Response to Reviewer comments

Response to Reviewer 2 (John R. Nimmo)

General Comments

This paper provides an extensive and valuable set of field observations of the subsurface flow patterns generated by three different irrigation intensities over four members of a soil chronosequence. As in previous works using similar methods, this study offers quantitative analysis of unsaturated flow features that otherwise would be evaluated subjectively and without quantification.

The main value is in providing evidence to elucidate how factors including soil age, input intensity, vegetative cover, and others influence the depth and homogeneity of the distribution of the infiltrated water. In particular, a major issue is the distinction between preferential and homogeneous flow patterns, understanding of which has tremendous importance to water supply and water quality matters, as well as to agriculture and ecosystem health. The linkage to physical phenomena is primarily through classification into six categories based on a modified version of the scheme of Weiler and Flühler (2004).

The paper provides useful documentation of soil developmental processes over 13500 years. Together with an earlier study of Hartmann et al. (2020a), it provides evidence of the differences resulting from calcareous-vs.-siliceous parent materials.

The authors would like to thank John R. Nimmo for spending his time to review and make valuable comments to improve our manuscript. We highly appreciate the detailed feedback and recommendations to improve the consistency of our manuscript.
We will address the comments and suggestions below.

The data analysis is extremely thorough. A great variety of statistical methods are employed, perhaps more than necessary. I see little or no value in the Pdye analysis because the constraint of monotonicity is a serious shortcoming that could distort the interpretation of how water behaves in the profile.

We will exclude the Pdye analysis in the revised manuscript, as we also see the point that it adds only little value.

Presentation of multifactor comparisons of many individual experiments is unavoidably complex, and is done here (figures 3-10) through an organization that requires the reader's time and effort to understand and evaluate, but it does show the results in a way that the effects of soil age, irrigation intensity, and spatial variability can be directly seen.

The main problem I find in the manuscript is confusion and inconsistency concerning the classification of types of subsurface flow. Much of this relates to the term "finger flow", for which I don't find a clear definition in this paper, and which seems to be used in different ways.

Some background from my own understanding: Three main categories of preferential flow are commonly used—funneled flow, which is directed into particular downward paths as a result of heterogeneities of the medium that provide faster flowpaths through the more conductive material; fingered flow, which is initiated at flow instabilities in the wetting front and sustained in downward preferential paths by the greatly enhanced hydraulic conductivity of the newly wetted material; and macropore flow, which proceeds through elongated continuous pores over significant distances within the medium.

We understand the problem with a missing definition of the used terms. We will include a more specific definition of the flow type classes in the revised manuscript and will change Page 7, Line 24+ to:

"[…] This classification method distinguishes between five flow types: (1) macropore flow with low interaction, (2) mixed macropore flow (low and high interaction), (3) macropore flow with high interaction, (4) heterogeneous matrix flow/finger flow, and (5) homogeneous matrix flow. We define macropore flow as water transport via root channel, earthworm burrows, and flow along fissures largely bypassing the matrix. The characteristic dye pattern shows narrow but long individual stains, which can be broader due to interactions with the surrounding soil matrix.

The term finger flow here summarizes all flow types that cause finger-shaped flow patterns, which includes finger flow caused by flow instabilities in the wetting front (Nimmo, 2021), finger-shaped flow paths due to water repellency, air entrapment or textural layering (Hendricks, 2001) and also funneled flow leading to vertical elongated finger-like flow paths. The latter is caused by the redirection and funneling of water by textural boundaries and large rocks (Hendricks, 2001) or by the heterogeneity of soil hydraulic properties (Nimmo, 2021). The characteristic flow patterns of all these flow types are very similar and thus cannot be distinguished by the image analysis: they show broader, vertically elongated, coherent flow paths, which indicate a preferential vertical water transport and leave large parts of the soil matrix dry.

Dye patterns, which could not be classified as one of the five flow types were categorized as undefined.

