Answers to Judith Eeckman comments on the paper "Assessing the seasonal compartmentalization of water fluxes in the soil-plant-atmosphere continuum of a high-elevation mountain grassland"

Alessio Gentile[1], Davide Gisolo[1], Stefano Brighenti[2,3], Giulia Zuecco[4,5], Chiara Marchina[4], Davide Canone[1], Tanzeel Hamza[1], Stefano Ferrari[1], Stefano Bechis[1] and Stefano Ferraris[1]

[1] Interuniversity Department of Regional and Urban Studies and Planning (DIST), University of Torino and Polytechnic University of Torino, 10125, Torino, Italy
[2] Faculty of Science and Technology, Free University of Bozen-Bolzano, 39100, Bozen-Bolzano, Italy
[3] Eco Research, 39100, Bozen-Bolzano, Italy
[4] Department of Land, Environment, Agriculture and Forestry (TESAF), University of Padova, 35020, Legnaro (PD), Italy
[5] Department of Chemical Sciences (DiSC), University of Padova, 35131, Padova, Italy

Correspondence to: Alessio Gentile (alessio.gentile@unito.it)

This work investigates the highly relevant question of the seasonal dynamics of water transfers in shallow soils (<60 cm depth) in an alpine grassland context. In particular, this work aims to distinguish between the seasonality of water available for vegetation and the water that percolates vertically to recharge groundwater. Isotopic transfers are modeled using the HYDRUS-1D model. Meteorological data are measured locally, and samples for isotopic analyses are collected monthly.

I mainly have a few substantive comments on this work, which is overall comprehensive.

We thank Dr. Judith Eeckman for the assessment of our work. We appreciate the recognition of the relevance of the research question and the overall comprehensiveness of the study. All the comments and feedback received are constructive and will help to improve the manuscript. Accordingly, we will thoroughly revise the paper to address all main and specific comments. Below, we provide our responses to the comments of Judith Eeckman, together with our proposed revisions, which we will be pleased to implement, pending a positive decision from the editor. At this stage, proposed revisions referring to specific portions of the manuscript are indicated using the notation "LXX–YY", where XX and YY represent provisional line numbers that will become definitive if the editor invites us to proceed with the revision and submit the revised manuscript.

1 Main comments

The use of snow depth measurements to estimate melt flux is very simplistic. Indeed, this does not account for processes such as compaction, refreezing, stratification, etc. Snow sublimation is not mentioned. The degree-day model is simplistic and poorly represents these fluxes. Is sublimation accounted for in the calculation of AET in winter? There are instrumental methods for directly calculating melt flux (see Eeckman et al., 2025).

This point could be specified in the “dataset” paragraph or in the discussion.

We thank Dr. Judith Eeckman for this constructive comment and for pointing out the relevant reference.

We agree that the degree-day approach represents a simplified description of snowmelt processes and does not explicitly account for mechanisms such as compaction, refreezing, stratification, or snow sublimation. Regarding sublimation, we would like to clarify that, in terms of the objectives of this study, distinguishing the partitioning of potential evaporation into sublimation and soil evaporation is not a key aspect. Our main interest is to adequately represent the outgoing flux (evaporation + transpiration) toward the atmosphere. This is also because we compare the AET obtained from the model with AET derived from eddy covariance measurements, which do not distinguish between sublimation, evaporation and transpiration. Given how HYDRUS-1D operates, we simply partition potential evapotranspiration into potential evaporation and potential transpiration using Eqs. 2.7 and 2.8 of the preprint. Clearly, during winter, potential evaporation mainly corresponds to sublimation. Moreover, explicitly accounting for the isotopic composition of sublimation would require additional model developments and dedicated investigations, as this process remains subject to ongoing research (Beria et al., 2018).

In line with the reviewer’s suggestion, we will explicitly highlight in the Discussion that one of the main limitations of our approach is the use of a simplified model to estimate the melt flux. We will also acknowledge that this flux could be directly calculated by using instrumental methods as reported in Eeckman et al. (2025).

