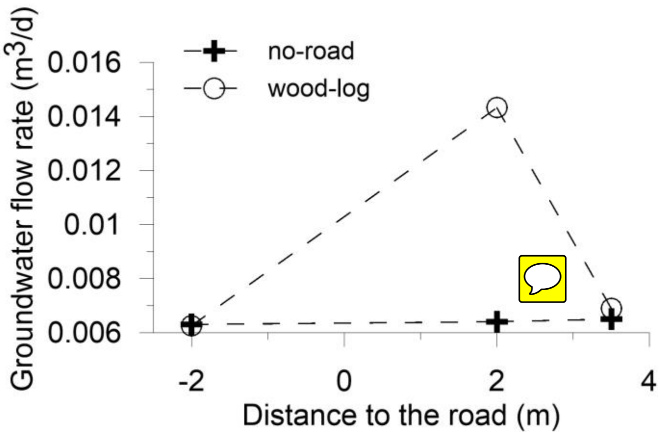

Figure 9 : Simulated groundwater flow rates along x direction for the KS3-KD1 models with the wood-log structure and without road.

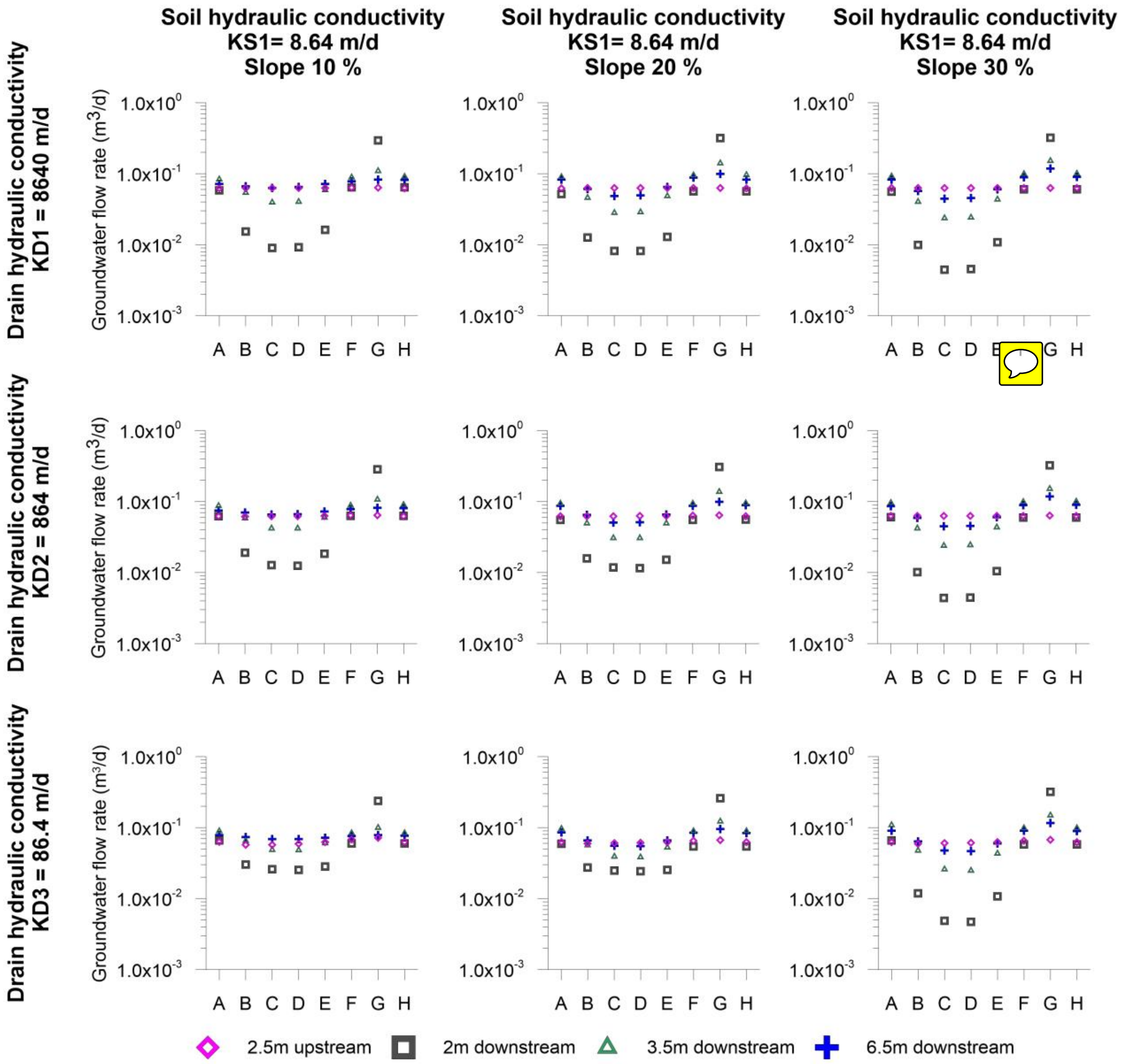

Figure 10 : Extent of perturbations due to the l-drain road type: Simulated groundwater v flow rates at G section at different distances the road.