We used a modified version (Hartmann et al., 2020a) of this classification which was more suitable for stony alpine soils. In the case of homogeneous matrix flow, the modified classification avoids that a high stone content leads to the detection of a heterogeneous flow pattern by breaking up the coherent stained area into smaller pieces, which then could be falsely classified as heterogeneous matrix flow, finger flow, or macropore flow depending on the abundance of rocks. In this case the flow type is assigned to a new flow type class called (6) 'homogeneous matrix flow between rocks'.

The modified classification also avoids a clear differentiation between 'macropore flow with high interaction' and 'finger flow'. As the original classification assigns finger-shaped flow paths only when both, the medium-sized stained path width (20–200 mm) and the biggest stained path width class (> 200 mm) account for approximately half of the dye coverage, fingers with smaller widths were not detected as such and automatically counted as macropore flow with high interaction. Hartmann et al., 2020a observed that finger-like flow paths with smaller widths were frequently present in alpine soils. Their dye patterns and distributions of stained path width classes are similar to 'macropore flow with high interaction'. Both classes cannot be distinguished from each other in the image analysis. Thus we renamed this class to (3) 'macropore flow with high interaction/ finger flow'. The classification was done for each pixel row per profile. […]"

I see these categories to be represented in the scheme of Weiler and Flühler (2004) (hereafter referred to as WF2004), which is designed specifically for use in interpreting dye-tracer results. Macropore flow needs matrix interaction to be visible, as acknowledged in the first three categories of WF2004. I see the term "matrix heterogeneous flow" as a synonym for funneled flow, and it is quite adequate in that usage. Instability-initiated fingered flow would be difficult or impossible to distinguish from matrix heterogeneous flow when the only evidence is from pictures of dye-tracer distribution. Thus it is appropriate to group both of these flow modes together as in the fourth WF2004 category, "Heterogeneous matrix flow and fingering". Absence of preferential flow is reasonably called homogeneous matrix flow in the fifth category. In the present study, the use of the WF2004 classification scheme is a suitable approach for evaluating dye-tracer patterns in terms of preferential flow. It is extended reasonably with the added sixth category to accommodate effects of large stones in the soil.

The other modifications adopted here are poorly explained, and appear to deviate significantly from some widely understood general features of preferential flow, and from the evidence available from this study as I understand it. Below, I explain these issues further in relation to finger flow and macropore flow.

Finger flow

Instability-initiated fingers are possible, though my expectation in such heterogeneous soil is that these are likely to be rapidly channeled into funneled flowpaths. Based on the images and other available information in the present study, I doubt that it is possible to discern whether instability-initiated fingering is an active process. In 18:24 (location noted as page:line) the term "finger flow" seems to mean any preferential flow that is identified by finger-like patterns of dye tracer, not limited to the downward-moving fingers of wetness generated at a wetting-front instability. The finger-like patterns in the dye could result from other modes of preferential flow. If what is meant is just that the patterns have a finger-like shape, without regard to specific process, "finger flow" would be better replaced by the general term "preferential flow". This issue occurs also in 1:14, 21:4, 22:3-6, 22:16, 23:21-22, 24:5-8, and 26:4-13.

We agree that is was not made clear in the manuscript that we are talking about the shape of the flow pattern when referring to finger flow and not specifically to finger flow in the narrow sense (generated at a wetting-front instability). We will address this issue by explaining our definition of the flow classes as written above and will further include the following changes into the revised manuscript:

Page 1, Line 14: we will change "finger flow paths" to "finger-shaped flow paths"
The same changes will be done on the following pages and lines: 21:4, 22:3-6, 22:16, 23:21-22, 24:5-8, and 26:4-13

On the other hand, the specific mode of instability-initiated finger flow is the subject of 23:4-6 and 24:11—25:2. It also is strongly related to the effects of hydrophobicity in 22:6 – 23:9. These passages need clarification and consistency. Overall, finger flow must be explicitly defined and the term used consistently. If the paper actually does claim that instability-generated finger flow is detected in these experiments, there needs to be justification for how this can be determined.

We see the point that using the term finger flow for finger-shaped flow paths without a previous definition what we count as finger flow leads to misunderstandings and inconsistencies.
We will replace the term "finger flow" in the listed sections with the term "finger-shaped flow paths" to make it clear that we are talking not only specifically about finger flow in the narrow sense, but name all possible reason that could have caused the development of finger-shaped flow paths.