At the same time, we would like to emphasize that the degree-day model is coupled with an isotope-enabled framework that simulates the isotopic composition of equivalent precipitation (i.e., rainfall + snowmelt) following the approach proposed by Ceperley et al. (2020). To the best of our knowledge, this represents one of the most recent and suitable approaches for simulating isotopic content in snow-dominated sites.

Notably, the method developed by Ceperley et al. (2020), despite the simplified assumptions, has been successfully applied in the Vallon de Nant catchment (i.e., the same site investigated in Eeckman et al., 2025), where it showed agreement with results of Eeckman et al., (2025) as also reported by the authors in the manuscript. Moreover, our results indicate that the degree-day approach provides overall reliable estimates of snowmelt dynamics at the Alpine study site where the melt is largely driven by latent heat transfers (Ceperley et al., 2020; Ohmura, 2001).

We propose to add the following paragraph in the Discussion section LXX-YY: "*As in our study, also Stumpp et al.* (2012)*, by assessing the effects of land cover and fertilization on water flow and solute transport of five lysimeters using HYDRUS-1D, found the main discrepancies between simulated and measured values because of the uncertainties related to infiltration during snowmelt. Therefore, for future studies, a more accurate estimation of these fluxes could be achieved by directly using instrumental methods, as reported in Eeckman et al. (2025).*

Overall, the degree-day approach used in this work has the limitation of providing a simplified representation of snowmelt processes, in which processes such as compaction, refreezing, stratification, and snow sublimation are not explicitly included. Regarding the latter, a further partitioning of potential evaporation into soil evaporation and snow sublimation is beyond the scope of the present study. The main interest here is to adequately represent the outgoing flux toward the atmosphere. Moreover, explicitly accounting for the isotopic composition of sublimation would require additional model developments, as this process remains subject to ongoing research (Beria et al., 2018). Therefore, no further distinction is made between soil evaporation and snow sublimation, as both processes are included within the potential evaporation term computed using Eq. 2.7. During winter, this term predominantly reflects sublimation due to the presence of snow cover. Accordingly, we compared the simulated AET with eddy-covariance measurements, which do not distinguish between sublimation, evaporation, and transpiration."

We also propose to add at the end of the paragraph:

LXX-YY: *"Despite these limitations, our results indicate that the degree-day approach provides overall reliable estimates of snowmelt dynamics at the Alpine study site where the melt is largely driven by latent heat transfers (Ohmura, 2001, Ceperley et al. 2020)"*

We also propose to add the following sentence at the end of section "Potential evapotranspiration (ET$_P$), evaporation (E$_P$) and transpiration (T$_P$)":

LXX-YY: *"No further partitioning of potential evaporation into soil evaporation and snow sublimation is made: this partitioning is beyond the scope of the present study. During winter, this term predominantly reflects sublimation due to the presence of snow cover at the study site"*

The issue of rain-on-snow is not addressed: how does the degree-day model respond in this case? There could perhaps be specific thresholds for such conditions. Have you observed this situation in your meteorological data? This is a very important point for estimating melt flux, especially in spring.

We thank Dr. Judith Eeckman for this insightful comment. We acknowledge that, from a methodological perspective, the approach proposed by Ceperley et al. (2020) and adopted in this study does not explicitly account for rain-on-snow

events. We will therefore further emphasize in the revised manuscript that the lack of an explicit representation of rain-on-snow dynamics constitutes a limitation of the adopted modelling approach that weakens the representation of meltwater generation during such events.

We would like to point out, however, that this aspect has been addressed in the manuscript, although it may not have been discussed in sufficient detail. Specifically, at L456 of the preprint we note that some discrepancies between modelled and observed data may be related to the occurrence of rain-on-snow events. In addition, we quantified in aggregated manner the occurrence of such conditions compared to total rainfall by defining rain-on-snow as precipitation falling as rain while snow water equivalent (SWE) is greater than zero.

Nevertheless, following the reviewer's comment, we further investigated this aspect to better assess the potential influence of rain-on-snow events on the results.

Over the study period, most of these events occur in June (Table 1, Figure 1), toward the end of the snowmelt season (Figure 1). During these events, the model quantifies melt fluxes (Figure 1), but no enhanced melt rates are used during rain-on-snow events. Indeed, Myers et al. (2023), highlighted that such events can increase melt rates. Accordingly, one potential implication about the use of Ceperley et al. (2020) model is that snowmelt is underestimated by the degree-day approach during rain-on-snow conditions.

