Reviewer 2

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. Information concerning this point will be added.

<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.

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).

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, they will certainly help to clarify the manuscript. Regarding a more detailed model parameter descriptions, section 2.2.3. You find below the suggested reworked section 2.2.3

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.

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

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) have a low hydraulic conductivity and van Genuchten parameters of fine material. Finally, the implemented soil and road surface flow properties correspond to a wetland and urban cover (Li et al., 2008).

Table 1 : 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*

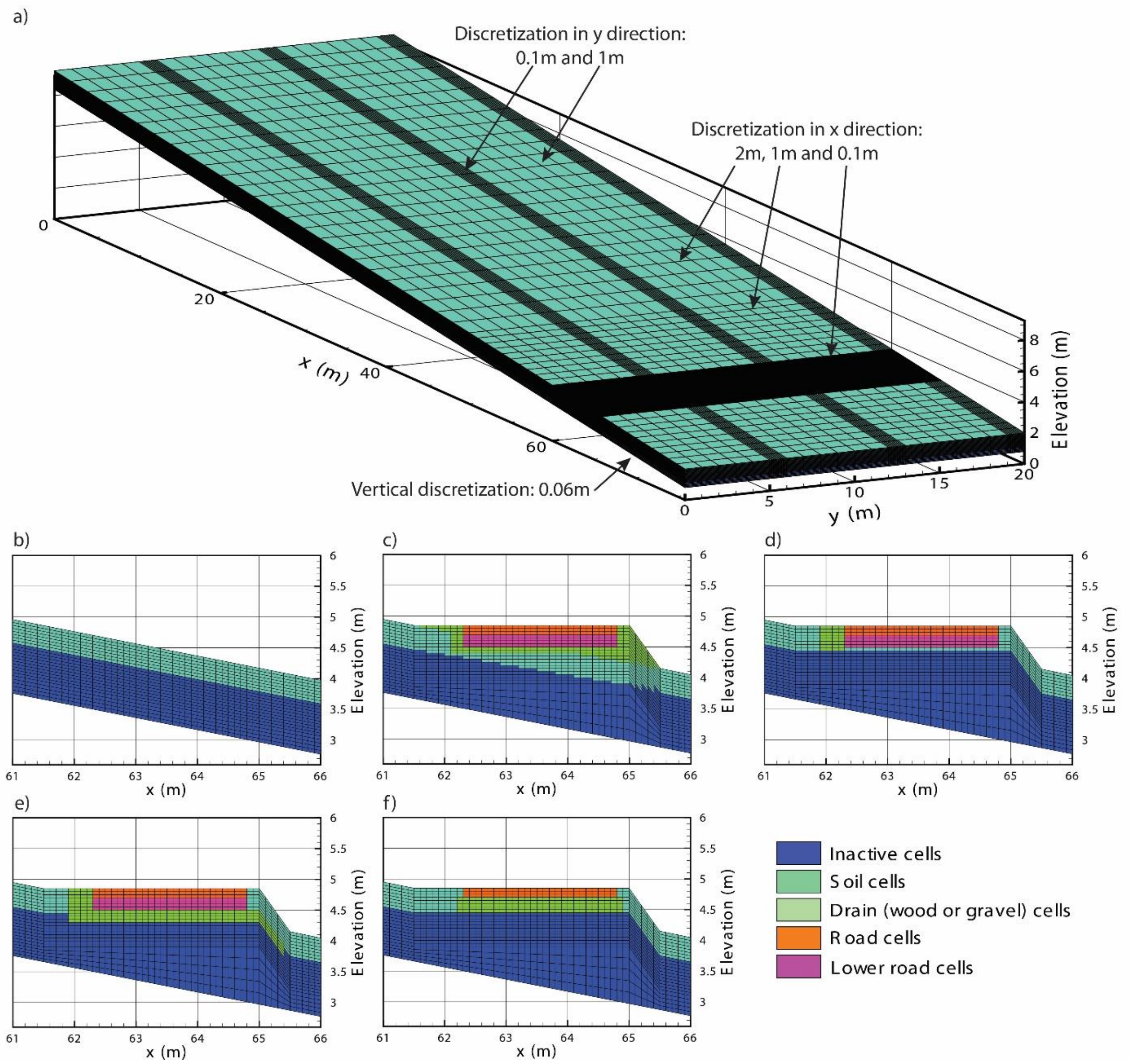
Surface flow properties					
	Coupling length	***Manning's roughness coefficient***		***Rill storage height***	***Obstruction height***
Units	***l_c [m]***	***n_x [m$^{-1/3}$s]***	***n_y [m$^{-1/3}$s]***	***D_t [m]***	***O_t [m]***
Soil	*1. x 10^{-2}*	*0.03*	*0.03*	*0.005*	*0.005*
Road	*1. x 10^{-2}*	*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 ***Erreur ! Source du renvoi introuvable.****. Changes in subsurface flow rates indicate a perturbation of flow dynamics and therefore, a comparison of velocities between each model was made to present the effect of each road structure and sloping fen properties on the dynamics.*