Macropore flow

There needs to be more discussion of the possible effects of macropores. The soils are likely rich in narrow macropores that result from growing and decaying roots (apparent in the images of both young and old soils), and other bioactive processes. If such macropores convey significant water that then has some degree of interaction with soil matrix material, they could create flow pattern features of the types observed. The statements in 18:15-22 are hard to understand and accept, where it is implied that finger flow can be distinguished from macropore flow, and stated that no macropore flow was found. If there are reasons to justify ruling out active macropore flow, they need to be carefully explained.

We see the point that we cannot rule out macropore flow in general, since macropores due to bioactivity (e.g. roots) are present and also very likely to conduct water. However, after carefully screening the photos, and from our observations during the excavation we cannot determine conclusively whether the staining pattern is a result of macropore flow with high interactions or whether finger-shaped flow paths, caused by a variety of site conditions, superimpose the water transport in existing macropores. Thus, we will change the statement about the possibility of an impact of macropore flow in the revised manuscript:

Page 18, Line 14+

"[..] At the youngest moraine matrix flow is the predominant flow type (relative frequency > 0.6) followed by the flow type class 'Macropore flow with high interaction/ Finger flow'.
A reliable distinction between macropore flow with high interaction and finger-shaped flow could neither be made through the image analysis nor through on-site assessment. As narrow macropores were present (e.g. thin root channels), they certainly also contribute to water transport, but it is also likely that this process is overlaid by finger-shaped flow paths, caused by site conditions. Since the water transport patterns of both flow types cannot be distinguished and show finger-shaped flow patterns, they are also referred to as finger-shaped flow in the following.
At the 160a the relative frequency of matrix flow decreased to 0.5 and the frequency of finger-shaped flow increased. At the two oldest moraines the dominant flow type is flow with finger-shaped flow paths and the relative frequency of matrix flow dropped below 0.3. [..]"

I cannot make sense of the statements in 7:30-33, which seem to imply that finger flow can be distinguished from macropore flow, but then contradict that in saying that no such differentiation is made. Then there is confusion in the statement that narrow finger flowpaths could somehow be misclassified as macropore flow with high (but not low or intermediate) interaction.

We will clarify the origin of this joint flow type class, as described above. We further will weaken the statement that macropore flow could be ruled out. We further include the statement that both flow class types cannot be distinguished from each other in the image analysis.

Page 7, Lines 30+ new phrasing:
"[..] The modified classification also avoids a clear differentiation between 'macropore flow with high interaction' and 'finger flow'. As the original classification assigns finger-shaped flow paths only when both the medium-sized stained path width (20–200 mm) and the biggest stained path width class (> 200 mm) account for approximately half of the dye coverage, fingers with smaller widths were not detected as such and automatically counted as macropore flow with high interaction. Hartmann et al., 2020a observed that finger-like flow paths with smaller widths were frequently present in alpine soils. Their dye patterns and distributions of stained path width classes are similar to 'macropore flow with high

interaction'. Both classes cannot be distinguished from each other in the image analysis. Thus we renamed this class to (3) 'macropore flow with high interaction/ finger flow' […]".

Section 3.2 (18:12-30) needs to be rewritten for consistency with other clarifications. The category "Macropore flow with high interaction/ Finger flow" is mentioned here and in Figure 10, but it is not mentioned in the definition of the categories on page 7 and is not in the scheme of WF2004.

