RC1:

**Summary:** A “double” irrigation experiment was undertaken where first an experimental plot was irrigated with waters enriched in deuterium, followed by isotopically depleted snowmelt infiltration under natural conditions. Through soil water, groundwater, and soil sampling, a conceptual model of macropore and matrix storage/flow was developed which brings new insights into the physical processes of infiltration and the role of snowmelt on vadose zone hydrology. The quality of the writing and extensive literature review incorporated throughout the manuscript is excellent. I have just a few general and specific comments for consideration.

We appreciate your positive assessment of our work, and suggestions for improving the manuscript quality. Please find our point-to-point response to the comments, questions and suggestions below.

**General:**

**1.** It’s unclear how the tree response data is supportive of the overall theme of the paper, which largely focuses on macropore infiltration processes and soil storage dynamics. Presently it feels a bit out of place. It may be worth asking, “What does this information add to the story?” If this isn’t clear, consider removing. While I recognize the importance of plant uptake as a pathway for removing soil water, I think additional efforts should be made to tie this piece together with the other components of the manuscript if it is to be kept. This includes:

- Abstract
- The introduction: The manuscript is well positioned in the literature from a macro-pore/soil storage perspective, but considering vegetation dynamics are part of the research questions, this should be better introduced.
- Discussion: Greater discussion on the importance of the tree uptake in the homogenization effect or other new/critical insights gained
- Conclusions: There should be a conclusion for each research question/objective and this is not present in the conclusions

Thank you for the suggestion, we agree that the overall presentation of the stem water data should be improved and linked to the rest of the manuscript in a better way. Although the amount stem water data is somewhat limited, compared to the amount of soil water data in this study, we feel that these findings should be included as they are important in the context of cold climate and seasonally snow-covered areas. Including the stem water data also ensures a more holistic view of the whole soil-plant continuum, rather than just the soil, and further shows that the homogenization effect of snowmelt is not only limited to the soil but extends to the plant water. Also, the literature regarding the stem water response to massive infiltration events in northern regions is currently scarce, although such events are particularly important for stem rehydration and happen on a yearly basis in the form of snowmelt.

To properly address the stem water dynamics part of the experiment, more details will be added to the Introduction section to provide a clear idea why we consider the stem water dynamics important in the context of this manuscript, and a further commentary later in Section 4.4. A summary of the stem water dynamics will be added to both Abstract and Conclusion sections.

**2.** Although in this case, the soil temperatures remained above freezing, this will not be the case for many cold regions throughout the winter. How do you expect your conceptual model to change in years where seasonal frost develops at this site and for other sites with frozen soils?

Due to the location of the study, infiltration into the frozen soil was considered when creating the model, so we presume that the model is very well suited to the regions with seasonal soil freezing. The main mechanisms behind the water movement through the frozen soils, focused on infiltration (through the patches of unfrozen soil) and macropore flow, are also the main mechanisms used in the first stage of the proposed frost-free model. The difference is that most of the soil matrix in the upper soil layer is frozen, so the onset of matrix flow occurs faster.

Furthermore, the second infiltration stage in the model is linked to the overall reduction of the downward transport capacity of the soil, and a general reduction of the infiltration capacity is one of the main consequences of soil freezing. The freezing front that extends into the deeper soil in the form of "fingers" of variable lengths can potentially negatively affect the horizontal hydrologic connectivity in the affected soil zones, by creating small impermeable zones. Such an effect should largely be offset by the overall reduction in the size of the unfrozen zone, due to the freezing of the upper soil layers, which constrains the movement and lateral fluxes of soil water fluxes to a smaller zone, thus enabling an increased connectivity.

The third stage, soil matrix refilling, depends on the height of the groundwater table and can be limited by the depth of the freezing front. This effect should be negligible in the case of shallow soil freezing, as the isotopic composition of uppermost soil layers shifts towards the infiltration water signal almost instantaneously.

We will formulate the above as an additional discussion paragraph about the applicability of the model in frozen soil conditions.

**Line Specific:**

**Figure 1:** The subscripts in 1a should be enlarged for clarity. The co-ordinates around the border of 1b should be removed or enlarged so they can be read. They are presently illegible, even zoomed in.

Subscripts will be enlarged and highlighted, and the coordinates removed.

**Line 72:** Some more background on the potential responses previously reported might help set up this research question a little better. At present it reads a bit disconnected from the other questions and introduction.

More details were provided in response to General 1 comment.