Table 1 Number of rain-on-snow days (i.e., precipitation falling as rain while SWE is greater than zero) for each month

Hydrologic Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Sep	Aug	Sep
2017-2018		2	1	0	0	1	1	1	9	0	0	0
2018-2019	3	0	3	0	0	1	3	2	14	0	0	0
2019-2020	0	1	1	1	3	0	2	2	7	0	0	0
2020-2021	4	4	3	1	0	0	0	6	8	0	0	0
2021-2022	0	3	3	2	3	1	0	0	0	0	0	0
2022-2023	2	4	4	2								

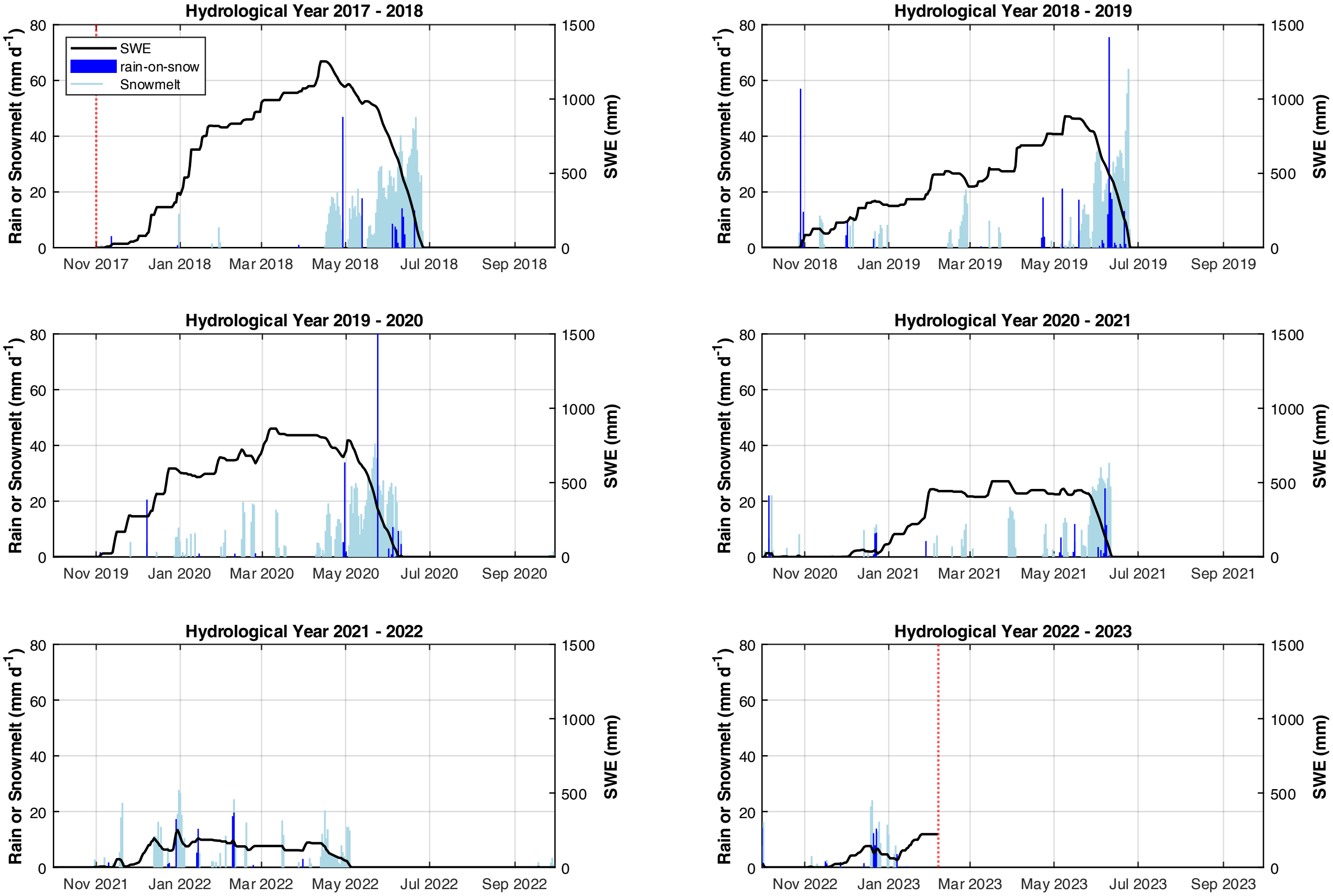

Figure 1 Daily snow water equivalent (SWE, right axis), rainfall occurring under rain-on-snow conditions (bars, left axis), and snowmelt (SM, left axis) derived from the Ceperley et al. (2020) model for each hydrological year. Rainfall is shown only for days when both rainfall and SWE are greater than zero (rain-on-snow conditions). Red dashed vertical lines indicate the start (1 November 2017) and end (6 February 2023) of the observation period.

In the revised version of the manuscript, we intend to report the previous analysis in the Supplementary Material.

L455-460: "Notably, at the end of snowmelt periods, measured volumetric water content is often slightly higher than modelled values. This discrepancy may be explained by the impact of rain-on-snow events, which are typically more intense and short-lived than melt events driven solely by temperature (Myers et al., 2023). Indeed, within the considered elevation range, approximately 26% of the total rainfall between November 2017 and February 2023 occurred under rain-on-snow conditions, that is, precipitation falling as rain while the SWE is greater than 0 (Ceperley et al., 2020)."

Will be replaced with:

LXX-YY: ***"Notably, at the end of snowmelt periods (June), measured volumetric water content is often slightly higher than simulated values. This discrepancy may be explained by the impact of rain-on-snow events. Indeed, most of these conditions (i.e., precipitation falling as rain while the SWE is greater than 0) occur in June (Table S1, Figure S1). During these events, the Ceperley et al. (2020) model simulates melt fluxes (Figure S1). However, the magnitude of snowmelt is likely underestimated, as rain-on-snow events are known to generate more intense and short-lived melt pulses compared to melt driven solely by temperature (Myers et al., 2023). The lack of an explicit representation of rain-on-snow processes therefore constitutes an additional limitation of the modelling approach. Nevertheless, it is worth noting that such conditions account for only 5.6% of the total study period, mainly occurring at the end of the melting season."***