<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.



In figure 5c, are soil cells upstream connected with the soil cells below the road (not visible in figure with this resolution)?

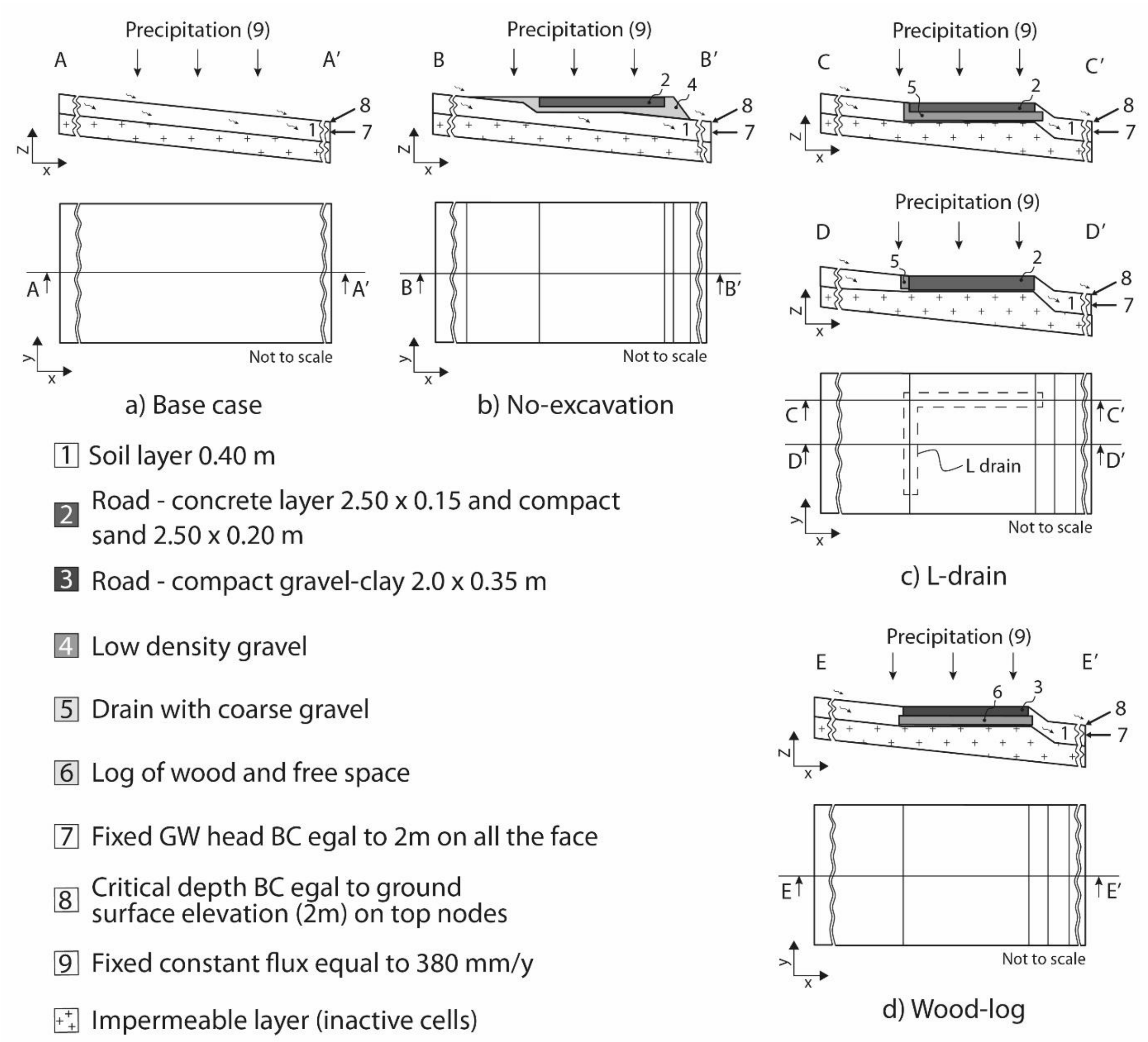
Yes in figure5c soil cells are connected. With the modification of figure5, now the connection can be seen

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.