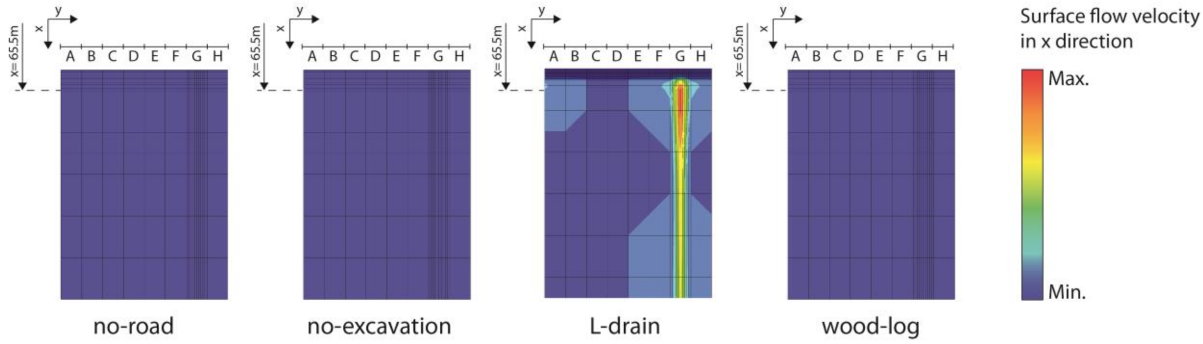

Figure 11 : Simulated surface flow of the KS2-KD2 model and a slope of 20% for each road structure

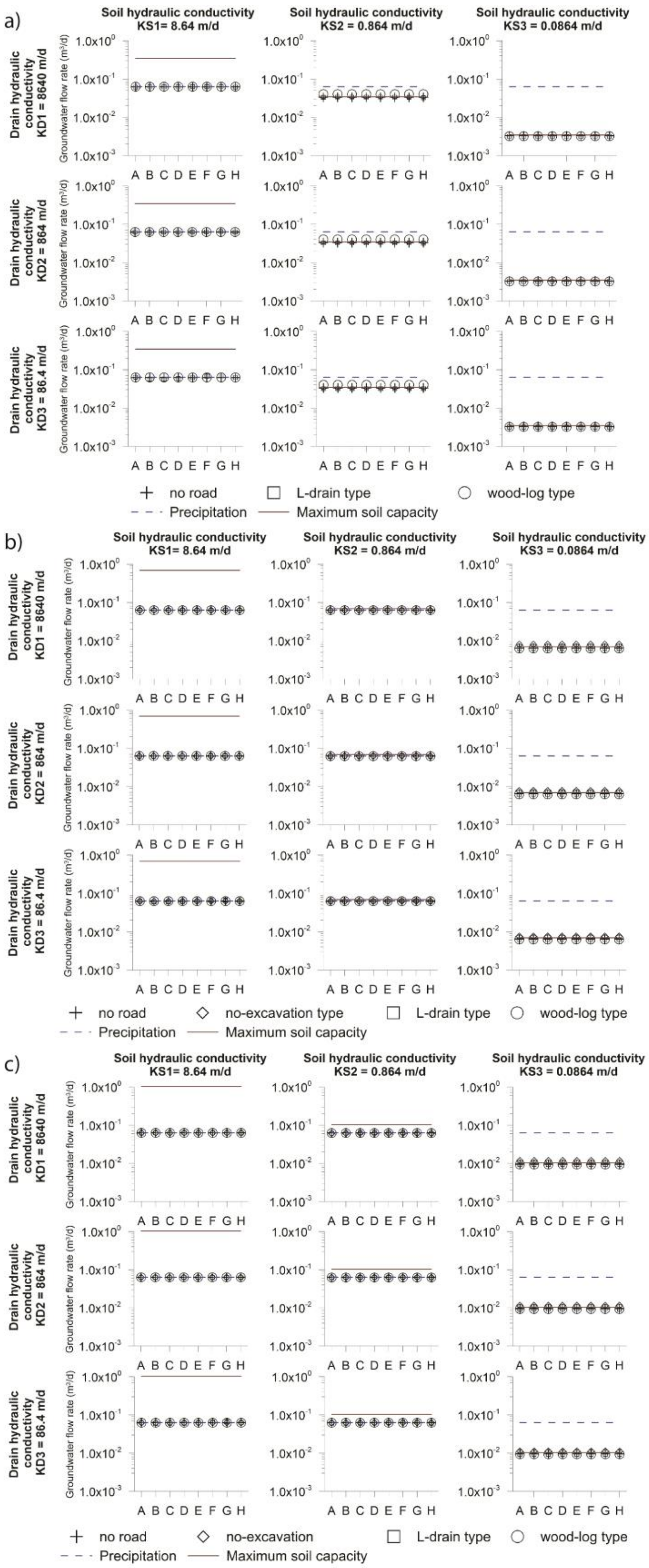

Figure 12 : Simulated groundwater flow rates 2.5m upstream each road structures and each parameter combination with a slope of a) 10%, b) 20% and c) 30%.

4 Conclusions

This study 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-based tracer tests and numerical models simulating groundwater flow for the different road structures.

It is the first time that the performance of these road-structures has 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 preferential flow paths in the soil. The presence of a transversal drain (L-drain) beneath the road constitutes a preferential flow path, however, which is of much greater importance than the naturally occurring preferential pathways. This was also confirmed by the models. Groundwater flow rates 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.

5 Acknowledgements

This research was funded by the Swiss Federal Office for the Environment (FOEN) and supported by Swiss Federal Office for Agriculture (FOAG). The authors are grateful to Benoit Magnin, Peter Staubli Andreas Stalder, Anton Stübi and Ueli Salvisberger for their collaborations. We thank the three anonymous reviewers and the editor for their constructive comments.

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