How do you consider lateral transfers? In steep slope contexts, infiltration upstream can be transferred laterally at shallow depths (<60 cm) and re-emerge downslope to supply the root zone again. In these specific contexts, infiltration at the bottom of the soil column does not necessarily lead to groundwater recharge or streamflow contribution.

We thank Dr. Judith Eeckman for this pertinent comment, which allows us to better clarify the role of lateral water transfers in our study area.

- **i) Although the hillslope hosting the monitoring station has an average slope of approximately 32° (Gisolo et al., 2022), the instruments (soil moisture and matric potential probes) are installed on a small, relatively flat plateau, as described in the "Study site and datasets" section. This local topographic configuration supports the assumption that water fluxes within the monitored soil profile are predominantly vertical, and thus reasonably represented by a 1D modelling approach.**

- **ii) Independent evidence at the catchment scale suggests that vertical processes dominate over lateral transfers. In Gentile et al. (2023), the fraction of young water (water younger than 2-3 months) in the main streamflow and spring of the study area was estimated to be very low, 0.18 and 0.11, respectively. These results are consistent with findings from mountainous catchments worldwide (Jasechko et al., 2016). These authors show that steeper catchments tend to exhibit lower fractions of young streamflow, stating that "*…the reduced prevalence of young streamflow in steeper terrain suggests that steeper landscapes tend to favour deeper vertical infiltration rather than shallow lateral flow. A tendency for greater infiltration in mountainous watersheds may seem counterintuitive but is consistent with conceptual models of runoff generation and groundwater flow that suggest that topographic roughness drives long groundwater flow pathways that bypass first-order streams. Smaller young streamflow fractions in steep regions may also reflect the tendency for rock stresses in steep landscapes to fracture bedrock, enhance permeability, and promote deep infiltration*".**