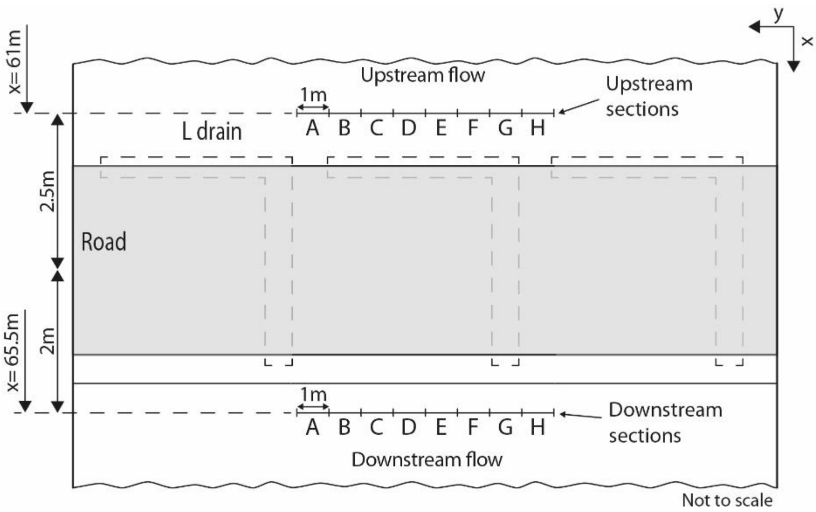
Paragraph l.243-249

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”.

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.



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 (Figure 1). 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 (Figure 2). In this way, the water distribution downgradient of the L-shape structure is addressed.
3) A graph in which flow rates are presented according to the slope, KS and KD to clearly identified which parameters govern the fen dynamics (Figure 3)