**Line 116:** What area do the sprinklers cover and where were they positioned relative to your sample locations? locations could be added to Figure 1.

The location of sprinklers and the irrigated area will be highlighted in revised Figure 1.

**Line 126:** I think this information would be more helpful presented with the soil core sampling. I was left wondering when you sampled the cores after reading this section, but then realized these detailed were in 2.3.

We will explicitly mention when and how the soil cores from the EP were collected during the experiment, and make a clear distinction between coring done during the long-term monitoring and during the experiment.

**Line 143:** Since it is common to include Supplementary Data in a supporting document/appendix, I suggest renaming Section 2.4 to avoid confusion.

Section 2.4 name will be changed to "Additional data".

**Figure 2 and 3:** include all data in the legend, not just in the caption. It is difficult to interpret as is. Suggest switching the colours between 30 and 35 cm so there is a gradation of colour from light to dark = shallow to deep. Also need a legend for (2d).

The legends will be added, and the colors altered.

RC2:

GENERAL COMMENTS

The manuscript presents an interesting study using deuterated water to observe the response of a forested hillslope to an application of a large quantity of water mimicking a snowmelt event, and to understand the interaction between soil matrix and macropore network. The field experiment is designed well and the data are of high quality. The manuscript is well organized and written in most parts, and the methods are clearly described. The study has strong potential to make a unique and significant contribution to hydrological science. However, I see a substantial room for improvements in the analysis and discussion of the results regarding the soil water dynamics. The manuscript could use more careful and quantitative interpretation based on the principles of soil physics. As it is written, some of the data interpretation is speculative and may not support the main conclusions. I will elaborate more in my specific comments below.

Thank you for an encouraging assessment of our work. The detailed suggestions helped us provide more quantitative, rather than descriptive data analysis, although the final extent of the analysis is limited by the number of observations relative to the strong soil heterogeneity. Please find our point-to-point response to the comments, questions and suggestions below.

SPECIFIC COMMENTS

Line 27. Unsaturated (vadose). The unsaturated zone and the vadose zone are not interchangeable. Please select the term that is most suitable for the context of this study and use it consistently throughout.

"The vadose zone is frequently called the unsaturated zone" (Nimmo, 2009, Encyclopedia of Inland Waters (2009), vol. 1, pp. 766-777, https://wwwrcamnl.wr.usgs.gov/uzf/abs_pubs/papers/nimmo.09.vadosewater.eiw.pdf). For consistency, we will use "vadose zone" throughout the manuscript.

Figure 1. Please delineate the actual area of irrigation using a polygon or rectangle. Open white squares and light gray squares are shown in Fig. 1a but not explained. Please include them in the legends and explain them in the figure caption. Please indicate latitudes and longitudes in Fig. 1c. Please use appropriate font sizes in these figures keeping in mind that Figure 1 may be published in a reduced size.

As mentioned in the response to Reviewer 1, the formatting of Figure 1 will be improved.

Line 90-91. Please pay attention to the number of significant digits in comparison to the accuracy of measurements.

The number of significant digits will be reduced to 1.

Line 117. 0.24. This is reported as a unitless number, but it should be either density (kg/m3) or snow water equivalent (mm).

The unit will be changed to 240 mm.

Line 120. 163.6 mm. How was this determined? Was it measured using one precipitation gauge (Fig. 1a)? If so, how representative is it of the entire irrigated area?  Unless the sprinkler system has a uniform rate of application over the entire area, one would normally need multiple precipitation gauges to estimate an average. Please explain the uncertainty in this value. Was there an attempt to calculate the application rate from the volume of water going through the sprinkler system?

We used the sprinkler setup that was previously installed by Korkiakoski et al., 2022. section 2.2 (doi: 10.5194/BG-19-2025-2022): They positioned sprinklers in the plot so that irrigated water can evenly reach their every measurement point, and their measurement points were generally more spatially distributed than the ones used in our experiment. They checked the spatial distribution of irrigation with rain gauges and plastic buckets, as the amount of water in each bucket was proportioned to the rain gauges (in mm) based on their dimensions. The irrigated area had 3–5.5 m width and 10–21 m length, depending on the wind conditions. This information will be added to the methods section.