iii) the comparison between the isotopic composition of the modelled bottom flux and that of spring water (Fig. 11d–e of the preprint) further supports that vertical processes dominate over lateral transfers, suggesting that snowmelt predominantly contributes to subsurface storage that feeds the spring, rather than being rapidly transferred laterally. This interpretation is consistent with isotope-based analyses presented in Gentile et al. (2023), and with global-scale findings (Jasechko, 2019), which show that event water typically represents only a minor fraction of streamflow, while discharge is largely dominated by pre-event water. These results suggest that equivalent precipitation (rainfall + snowmelt) primarily infiltrates into the subsurface, displacing pre-event water that is subsequently released to the stream. This appears to be the dominant process in the study area.

In general, we agree that infiltration occurring upslope could be redistributed laterally at shallow depths (<60 cm) and subsequently re-emerge downslope, contributing to the root zone. Indeed, we cannot entirely exclude the presence of such process. However, based on the combined topographic, hydrological, and isotopic evidence, deep vertical infiltration is the dominant process at the site. In the revised manuscript, we will explicitly include this aspect in the Discussion section.

We propose to add the following paragraph LXX-YY: *"It should be noted that, in steep slope contexts, infiltration occurring upslope could be redistributed laterally at shallow depths (<60 cm) and subsequently re-emerge downslope supplying again the root zone. In these specific contexts, infiltration at the bottom of the soil column does not necessarily lead to groundwater recharge or streamflow contribution. Accordingly, we cannot entirely exclude the presence of such process. Nevertheless, this mechanism can reasonably be considered less relevant at the study site for three main reasons.*

First, although the hillslope hosting the monitoring station has an average slope of approximately 32° (Gisolo et al., 2022), the instruments are installed on a small, relatively flat plateau. This local topographic configuration supports the assumption that water fluxes within the monitored soil profile are predominantly vertical and can thus be reasonably represented using a 1D modeling approach.

Second, independent evidence at the catchment scale suggests that vertical processes dominate over lateral transfers. In Gentile et al. (2023), the fraction of young water (i.e., water younger than 2–3 months) in both streamflow and spring water was estimated to be low (0.18 and 0.11, respectively). These values are consistent with findings from mountainous catchments worldwide (Jasechko et al., 2016), suggesting that, although seemingly counterintuitive, steeper catchments tend to favour deeper vertical infiltration rather than shallow lateral flow.

Third, the comparison between the isotopic composition of the modeled bottom flux and that of spring water (Figure 11 d–e) further supports the dominance of vertical processes over lateral transfers. This interpretation is consistent with isotope-based conceptualizations presented in Gentile et al. (2023) and with global-scale findings (Jasechko et al., 2019),

which show that event water generally represents only a minor fraction of streamflow, while discharge is largely dominated by pre-event water. These results suggest that equivalent precipitation (rainfall + snowmelt) primarily infiltrates into the subsurface, displacing pre-event water that is subsequently released to the stream. This appears to be the dominant process in the study area.”

2 Minor remarks

l. 99 “In Swiss catchment”: please provide references and/or describe which catchments.

We thank Dr. Judith Eeckman for this comment. The relevant references will be added in the revised manuscript. L99-100: “In Swiss catchments, for example, SOI in streamflow ($\mathrm{SOI_Q}$) was found to be ≈ 0, reflecting that streams are sustained by nearly equal fractions of summer and winter precipitation.”

Will be replaced with:

LXX-YY: ***“For example, in Swiss catchments having at least 4 years of streamwater isotope measurements previously analyzed by Seeger and Weiler*** **(2014)*****, von Freyberg et al. (2018) and Bovier et al., (2025), SOI in streamflow ($\mathrm{SOI_Q}$) was found to be ≈ 0 (Allen et al., 2019), reflecting that streams are sustained by nearly equal fractions of summer and winter precipitation.”***

Figure 1: how is the AET presented in this figure calculated?

We thank Dr. Judith Eeckman for this comment. Actual evapotranspiration (AET) shown in Figure 1 is derived from eddy-covariance measurements. This will be clearly specified the figure caption of the revised manuscript.

l. 245: do you have a reference for this thermal lapse rate in the region?