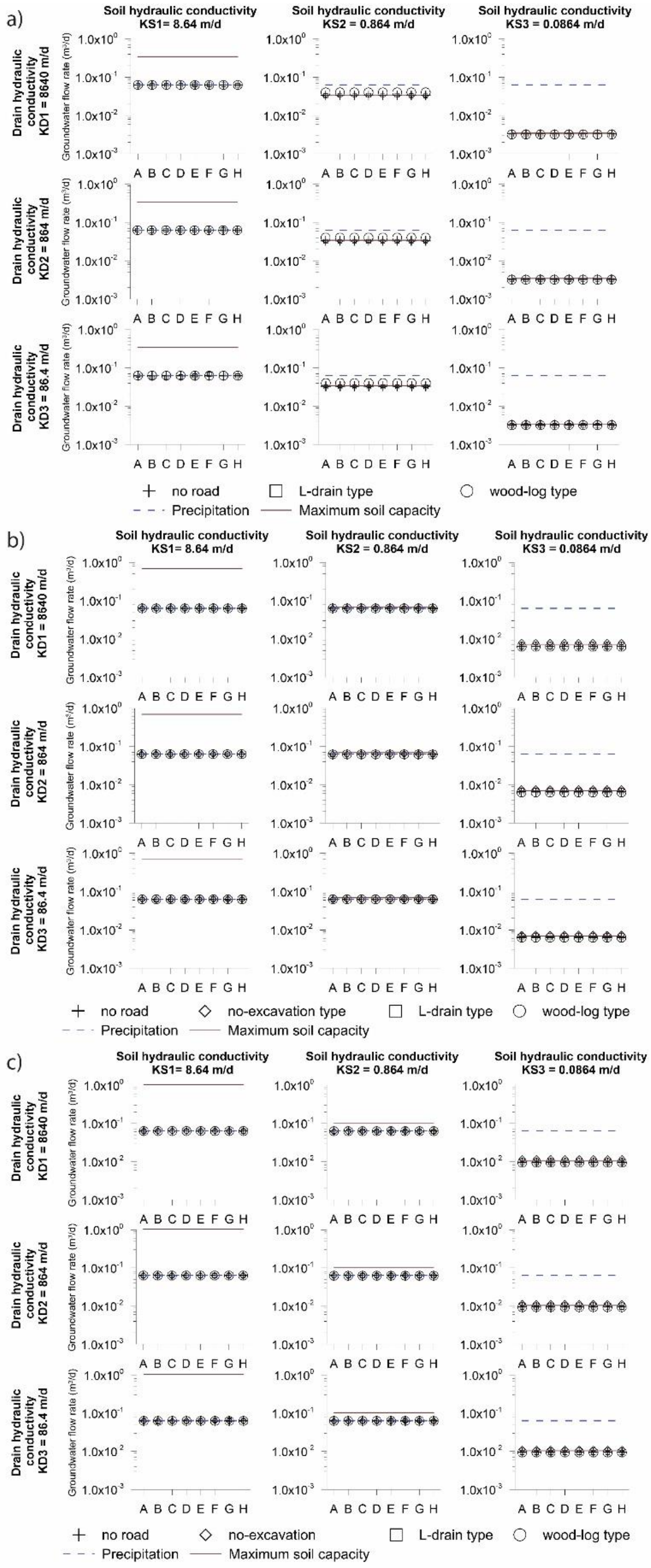


Figure 1 : Simulated groundwater velocities 2.5 m upstream each road structures and each parameter combination with a slope of a) 10%, b) 20% and c) 30%.