The wind speed was relatively low (2.98 m/s on average, with occasionally wind gust up to maximum of 9.5 m/s) and wind direction stable (~200-250 degrees) during the irrigation experiment. Overall, 20 tanks of 1000 L volume were applied to the plot, and 163.6 mm recorded by the rain gauge on the far side of the plot proves that most of the water reached all the parts of the plot. A network of soil moisture sensors at 7 cm depth, installed within the experimental plot by FMI (see figures below), as well as visual observations of the surface water ponding (Fig. S4 in Supplement) in all parts of the plot, confirm this. While the spatial distribution of the irrigation was not perfect, the main goal of the experiment, i.e. simulating a large magnitude infiltration event that significantly alters the antecedent soil isotopic signal, was achieved.

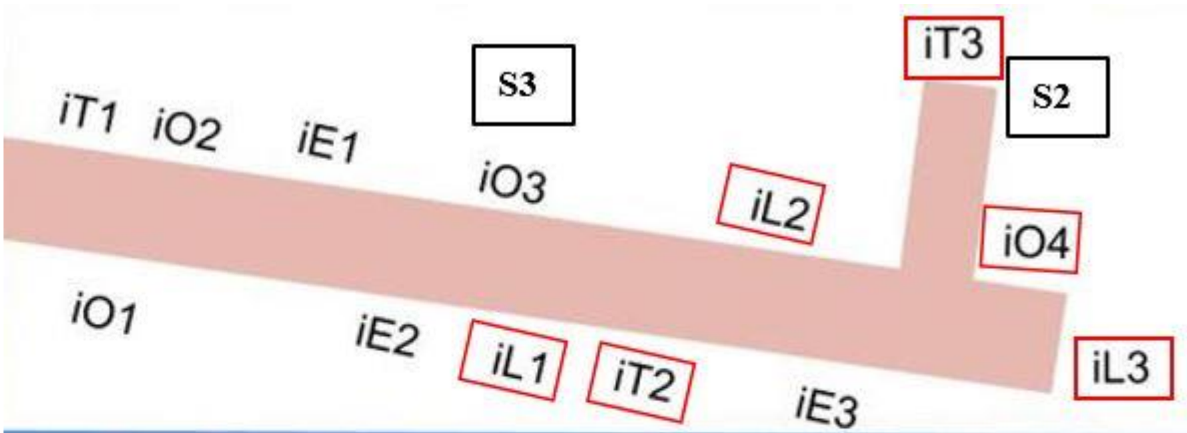


Figure1. Sketch of the planned FMI sensor locations within the experimental plot. Note that most sensors were not installed. Profiles S2 and S3 have been added for the reference.