We thank Dr. Judith Eeckman for this comment. The thermal lapse rate was not taken from literature but was directly estimated from observational data. Specifically, it was calculated using air temperature records from our meteorological station together with data from additional stations managed by the Functional Centre of the Aosta Valley Region, all located within the same valley (Valsavarenche Valley). Overall, the used stations cover an elevation range from 1651 to 2555 m a.s.l.. This is described in the “Snow accumulation and melt model” section. However, we will add a relevant reference regarding local site effects previously discussed in Eeckman et al. (2022).

l. 310: eq. 2.7, 2.8: please provide references for these equations.

We thank Dr. Judith Eeckman for this comment. We will report the reference in the revised manuscript.

L307: "$ET_{P,HSM}$ is then partitioned into potential evaporation (E_P) and potential transpiration (T_P) using the following expressions:"

Will be replaced with:

LXX-YY: "*$ET_{P,HSM}$ is then partitioned into potential evaporation (E_P) and potential transpiration (T_P) using Beer's law that partitions the solar radiation component of the energy budget via interception by the canopy* (Ritchie, 1972) *as follows:*"

Figure 7: the measured and simulated data are not distinguishable in the figure.

We thank Dr. Judith Eeckman for this comment which is similar to a comment reported by Anonymous Referee #1. Accordingly, the visualization will be revised to enhance readability by adopting contrasting colors and adjusting line styles and widths to clearly distinguish simulated and measured data. Below we provide the proposed revised version of Figure 7:

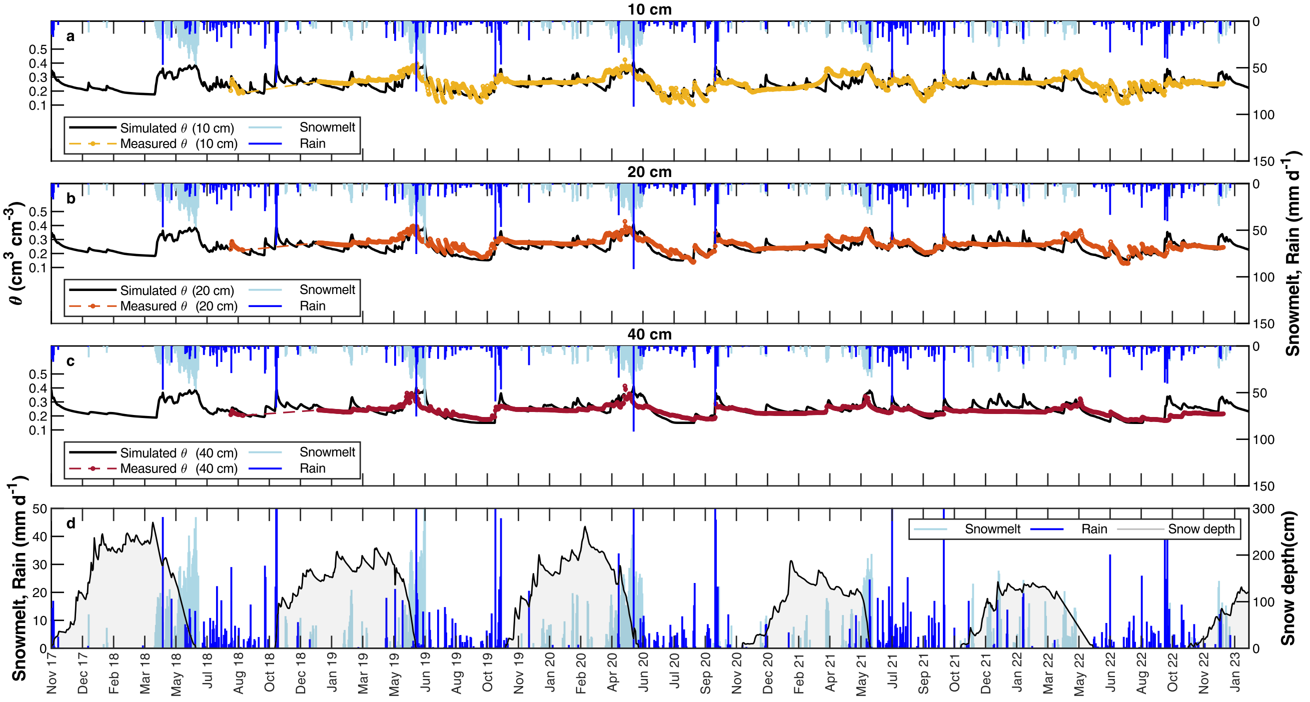

Figure 8: there are many overlapping curves. Could these be separated into multiple panels for better readability?

