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. Text added to the manuscript is marked in red italics, while the text that remained the from previous version is marked with black italics. Line numbers correspond to the version with tracked changes.

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

To properly address the stem water dynamics part of the experiment, as suggested, more details were added to different sections of the manuscript.:

Abstract: *Extensive soil saturation induced the flow of labelled water into the roots of nearby trees.*

Introduction (lines 40-44): *Plant water uptake, as one of the most important factors of ecosystem functioning, can be dependent on both soil water compartmentalization (Brooks et al., 2010) and seasonal availability (Allen et al., 2019). On the other hand, soil water dynamics is also influenced by the vegetation, as soil water content and isotopic variability can be dependent on the plant cover (Oerter and Bowen, 2019), meaning that both soil and stem water observations are required to understand the fate of the water that infiltrates the soil.*

and (lines 63-64)

The effect of high water availability during the period of low radiation forcing on seasonal variability of stem water in sub-arctic forests, which often occurs during the snowmelt season, is still underexplored.

Discussion (section 4, lines 335-336): *Furthermore, the homogenization was not only limited to the soil, but it extended throughout the soil-vegetation interface.*

Discussion (section 4.4, lines 555-557): *We speculate that timing of the experiment allowed us to first detect quick and short-lasting stem water enrichment caused by fast soil saturation, and afterwards a more gradual enrichment that resulted from transpiration-related root water.*

and (lines 572-574)

The isotopic signals of stem samples collected one day after the irrigation were already reverted to their pre-experiment values, suggesting that the initial influx of labelled water got quickly removed from the trees despite the low evaporation demand.

and (lines 580-585)

Although isotopic offset between soil waters and bulk stem water is typically observed in cool wet environments (de la Casa et al., 2022), this may not be the case in brief period following the snowmelt. Collected data show that full or partial refilling of the tree water storage can typically occur during large infiltration events, such as snowmelt, and affect the seasonal isotopic cycle of sub-arctic forests. Knighton et al. (2020) found that simulating tree storage, especially during the periods of low transpiration, can be relevant for estimation of tree water dynamics and water residence times in critical zone.

Conclusion:

In sub-arctic areas, the homogenization effect can also extend to the stem water.

and

We found that the soil saturation caused water inflow into the root system of nearby trees, despite the very low radiative forcing.

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?

An additional discussion paragraph about the applicability of the model in frozen soil conditions was added to the Discussion (section 4.3, lines 535-547).

To understand the limits of the conceptual model applicability, it is important to assess how the described mechanisms would work in the frozen soil conditions that are expected in the sub-arctic catchments. Although soil freezing in the EP was not directly observed during the experimental period, *we suggest that the proposed model is theoretically well suited to the frozen soil conditions. Namely, the main the mechanisms of water movement in frozen soil conditions, focused infiltration and macropores flow, are also key mechanism that were observed during the first infiltration stage in this study. The freezing of the upper soil layers is advantageous for macropore flow development and can possibly trigger the onset of macropore flow even faster than in the case of unfrozen soil. One of the requirements for the groundwater rise through the macropores, that defines the second infiltration stage, is that infiltration exceeds the transport capacity of the soil. As soil pores are getting filled by the ice, their overall volume and consequently soil transport capacity get reduced, again supporting the proposed infiltration mechanism. At the same time, the ice-filled pores can act as flow restricting zones that limit the hydrologic connectivity between different soil patches, especially in the surficial soil layer where more extensive freezing should be present. The depth of the freezing front could additionally limit the homogenization effect that is caused by shallow and long-lasting groundwater table, but this effect should however be limited to the surficial soil.*

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 were 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 context about the importance of stem water was added to the Introduction, as described in the response to the 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 are highlighted in the 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.

Sections 2.2 and 2.3 were reorganized, the experiment was described in section 2.2 and all sampling is described in section 2.3 (Data collection). The part about soil coring (lines 160-166):

Soil cores from the EP were collected 4 times during the experiment, using a percussion drill (Cobra 148, Atlas Copco) with a window sampling tube extension (RKS with a reinforced cutting edge with a core cutter Ø80 mm x 1 m, GEOLAB Paweł Szkurłat). Two replicate cores were collected each time, and all cores were sampled at 5 cm increments down to a 50 cm soil depth and at 10 cm increments from a 50–100 cm depth. Furthermore, soil coring campaigns monitoring the seasonal changes in the EP were conducted 2 weeks after the experiment, at the peak snowpack in April 2020 and after 2020 *snowmelt in mid-June. Soil cores immediately downslope of the EP were collected 1 day after the experiment, and again 2 weeks later and under deep snowpack in April 2020.*

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 is 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 are 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. Text added to the manuscript is marked in red italics, while the text that remained the from previous version is marked with black italics. Line numbers correspond to the version with tracked changes.

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.