The class "Macropore flow with high interaction/ Finger flow" is part of an adapted version of the scheme of WF2004 by Hartmann et al., 2020 to also include smaller sized finger-shaped flow paths. We will include this clarification into the revised manuscript as stated above.
In the revised manuscript we will rewrite section 3.2 (18:12-30):

"[…] Using the VD-profiles of the three SPW classes and their proportion on the total dye coverage to characterize flow types (Weiler, 2001) we found that over the millennia flow types transition from matrix flow to preferential flow in form of finger shape flow paths (Figure 10 a).
At the youngest moraine matrix flow is the predominant flow type (relative frequency > 0.6) followed by the flow type class 'Macropore flow with high interaction/ Finger flow'.
A reliable distinction between macrpore flow with high interaction and finger-shaped flow could neither be made through the image analysis nor through on-site assessment. As narrow macropores were present (e.g. thin root channels), they certainly also contributed to water transport, but it is also likely that this process is overlaid by finger-shaped flow paths, caused by site conditions. Since the water transport patterns of both flow types cannot be distinguished and show finger-shaped flow patterns, they are also referred to as finger-shaped flow in the following.
At the 160a the relative frequency of matrix flow decreased to 0.5 and the frequency of finger-shaped flow increased. At the two oldest moraines the dominant flow type is flow with finger-shaped flow paths and the relative frequency of matrix flow dropped below 0.3.
Considering the entire profile depth of 1 m, the frequency of matrix flow decreases and the frequency of finger shape flow paths increase continuously with moraine age. A depth differentiated view shows a higher proportion of finger-shaped flow at the 4.9ka than at the 13.5ka in the upper 20 cm (Figure 10 a1). In the other depths (Figure 10 a2 to a4), however, a continuous increase in finger-shaped flow frequency with moraine age was observed. With regard to the irrigation intensity no consistent impact on the flow type distribution across the millennia could be identified (Figure 10 b). At the 110a and 160a moraine the two dominant flow types (matrix flow and finger-shaped flow paths) show an almost equal distribution across all irrigation intensities. A tendency to less matrix flow is observed at the 4.9ka, whereas at the 13.5ka the frequency of matrix flow increases with increasing irrigation intensity. Differentiated by depth, we observed no systematic trend in flow type frequency distribution with increasing irrigation intensity in the upper 20 cm for all age groups (Figure 10 b1). From a depth of 20 cm, the 4.9ka and 13.5ka each show a trend-like behavior in the shift of the frequency distribution with irrigation intensity analogous to the observation of the entire soil profile (Figure 10 b2 to b4). From a depth of 40 cm, the relative frequency of matrix flow also increases with increasing irrigation intensity at the 110a and 160a (Figure 10 b3 to b4). […]"

Overall:
This paper is dense with useful information and provides insights into the development of preferential flow paths during landscape evolution and several other important facets of unsaturated flow in calcareous soils. It needs revision for consistency and adherence to evidence and general understanding of the different types of preferential flow paths. Because the basic experimental work and presentation of data are sound, I have classed these revisions as minor, though I see them as extremely important.

Specific Comments

6:16-18. Rewrite for clarity. Use of "below" in line 16 suggests that the excavation is downward to produce horizontal planes, but "vertical profiles" in 17 suggests otherwise. Does "below" mean "downslope of"? The operation suggests that a trench was first excavated off to the side of the plot to provide access for vertical profiling. More details on this would be helpful.

We will clarify in the revised manuscript:
"A first vertical profile was excavated 10-15 cm downslope of the lower edge of the irrigated plot to check for subsurface lateral flow."

7:17. What is meant by "amount"? The number of flow paths?

We will clarify in the revised manuscript:
"The surface area density (SAD) is an indicator for the number of individual flow paths and was calculated for each pixel row of the five profiles by using the intercept density, which describes the number of interfaces between stained and unstained pixels divided by the horizontal width of the soil profile."

7:28-29. Clarify—maybe make two sentences. Start with a clear description of the problem caused by rocks. Then the solution devised.

We will clarify in the revised manuscript as also described above:
"We used a modified version (Hartmann et al., 2020a) of this classification which was more suitable for stony alpine soils. In case of homogeneous matrix flow, the modified classification avoids that a high stone content leads to the detection of a heterogeneous flow pattern by breaking up the coherent stained area into smaller pieces, which then could be falsely classified as heterogeneous matrix flow, finger flow, or macropore flow depending on the abundance of rocks. In this case the flow type is assigned to a new flow type class called (6) 'homogeneous matrix flow between rocks'."