We thank Dr. Judith Eeckman for this comment. Below we provide the proposed revised version of Figure 8:

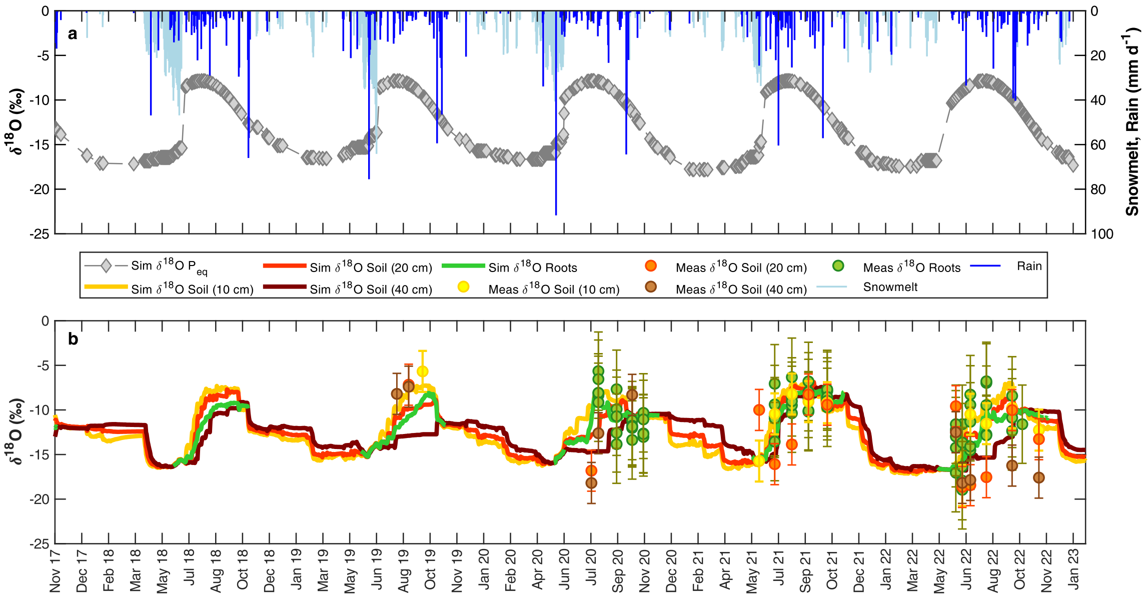

Figure 12: specify the variables simulated with HYDRUS-1D.

We thank Dr. Judith Eeckman for this comment. All the variables reported in Figure 12 have been simulated with HYDRUS-1D. We will specify this at the end of Figure 12 caption in revised manuscript.

LXX-YY: "*All the variables over time and soil depth have been simulated with HYDRUS-1D.*"

3 References

Allen, S. T., Freyberg, J. von, Weiler, M., Goldsmith, G. R., and Kirchner, J. W.: The Seasonal Origins of Streamwater in Switzerland, Geophys. Res. Lett., 46, 10425–10434, https://doi.org/https://doi.org/10.1029/2019GL084552, 2019.

Beria, H., Larsen, J. R., Ceperley, N. C., Michelon, A., Vennemann, T., and Schaefli, B.: Understanding snow hydrological processes through the lens of stable water isotopes, WIREs Water, 5, e1311, https://doi.org/10.1002/wat2.1311, 2018.

Bovier, M. C., Fedotov, S., Ferraris, S., Gentile, A., and Toaldo, B.: Stochastic model for subsurface water flow in Swiss catchments, Adv. Water Resour., 196, 104883, https://doi.org/10.1016/j.advwatres.2024.104883, 2025.