It was changed to vadose zone.

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 is 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 is 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 is 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?

The information about the sprinkler system was added to the methods section 2.2 (lines 124-128):

The sprinkler setup was installed and maintained by Korkiakoski et al. (2022), and sprinklers were positioned so that irrigation water can be distributed evenly within the EP, covering the area of 3-3.5 m width and 10-21 m length depending on the wind conditions. Weather conditions during the experiment were favourable, with relatively low wind speed (2.98 m/s on average, with occasional wind gust of up to 9.6 m/s), stable wind direction (mostly between 200 and 250 degrees) and no rainfall.

and (lines 136-138)

Although spatiotemporal distribution of irrigation water was not completely uniform, plot-wide surface water ponding and soil moisture increase showed that the main goal of the experiment, i.e. simulation of a high magnitude infiltration event, was achieved.

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.

The value was changed to 600 hPa.

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.

A paragraph describing assumptions for different water samples was added to the section 2.3 Data collection (lines 170-177):

We define the bulk soil water in line with other isotope related soil water works such as Geris et al. (2017), as the water extracted from the soil that represents a mix of all waters stored in the soil, from soil matrix water to highly mobile water. Suction lysimeters are assumed to sample the soil waters of lower mobility than the water moving through macropores, but higher mobility than the soil matrix water. The difference in isotopic signal between bulk soil samples and suction lysimeter samples represents a combination of tightly bound soil matrix water and macropore water isotopic signals, depending on the soil moisture content. The isotopic signal of pan lysimeter water is assumed to be the most realistic representation of highly mobile soil water. Bulk stem water is considered to reflect a mixture of various stem water pools that contain waters of different ages.

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 is adjusted.

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

As mentioned previously, the color scheme is 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 sentence is moved to the end of section 3.1 (lines 258-260).

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

The color scheme is 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 is reworked.

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

The information is now included into the manuscript, section 3.1 (lines 246-248):

The EP was used in another irrigation study in 2018 and 2019, with an aim of to increase the overall soil water content at the plot (Korkiakoski et al., 2022). Due to the and thus frequently irrigated using tap water with a constant isotopic signal. As the study ended only several weeks before the onset of this study, bulk soil water d^{2}H depth profile variability (Fig. 3) was relatively low at the start of the experiment.

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^{2}H value was -104.36 ‰. The information is added to section 2.2 (Irrigation experiment, line 123) of the revised manuscript.

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

The color scheme is 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. is adjusted.

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.

The first stage description is reworded (Section 4, lines 344-347):

1) First stage – the initiation of macropore flow: Surface microtopography induces surface ponding and focused infiltration. Infiltrating waters first fill the surficial soil matrix, but due to the *limitations in infiltration and water holding capacity of the surficial soil matrix, the water fluxes are conveyed downwards through the macropore network. The fluxes are largely vertical and macropore flow is unsaturated. Soil matrix in deeper soil layers is bypassed.*

A Figure with pF curves is included in the Supplement as Fig. S6.

Additional comments regarding the infiltration capacity are included in section 4.1 (lines 400-401):

The transfer of flow towards the macropore network is further increased by the low water holding capacity of surficial soil at Pallas (Fig. S6).

and (lines 415-416)

These factors of heterogeneity explain how the observed surface water ponding could occur in isolated patches of soil although the irrigation rate was lower than the measured infiltration capacity of surficial soils.

and (lines 421-425)

As the irrigation progressed, and over 60 mm of water was applied to the EP, the movement of water through the soil was no longer only limited by the infiltration capacity of the surficial soil, but by the infiltration capacity of deeper soil layers too. As previously infiltrated water reached deeper, strongly compacted soil layers, its further percolation was halted and subsequent infiltrating water started accumulating in the upper soil layers, eventually exfiltrating to the surface.

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.

Short discussion about the macropore saturation was added to section 4.2 (lines 463-473):

Although direct observations of macropore flow were not possible due to the scale and setup of the study, the enrichment of bulk soil water isotopic signal in the upper layers, compared to the isotopic signal of water from suction lysimeters, can serve as an indicator that the water of higher mobility was present in the soil and moved through the macropore network already during the first hours of the irrigation. The isotopic enrichment observed at 60 cm depth (Fig. 2b) during the irrigation, that occurred before the enrichment in upper soil layers, further shows that preferential flow pathways were active even in the early stages of the experiment. On the other hand, the abrupt appearance and disappearance of large quantities of water in pan lysimeters, observed both during the irrigation experiment and the snowmelt, can be used to infer lateral flows and the near saturation of the macropore network.

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 was removed from the graphs.

More discussion about groundwater rise was added to section 4.2 (443-460).