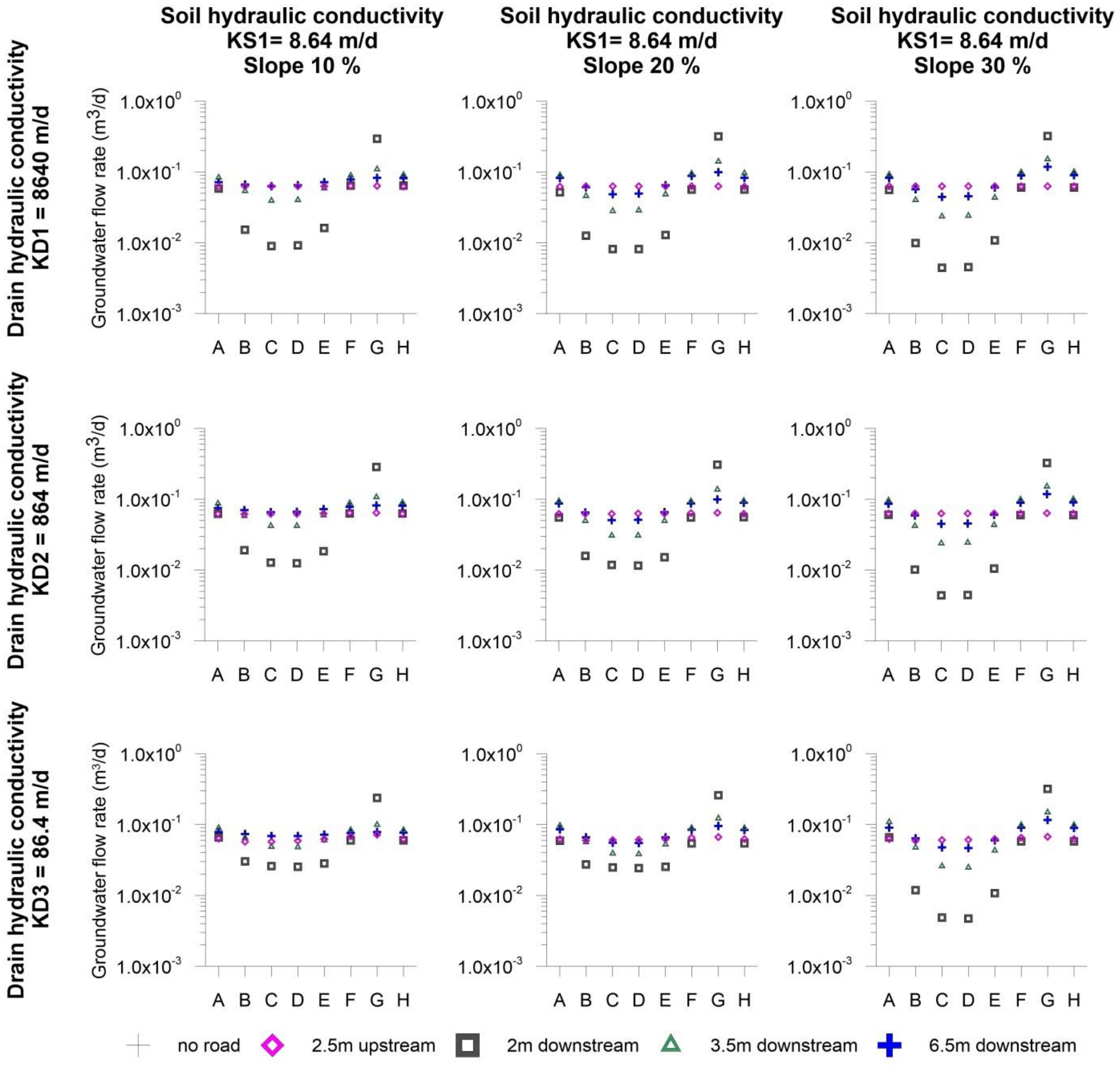


Figure 2 : Extent of perturbations due to the l-drain road type: Simulated groundwater flow rates at different distances of the road.

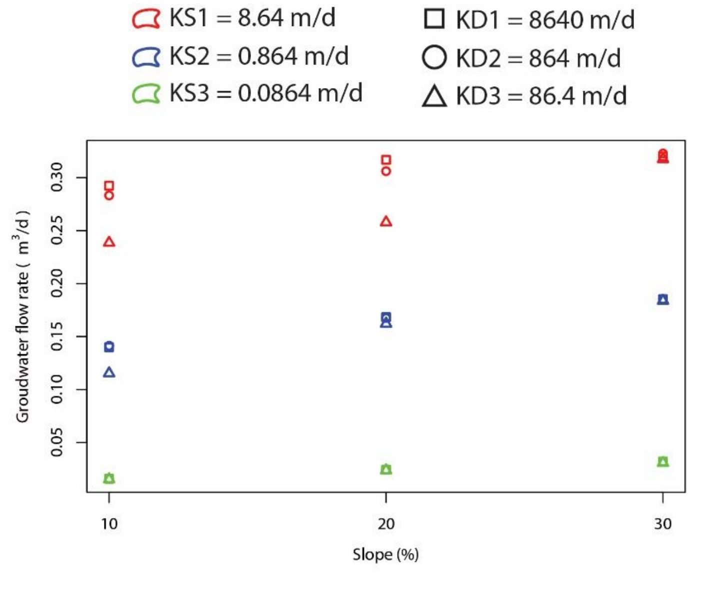


Figure 3 : Simulated groundwater velocities at observation point G depending on the slope, KS and KD

Section 3

This section will be reworked to be less repetitive as you mention. In addition, a new section will be 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.

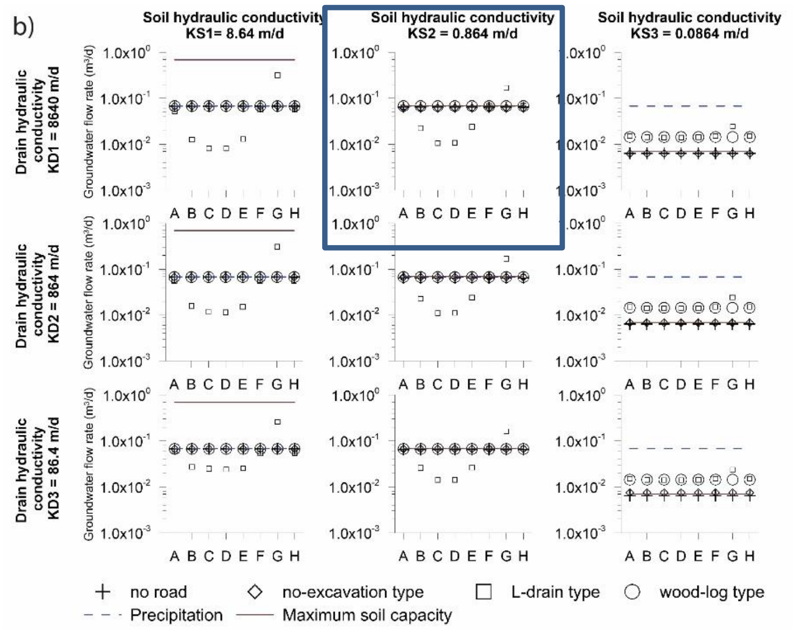


Figure 4 : Simulated groundwater velocities 2 m downstream each road structures and each parameter combination with a slope 20%.