7:31-33 Why "misclassified"? What is unreasonable about "macropore flow with high interaction"?

As stated above, we will remove this statement and clarify in the revised manuscript as follows:

Page 7, Lines 30+:
"The modified classification also avoids a clear differentiation between 'macropore flow with high interaction' and 'finger flow'. As the original classification assigns finger-shaped flow paths only when both the medium-sized stained path width (20–200 mm) and the biggest stained path width class (> 200 mm) account for approximately half of the dye coverage, fingers with smaller widths were not detected as such and automatically counted as macropore flow with high interaction. Hartmann et al., 2020a observed that finger flow paths with smaller widths were frequently present in alpine soils. Their dye patterns and distributions of stained path width classes are similar to 'macropore flow with high interaction'. Both classes cannot be distinguished from each other in the image analysis. Thus we renamed this class to (3) 'macropore flow with high interaction/ finger flow'."

7:34. Proportion in relation to what? PFF needs to be defined more clearly.

We will clarify in the revised manuscript:

"A preferential flow frequency index (PFF) was calculated based on the frequency of preferential flow type classes (1-4) across the profile at each experimental plot. As the flow type classification was done for each pixel row, the PFF is the number of pixel rows classified as a preferential flow type (1-4) divided by the total number of pixel rows."

12:8-10. Split sentence into two, for clarity.

We will clarify in the revised manuscript:

"At the 4.9ka and 13.5ka the fraction of SPW>200 mm is lower in the upper 10-20 mm compared to the young moraines. Over the entire profile range, path widths of the category 20<SPW<200 mm most often have the largest share on the dye coverage."

14:1. Replace "Whereas" with "In contrast," or similar expression.

We will update the sentence in the revised manuscript to:

"In contrast the old moraines have a high fraction of 20<SPW<200mm combined with a high SAD, which indicates a higher number of smaller, narrow blue-colored areas and thus more individual active flow paths at the older moraines and less individual flow paths but larger continuous areas used for water transport at the young moraines."

17:4-5. It seems at best to be a very subtle effect for the middle portion of the profiles to be less significantly different. Maybe not worth mentioning.

We will exclude this statement in the revised manuscript.

21:30-31. Delete “influence the water transport and”.

We will update the sentence in the revised manuscript to:

“Only larger stones and occasional clay lenses (the size of a few centimeters) or other material heterogeneities create heterogeneous matrix flow.”

22:2-3. Word missing from sentence?

We will update the sentence in the revised manuscript to:

“At both moraines deep infiltration, almost no surface runoff, and no subsurface lateral flow was observed.”

22:4-5. The point is not about the water transport in general but the pattern of the water transport that is affected. Insert “pattern” or some similar expression.

We will update the sentence in the revised manuscript to:

“Thus, water infiltrated heterogeneously and/or the water transport pattern was affected by properties of the soil surface or of the upper soil layer.”

23:22. Word wrong or missing.´

We will update the sentence in the revised manuscript to:

“After more than 10000 years of landscape development, subsurface hydrology at the calcareous geology is ruled by finger-shaped flow and deep infiltration, whereas at the siliceous geology storage capacity in the top soil strongly increased with a corresponding reduction in infiltration depths and a shift to macropore flow.”

23:29. “Matric potential”, not “Matrix potential”.

We will correct “Matrix potential” to “Matric potential” in the revised manuscript.

23:32. The paragraph starting here, and also the next one, are all about the two older soils. This should be made clear to the reader in the first sentence at line 32. Consider rearranging discussion from this point through 25:13 in order to proceed in the logical order of young to old.

We will rearrange the discussion from page 23, line 32 to page 25, line 13 in the logical order of young to old:

"At the young moraines (110a and 160a), we observed an in increase in the frequency of matrix flow at greater depths with increasing irrigation intensity, which is caused by an increase in the SPW>200 mm with a simultaneous decrease in the median dye coverage and a decrease in the number of flow paths (SAD) (Figure 5e). The decrease in median dye coverage with increasing intensity is particularly pronounced at the bare plots (data not shown). No clear trend can be seen at the plots with a higher vegetation cover. However, the decrease in SAD and the increase in stained path widths indicates that water flow paths that reach greater depths tend to widen and to merge together with increasing irrigation intensity. This process might be facilitated by higher water contents at greater depths or by a change in material properties.