A much faster groundwater response can occur in nearly saturated soils in the capillary fringe. As the groundwater level in the EP is typically at least 1 m below the ground during the summer and autumn (Fig. 4b), the capillary rise in sandy till soils in the EP should be limited to the soil layers at similar depth. Despite this, we observed that the groundwater level increased by 77 cm during an 8-hour period, between hour 6 and hour 14 of the experiment. The observed rate of groundwater rise and isotopic signal enrichment indicate that groundwater moves via bypass flow through the macropore network. In this way, a hydrological connection between infiltrating water and groundwater is established through the macropore network and a flow constricting zone in deeper soil layers is largely bypassed. A strong correlation between the total amount of irrigated water applied to the EP and groundwater isotopic signal shows that the enriched irrigation water reaches groundwater directly through the macropore network. The increase of soil moisture during the soil wetting stage is clearly an important driver and a necessary precondition of the groundwater level rise, based on the fact that they showed similar dynamics during the entire observation period (Fig. 4b and c). Still, generally high soil moisture and correspondingly low soil matric potential in the EP helped convey the infiltrating water towards macropores rather than in the soil matrix and limited the pore water exchange between soil matrix and macropores. Although macropore flow is typically unsaturated due to its high transport capacity (Cey and Rudolph, 2009; Jarvis, 2007) and relative hydrophobicity compared to the soil matrix, we can assume that the groundwater rise through the macropore network signals the temporary excess of water in the soil and near-saturation of vertical macropores, which consequently intensifies the lateral movement of water and strengthens horizontal hydrological connectivity in the macropore network.

Also, the description of stage 2 in section 4 (lines 348-351) was modified:

2) Second stage – development of lateral fluxes: As the transport capacity of certain parts of the macropore network in deeper soil is surpassed, and infiltrating water percolates towards the soil layers with lower permeability, groundwater rises towards the surface through the macropore network.

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.

The term is changed to “advances”.

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 was restructured (lines 374-379):

The amount of water applied to the soil during this experiment was relatively large, considering the shallow soil at this location, yet soil water storage continuously displayed a strong heterogeneity in soil moisture and isotopic measurements in the two observed profiles. Our data shows that some soil patches at a 5 cm depth remained largely isolated from infiltrating waters for a long period (solid yellow lines in Fig. 2c and Fig. 2d), despite isotopic changes in deeper soil layers at the same profile already taking place (solid red lines in Fig. 2c and Fig. 2d) and plot-wide surface water ponding.

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

A reference is 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.

A short discussion, describing possible reasons for difference in hydrometric and isotopic response was added to section 4.1 (lines 384-392):

During the first 5 hours of the experiment, the soil moisture content in first 10 cm of depth increased by less than 10 %, while the bulk soil d^2H values increased by some 90 ‰ (from -77 to +11 ‰). Such d^2H increase could not be caused by simple mixing of the antecedent soil water with the infiltrating water, as the amount of antecedent water (~35 %) was much higher than the soil moisture increase. This indicates that the process of soil water displacement in the upper soil layers was initiated in the early stages of the experiment, as the enriched water started entering the soil matrix and altering the isotopic signal of the soil water. It should be noted that the observed soil water enrichment could not only be caused by mixing and displacement processes, as the bulk soil water also contains a certain fraction of very mobile infiltrating water, which can further skew the isotopic values towards the enriched values.

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.

As described previously, a paragraph describing assumptions for different water samples was added to the section 2.3 Data collection, lines 170-178.

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.

The infiltration capacity was addressed in our previous answer to the question regarding the line 284.

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.

The groundwater table rise was addressed in the answer to the question regarding the line 288.

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.

"Upwards water flow" is rephrased to "groundwater rise through the macropore network". Additionally, the mention of flow reversal at line 288 (now line 350) is removed. Figure 7 was modified to incorporate the changes.

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.

The term sub-arctic is 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.

Clarification is added to the text (lines 498-499):

The deuterated water signal was fully removed from the topsoil after rainfall events following irrigation (Fig. 5), consistent with the findings of Rothfuss et al. (2015) who identified that isotopic composition of surface soil immediately shifts towards the isotopic composition of the infiltrating water.

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

The paragraph was restructured (lines 527-534):, and included in a wider discussion about the model applicability:

Prolonged soil saturation is also less likely to occur on steep slopes, as Mueller et al. (2014) found highly spatially variable soil isotopic signals during the snowmelt period. However, they note that soil sampling campaign in their study took place roughly 4 months after the snowmelt, which is arguably longer time span than the transit times in upper 1 m of the soil. In a more recent study conducted in a steep alpine catchment, Michelon et al. (2023) recognized the potential of snowmelt to strongly flush the entire subsurface system and reset the isotopic values of soil waters. Furthermore, homogenization of soil waters during snowmelt should be expected in topographical lowlands with shallow groundwater table, where groundwater – surface water interactions are commonly observed in sub-arctic (Autio et al., 2023).

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

The axis label is adjusted.