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.

The modification will be done according to your comments.

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.

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:

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

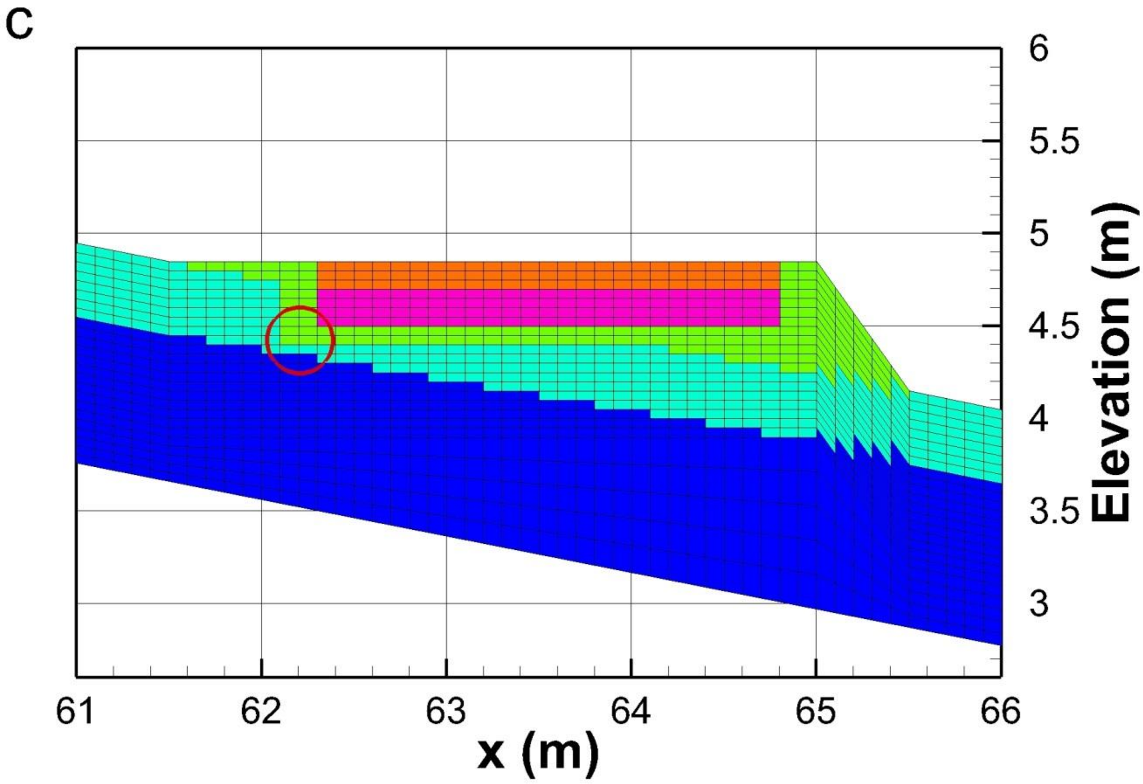
It means that the maximum flow rate in the soil may be more important than precipitation. It is however not always the case in the other models. In the new analysis of model results, we will compare the simulated flow rate vs. the maximum of flow rate of the soil to see if the simulate flow rate is close 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. 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.



<u>paragraph l. 314-324:</u>
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 <u>in a same model</u>.

"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 will be reworked because it is not very clear as you mention. Another word will used instead of transect to describe simulated flow rate downstream the road.

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?

Drains located along the road act like an infiltration drain because it drains a part of the runoff water.

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 may be usefull to have a better understanding on the dynamics. In the interests of brevity we suggest to create this profile for cases in which the flow rate is increased (when the soil layer = KS3).

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 will also 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 remplaced 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.

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 true, it is clearer if 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.

discretization