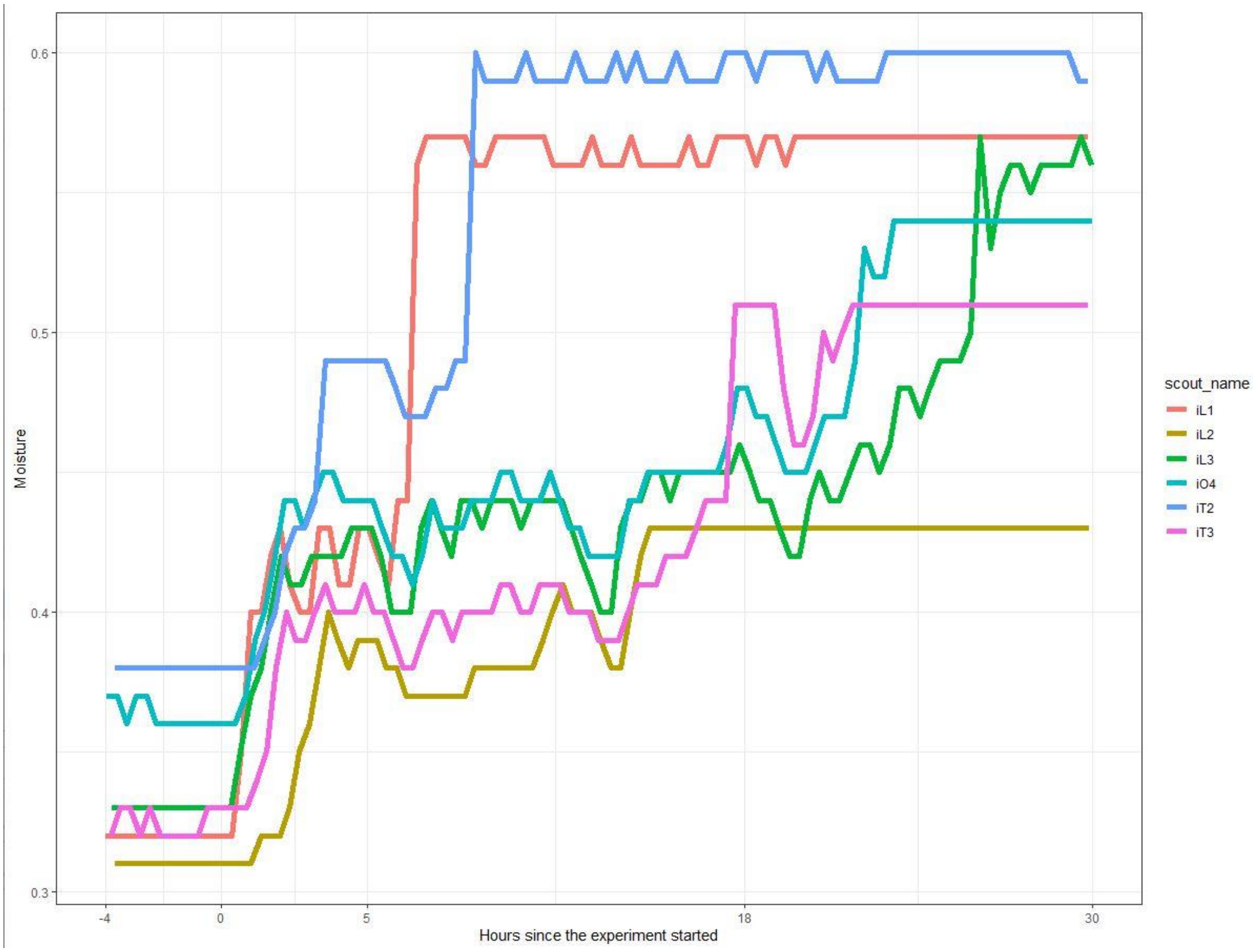


Figure 2. Volumetric soil moisture content in the experimental plot at 7 cm depth recorded by FMI sensors.

These figures will be reworked and included in the Supplement.

Line 123. 600 kPa. This is roughly 6 bar. What was the bubbling pressure of the suction cup? How was this value chosen? Does it represent the actual condition of soil pores? Please explain.

Thank you for noticing this. There is an editing lapse in manuscript at lines 123 and 137, the listed values should be in hPa, rather than kPa. The real value is 60 kPa, which is equal to the bubbling pressure of the suction cup (https://www.dmr.eu/product/prenart-super-quarts-suction-cells/). The value of the applied suction was chosen based on the values that have been commonly used in isotope studies, such as Brooks et al., 2010, (doi: 10.1038/ngeo722) for the purpose of comparability.

Line 156. Bulk soil water. Does this mean the bulk of an entire core? Or, does it refer to individual core sections? What does 'bulk' mean in the context of this study? Please explain.

We define "bulk water" in line with other isotope related soil water work (e.g, Geris et al., 2017, doi: 10.1016/j.scitotenv.2017.03.275, Sprenger et al. 2018, doi: 10.2136/VZJ2017.08.0149) as the water that represents a mix of all water stored in the soil, from matrix water to highly mobile water. The real amount of extracted water can vary depending on the clay content (negligible in our case) and soil matric potential. With the currently available soil water isotope sampling methods it is not possible to make a more clear/precise definition of the sampling range and associated water amount. An explicit definition of “bulk soil water” will be added to the manuscript. We always refer to the individual 5 or 10 cm core sections, and this information will also be added to the manuscript.

Figure 2c. This figure is difficult to comprehend. Symbols and colours are difficult to differentiate, and there are too many data series in one graph. Please improve the presentation. At least, more clearly distinguishable symbols and colours need to be used. Pale yellow is not easy to see on the white background. Also, it will be easier for the reader if Profile 2 and Profile 3 are presented in separate graphs.

The formatting will be adjusted.

Figure 2d. This figure is also difficult to comprehend. Please improve the presentation.

As mentioned previously, the color scheme will be changed.

Line 186. This sentence describes the response of 35-cm depth. However, I see that the 60-cm sensor responded before the water table started to rise, but this sampler was located far above the water table. This seems contrary to the sentence. Please explain. Overall, this paragraph could use a clearer writing that is consisted with the data presented in figures.