At the 4.9ka moraine, we also observed an increase in dye coverage (Figure 5 (a)) and an increase in the number of flow paths (Figure 5 (e)). The proportion of 20<SPW<200 mm increases (Figure 5 (c)) and the proportion of SPW>200 mm decreases (Figure 5 (d)), which then leads to an increase in the frequency of finger flow paths in the flow type classification (Figure 10 (b2) to (b4)).

At the 13.5ka we observed an increase in dye coverage (Figure 5 (a)), an increase in infiltration depth (Figure 3), a broadening of the flow paths (Figure 5 (c-d)), and an increase in the number of flow paths (Figure 5 (e) and Figure 6) with increasing irrigation intensity. Other than at the 4.9ka, the increase in the proportion of SPW>200 mm on the dye coverage leads to a transition to more matrix flow (Figure 10) in the flow type classification.

However, the process of flow type classification is only based on the proportions of the three SPW classes on the dye coverage (Weiler, 2001). The number of flow paths or the dye coverage itself are not taken into account. We observed at both age classes that with increasing irrigation intensity more fingers are generated and more soil space is used for water transport (Figure 5). It also has to be stated that at sites where preferential flow occurs in form of macropore flow the relations can be different, since the controls inducing macropore flow are different (Nimmo, 2021). The formation of finger flow paths and their properties such as number, flow velocity, or width are in a complex interplay with the surrounding soil moisture, the flux rate and soil properties (Nimmo, 2021).
Studies focusing on the formation of finger-shaped flow paths found the finger width not only to be influenced by soil properties, and initial and boundary conditions (Glass et al., 1989), but also by the flow rate through the finger (Parlange and Hill (1976), White et al. (1976)) with higher flow rates leading to an increase in finger width. This was also observed by Ma et al. (2008), who also found a positive correlation between rainfall intensity, time of finger flow occurrence and mean velocity. The increase in mean velocity of the fingers leads to a faster downward transport and thus deeper infiltration depths with higher irrigation intensities (Cremer et al., 2017). An increase in the number of fingers with higher flux rates was also observed (Sililo and Tellam, 2000). These findings by other studies are similar to our observations at the 13.5ka moraine. It is unclear what causes the different observations in the dominant flow path widths at the 4.9ka and 13.5ka moraines. We can only speculate whether the higher organic matter content, the higher root density, or soil properties such as the lower hydraulic conductivities and

higher porosity play a role in producing narrower flow paths with increasing irrigation intensity at the 4.9ka moraine."

25:24-27. Confusing. Which of the plots were less affected by the direct application of water? Why is there consideration of the boundaries in this?

We mention the observations of the deep infiltration at the plot boundaries of the bare plots at both young moraines to support the assumption that water would have infiltrated deep into the soil, when the soil surface was not affected by structural sealing due to the irrigation process.
We will rephrase this part in the revised manuscript for clarification:

"We further assume that the irrigation with the hand-operated sprayer, which had to be held close to the soil surface due to strong winds, in part led to a high force of application and promoted structural sealing at the barer plots of the 110a and 160a moraines. At both moraines, deep infiltration was often found at the boundaries of the bare plots. Since the plot boundaries were not irrigated, they were also not affected by structural sealing. Water running off to the sides infiltrated deep into the soil. This observation suggests that a more homogeneous and deep transport of the water can take place in this quite homogeneous and unsorted material (Hartmann et al., 2020b), if the surface is not influenced by particle displacement.
Thus, it is assumed that the proportion of preferential flow paths at the young moraines is generally overestimated and homogeneous to heterogeneous matrix flow with deep infiltration are probably the dominant flow types under natural rainfall conditions. As the plot boundaries (outer boundaries and boundaries of neighboring subplots) are excluded from the image analysis to avoid edge effects, the here observed deep percolation could not be accounted for in our quantitative analysis."