Ceperley, N., Zuecco, G., Beria, H., Carturan, L., Michelon, A., Penna, D., Larsen, J., and Schaefli, B.: Seasonal snow cover decreases young water fractions in high Alpine catchments, Hydrol. Process., 34, 4794–4813, https://doi.org/https://doi.org/10.1002/hyp.13937, 2020.

Eeckman, J., Fallot, J.-M., and Broennimann, O.: Air temperature estimation at very high resolution in mountainous areas, Dyn. Environnementales J. Int. Géosciences L'environnement, 85–97, https://doi.org/10.4000/dynenviron.6870, 2022.

Eeckman, J., De Grenus, B., Miesen, F. M., Thornton, J., Brunner, P., and Peleg, N.: Multi-instrumental monitoring of snowmelt infiltration in Vallon de Nant, Swiss Alps, Hydrol. Earth Syst. Sci., 29, 4093–4107, https://doi.org/10.5194/hess-29-4093-2025, 2025.

von Freyberg, J., Allen, S. T., Seeger, S., Weiler, M., and Kirchner, J. W.: Sensitivity of young water fractions to hydro-climatic forcing and landscape properties across 22 Swiss catchments, Hydrol. Earth Syst. Sci., 22, 3841–3861, https://doi.org/10.5194/hess-22-3841-2018, 2018.

Gentile, A., Canone, D., Ceperley, N., Gisolo, D., Previati, M., Zuecco, G., Schaefli, B., and Ferraris, S.: Towards a conceptualization of the hydrological processes behind changes of young water fraction with elevation: a focus on mountainous alpine catchments, Hydrol. Earth Syst. Sci., 27, 2301–2323, https://doi.org/10.5194/hess-27-2301-2023, 2023.

Gisolo, D., Previati, M., Bevilacqua, I., Canone, D., Boetti, M., Dematteis, N., Balocco, J., Ferrari, S., Gentile, A., Nsassila, M., Heery, B., Vereecken, H., and Ferraris, S.: A Calibration Free Radiation Driven Model for Estimating Actual Evapotranspiration of Mountain Grasslands (CLIME-MG), J. Hydrol., 610, 127948, https://doi.org/10.1016/j.jhydrol.2022.127948, 2022.

Jasechko, S.: Global Isotope Hydrogeology—Review, Rev. Geophys., 57, 835–965, https://doi.org/10.1029/2018RG000627, 2019.

Jasechko, S., Kirchner, J. W., Welker, J. M., and McDonnell, J. J.: Substantial proportion of global streamflow less than three months old, Nat. Geosci., 9, 126–129, https://doi.org/10.1038/ngeo2636, 2016.

Myers, D. T., Ficklin, D. L., and Robeson, S. M.: Hydrologic implications of projected changes in rain-on-snow melt for Great Lakes Basin watersheds, Hydrol. Earth Syst. Sci., 27, 1755–1770, https://doi.org/10.5194/hess-27-1755-2023, 2023.

Ohmura, A.: Physical Basis for the Temperature-Based Melt-Index Method, J. Appl. Meteorol. Climatol., 40, 753–761, https://doi.org/10.1175/1520-0450(2001)040%3C0753:PBFTTB%3E2.0.CO;2, 2001.

Ritchie, J. T.: Model for predicting evaporation from a row crop with incomplete cover, Water Resour. Res., 8, 1204–1213, https://doi.org/10.1029/WR008i005p01204, 1972.

Seeger, S. and Weiler, M.: Reevaluation of transit time distributions, mean transit times and their relation to catchment topography, Hydrol. Earth Syst. Sci., 18, 4751–4771, https://doi.org/10.5194/hess-18-4751-2014, 2014.

Stumpp, C., Stichler, W., Kandolf, M., and Šimůnek, J.: Effects of Land Cover and Fertilization Method on Water Flow and Solute Transport in Five Lysimeters: A Long-Term Study Using Stable Water Isotopes, Vadose Zone J., 11, https://doi.org/10.2136/vzj2011.0075, 2012.