The fact that the 60-cm sensor had the fastest response is mentioned at lines 196-197. The idea behind mentioning the pan lysimeters at line 186 was to show that they only responded to the irrigation when the groundwater level was above their installation depth. This was further elaborated in section 4.2, at lines 372-377. We understand that the current text arrangement can cause confusion, so the sentence from line 186 will be moved to the end of section 3.1.

Line 190. Orange and yellow are difficult to distinguish. Please use different colour schemes.

The color scheme will be changed.

Line 192. Brown vertical lines. These lines look more purple than brown. Please include this in the graph legends, instead of describing it verbally.

The legend will be reworked.

Line 202. What was the date of another irrigation study? Was it before or after the study in the manuscript?

It happened before this study. From Korkiakoski et al., 2022: *The irrigation periods were 28 May to 7 September 2018 and 6 June to 29 August 2019.* Note that these dates also include this experiment with deuterated water, since Korkiakoski et al., have taken samples after our irrigation. Their non-labelled irrigation was stopped a few weeks before our experiment started. We will clarify this in the methods section of the revised manuscript.

Line 203. What was the deuterium value of the tap water? Please indicate it here.

Based on the 46 tap water samples from 2018, the average $d^2H$ value was -104.36 ‰, with a standard deviation of 0.45 ‰. This information will be added to the methods section of the revised manuscript.

Line 220. Soil moisture levels. Pale yellow lines are difficult to see on white background. Please use a different colour.

As mentioned previously, the color scheme will be changed.

Line 238. Reference plot. This is described as ‘natural soil’ in the legend of Fig. 5d. Please use a consistent term.

The legend of Fig. 5d. will be adjusted accordingly.

Line 284. Infiltration capacity of surficial soil matrix is exceeded. This is an example of statement that is lacking quantitative consideration. Infiltration capacity of surface soil is quite high when it is unsaturated and decreases as the soil becomes saturated. The lower limit of infiltration capacity is the saturated hydraulic conductivity, which is on the order of 10^-6 to 10^-5 m/s (Line 90-91). These were determined using a falling-head permeameter on soil samples, implying the soil matrix conductivity. The intensity of irrigation was generally less than 10 mm/h or 3 x 10^-7 m/s (Figure 2a). Given this, it is not clear how the infiltration capacity of the surficial soil matrix can be exceeded. Please present a convincing explanation.

We used metal cylinders to collect undisturbed soil samples for the falling-head permeability test, so they can contain macropores too, which should result in higher conductivity than the soil matrix itself. But we do agree that infiltration capacity might not be the only relevant factor in this case. Another limiting factor is the water holding capacity of the surface soil layers, which is relatively low due to the high porosity and low bulk density. A figure with pF curves is attached for the reference. It is clear that the field capacity of the surface soil can be exceeded, even for infiltration events of lower intensity than 10 mm/h.

We will add a mention of this to the manuscript discussion part and highlight the role of the low water holding capacity of surface soil layers. A Figure with pF curves will be included in the Supplement.

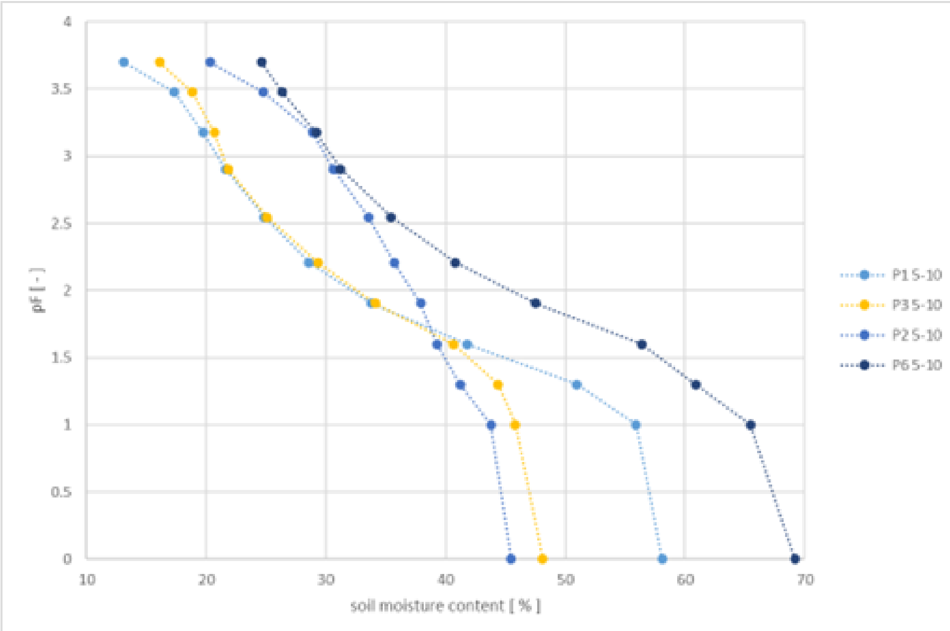


Figure 3. pF curves

Line 285-286. Macropore flow is unsaturated. What is the evidence of unsaturated condition? The soil moisture sensors measure soil matrix, and are insensitive to macropores that occupy relatively small volume. Again, please present a convincing explanation.

Direct observations of the macropore saturation were not made, due to the scale of the experiment. Unsaturated flow in macropores is assumed as the default condition, as observed in many previous studies. This should especially be the case in unsaturated conditions, as macropores tend to be hydrophobic relative to the soil matrix. During the first ~12 hours of the experiment, the soil moisture values were generally below their maximum and there was no surface water ponding, all together indicating that soil matrix was unsaturated, and majority of infiltrating water could propagate through the soil matrix. Nevertheless, bulk soil water isotopic signal, at least in surface soil layers, was continuously more enriched than the suction lysimeter signal (Fig. 3 and lines 209-2011), indicating that some amount of the enriched irrigation water was moving through larger pores.

Line 288. Groundwater rises toward towards the surface. The rise of the water table is indeed shown in Fig. 2b. However, Fig. 2d shows constant moisture content at 60 cm in Profile 2, which is located adjacent to the water-table monitoring well. This implies that the soil at 60cm was saturated before the water table rose to 60cm. This does not seem likely because the capillary fringe cannot be as thick as 50cm in near-surface soil. I feel that something is missing here. Please present more careful interpretation of soil water dynamics based on the principles of soil physics.

The soil moisture sensor at 60 cm depth in profile 2 generally remains stable during the whole observation period, even during the snowmelt event. Unfortunately, this points to the possibility of sensor malfunction. The measurements from this sensor will be entirely removed from the manuscript, as there is a reasonable doubt that it wasn't functioning properly. Furthermore, no conclusions were previously made based on the measurements from this sensor, so its removal will not affect the discussion section. The note that these observations were removed will be added to the methods section.

Line 289. Groundwater exfiltration. The term exfiltration specifically means that groundwater is discharging at the ground surface. It seems unlikely that exfiltration was happening while the water table was below the ground surface (Fig. 2b). Was exfiltration visually observed? Please present an explanation.

Thank you for the suggestion. We mention that it is exfiltration to the upper soil layers, rather than the surface, but agree that changing the term to "advances" would make the terminology more accurate.

Line 308. Dashed red lines. The red lines indicate 30cm, not 5cm, in this figure. Please be consistent between the texts and figures.

The sentence will be restructured for more clarity. We refer to soil patches at both 5 and 30 cm depth, as it can be seen from Fig. 2d that soil moisture at both locations (solid yellow and dashed red) changes very little, despite the changes at other depths in the same profiles.

Line 311. Please refer the reader to Fig. 3.

A reference will be added.

Line 313. (Smaller pores in the soil matrix) is filled first. Figure 2d indicates only 5% increase in water content at 5-cm depth. This seems inconsistent with a major shift in isotopic composition depicted in Fig. 3. Does it make sense in terms of mass balance consideration? Please explain.

Referring to the period between -4 hours and +5 hours, at 0-10 cm soil depth. The initial conditions were ~35% volumetric soil moisture content with an average isotopic signal of ~ -77 ‰, which changed to ~40% and ~ +11 ‰, respectively. The average isotopic signal of the infiltrating water was ~ +72 ‰. Considering bulk density of ~1 g/cm$^3$ and simple two end-member mixing, we can estimate that a 5 % increase in soil moisture would change the overall isotopic composition to ~ -58 ‰. Nevertheless, the amount of water applied to the soil, 36.2 mm, was much higher than the amount needed to increase moisture by 5 %. It can be expected that a certain fraction of antecedent soil water was displaced by the infiltrating water, thus changing the ratio of enriched and depleted water. This ratio, and the final bulk soil isotopic composition, are also affected by the soil heterogeneity. Lastly, bulk samples of soil sections with high moisture content, taken during the irrigation event, also contain a fraction of more mobile irrigation water. This irrigation water produces a stronger isotopic than hydrometric (i.e., soil moisture response) effect. A mention of soil water displacement effect, and a brief discussion regarding the relationship between bulk soil water isotopic signal and soil moisture content will be included.

Line 323. Does lysimeters preferentially sample macropores? They are subjected to high magnitude of matric potential (600 kPa). Please interpret the data more carefully considering the actual function of lysimeters.

Suction lysimeters (at 600 hPa) should in theory sample soil water of lower mobility than the water in macropores, but of a higher mobility than the matrix soil water. The difference between suction lysimeter water and bulk and macropore soil water also depends on the soil moisture. According to this comment and the comment for line 156, regarding the bulk soil water definition, a short explanation related to different soil water sampling methods, and soil waters of different mobility that they sample, will be added.

Line 345. Inability to infiltrate deeper. Many of the papers cited in this paragraph were on frozen soil infiltration, but this experiment was conducted under unfrozen condition. What prevents infiltration when the irrigation rate was much below the saturated hydraulic conductivity of surface soil? Please present a convincing explanation.

Surface water ponding was observed after 12 hours, after over 60 mm of irrigation water was sprinkled onto the soil. Although the infiltration capacity of surface soil was maybe not exceeded, the infiltration capacity of heavily compacted, lower soil layers surely was exceeded. These low permeability layers, combined with strong spatial heterogeneity of the soil and low water holding capacity of the surface layer, result in surface water ponding. We will add this to the discussion section.

Line 354-355. This sentence compares the rate of water-table rise and the soil saturated hydraulic conductivity. I cannot understand the logical connection between the two quantities. The rate of water-table rise does not indicate groundwater flux. The water table can rise quickly with a small addition of water if the soil is nearly saturated in the capillary fringe. The rise in the water table can occur when the flow direction is downward. Please revise the conceptual model of the water table dynamics and reinterpret the data based on the principles of soil physics.

We acknowledge that groundwater rise coincides with an increase of the soil moisture at certain depths and profiles, and that fast groundwater level rise occurs during the soil wetting stage, thus showing a link between soil saturation in the capillary fringe and the rate of groundwater level increase. On the other hand, a strong correlation between the groundwater isotopic signal and the total amount of applied irrigation water (line 185) shows that irrigation water reaches groundwater storage without much mixing with the soil matrix water that still largely has more depleted isotopic signal. This indicates that the irrigation water mostly reaches and mixes with groundwater via macropores. The saturation of the capillary fringe should also result in the increase of the macropore flow (referring to line 346 in the manuscript and Jarvis, 2007, doi: 10.1111/j.1365-2389.2007.00915.x). 1-2 sentences about the groundwater level rise during the soil wetting stage, and the source of groundwater replenishment, will be added to the discussion section. The effect of soil saturation in the capillary fringe on groundwater dynamics will be included in the conceptual model.

Line 364. Upward water flow. This requires the matric potential gradient in excess of 1. Is there direct evidence of such a gradient? Please present the data.

There were no direct measurements of the matric potential, but here we refer to the groundwater level rise that mostly occurs via the macropore network. Macropores allow non-equilibrium flow that should be less influenced by the matric potential. The strongest evidence is derived from the pan lysimeter dynamics, as there was no water in the pan lysimeters until the ground water level exceeded their installation depth (35 cm). Afterwards, large amounts of water were extracted from the collection bottles every hour. We do concur that a change of terminology is needed. “Upwards water flow” will be rephrased to “groundwater rise through the macropore network”. Additionally, the mention of flow reversal at line 288 will be removed.

Line 378. Stumpp and Hendry (2012). This study was not conducted in a sub-arctic catchment. Please read the paper carefully and revise the sentence.

Thank you for the correction. The term sub-arctic will be replaced with seasonally snow-covered.

Line 397. Rothfuss et al. (2015). What were the findings, and where was the study conducted? Please add the information, so the reader can understand the context.

Rothfuss et al. (2015) found that the isotopic composition of the surface soil immediately shifts towards the isotopic composition of the infiltrating water. Clarification will be added to the text.

Line 407. Michelon et al. (2023). Where was this study conducted?

The study was conducted in a steep mountain catchment in Switzerland. Indeed, this is somewhat in contrast with the findings of Mueller et al., (2014), mentioned on line 418, and will be further disseminated in the discussion.

Line 431. Net radiation. Please indicate the unit in the graph.

The axis label will be changed accordingly.