Dear Prof. Dr. Markus Weiler,

We would like to thank you and the three reviewers for the inspiring comments, which were really helpful for improving the manuscript. Please follow our discussion regarding the reviewers' comments in this document. We provide both, a revised manuscript and a version with all changes marked. Please note that in our replies to the reviewer's comments we refer to the line numbers in the original manuscript, whereas references to changes in the revised manuscript refer to the line numbers in the manuscript version with all changes marked.

The individual replies below consist of the original reviewer´s comment, our reaction that has emerged from the on-line review *(italic),* and the actual changes and/or adjustments performed in this final manuscript to address the original comments.

Thank you

Yours sincerely

Roman Juras (on behalf of the authors)

Reply to general comments of anonymous Referee #1:

The authors describe interesting sprinkling experiment, which were performed to study rain-on-snow events. They measured both outflow volumes and isotopic signals, which was possible due to the use of Deuterium enriched sprinkling water. They found that in cold/dry snow (unfortunately only one replicate) the outflow from the snow was faster both in terms of outflow reaction and rainwater travel times. While this finding could be expected with regard to the latter (i.e. rainwater travel times), the former (i.e. slower response of the outflow in wet/warm snow) seems counterintuitive. One explanation might be the development of preferential flow pathways, but without internal measurements/observations, this remains a bit speculative.

My major concern with this study is the not fully satisfactory explanation of the processes leading to the counterintuitive findings. Here I would find some more discussion/reasoning helpful, including a detailed discussion of potential errors, which could (not) explain this (especially since there was only one sprinkling experiment on cold/dry snow).

We would like to thank the referee for his/her helpful comments. We agree that finding a faster runoff response to the onset of sprinkling for cold snow may appear counterintuitive. While some discussion was already available we have expanded the section in this regard specifically. We have also extended the discussion on differences between Ex2-4 (warm/wet snow) to address possible uncertainties. Note that we have further evidenced preferential flow paths in Ex. 1 by way of colour tracer, which we will document more clearly (Würzer et al., 2017)*. Also the quick recession of runoff after the end of sprinkling hints at the presence of preferential flow during exp. 1.*

Changes: **We expanded Section 4.2, where the generation of preferential flow is now discussed in more detail. As a consequence, this section was also renamed to "Rainwater transport within different flow regimes".**

Reply to specific comments of anonymous Referee #1:

Beyond this, my comments as listed below are rather minor:

Reading the manuscript, at some point I was confused by the four experiments and four rain pulses … Probably it was me missing something, but this could perhaps also be described clearer. The author present much of their observations in form of tables. The manuscript would become much more attractive if these results could be presented (also?) in form of figures. While there obviously is a difference in scale, it would be useful to link the isotope studies in the present study to isotope studies at the catchment scale (e.g., Rodhe,1981, Spring Flood Meltwater or Groundwater?)

We apologize if we failed to describe all four experiments as well as the respective four sprinkling periods in a clear way, obviously there was a need for improvement. We have tried to better clarify our approach while revising the manuscript. Each of the four experiments consisted of four sprinkling periods lasting 30 minutes, separated by a 30 minutes break (See Fig. 4 in the manuscript). This approach was chosen to be able to investigate the temporal progression of response times to signals in the sprinkling input as the snowpack conditions changed over the course of the experiment. Additionally, note that rainfall intensity changes on sub hourly timescales can also be observed in nature.

Changes: **We rewrote the description of the experimental procedure and better clarified the sprinkling process (Section 2.3, Lines 20-24, Page 5).**

We have further considered to present some results in form of figures and deleted one table (original Table 2) and added one figure (new Figure 4)

We have expanded our discussion on the possible implications of the study results on the catchment scale. We argue that some of the described mechanisms in the point scale have implications on the catchment scale, however processes such as overland flow or lateral flow in snow further add to the complexity of runoff generation if concerned with the catchment scale. The presented hydrograph separation technique is transferable to larger scale, if the natural rain has constant isotopic signature (McDonnell et al., 1990). But linking to respective catchment studies is certainly beneficial for the discussion which we will implement as suggested.

Changes: **We extended the discussion in Section 4.3, where the transferability of results between point scale and catchment scale is now discussed in more details. Furthermore, more relevant references were added. Please see Lines 13-21, Page 12.**

P2L33: while melting snow and rain can have (and often have) a different isotopic composition, this difference is not a 'fact'.

We agree and have therefore rewritten the sentence to read: "Due to the often different isotopic signature of rain and snow, hydrograph separation can be applied to differentiate rainwater from the melt water in the total runoff from the snowpack."

Changes: **Lines 16-17, Page 3.**

P3L3: What is meant by discrepancy here? Isn't this just the consequence of the GMWL?

The sentence is redundant and has been deleted in the revised manuscript.

Changes: **The sentence was deleted.**

P4L34: is there any evidence for these temperatures being representative?

Assuming that rain temperatures are approximately equal to air temperatures, these temperatures are comparably warm but within range of observations. Unpublished data of rain temperatures during over 1000 natural ROS events evaluated in the context of (Würzer et al., 2016a)*, shown in Fig. a demonstrate that. Note that the direct effect of rain temperature on snowmelt is very small in comparison with other energy fluxes.*

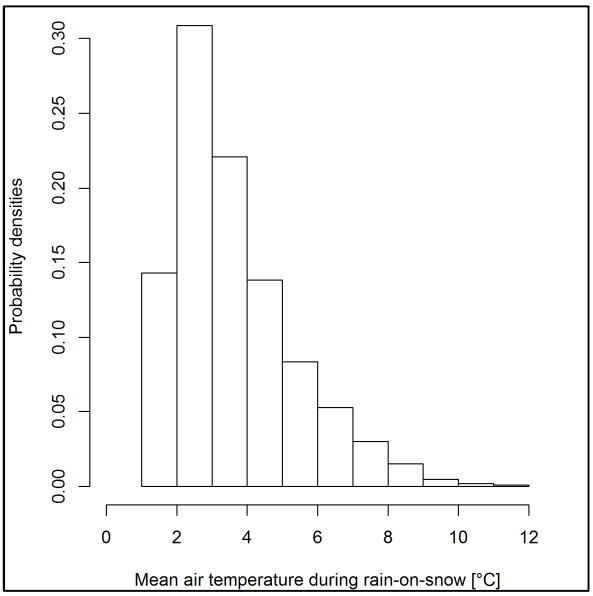

Fig. a – Representative mean air temperature during rain-on-snow events in Switzerland.

Changes: **No changes.**

Eq1: please avoid using x as multiplication sign

We now use the symbol "×" instead.

Changes: **(Updated Eq. 1.)**

P5L15: delta values are no concentrations

We agree that the delta values are deficits to the V-SMOW standard deuterium concentration and have rewritten the sentence accordingly.

Changes: **We changed the nomenclature, where only the term "deuterium signature" is used instead of terms such as "deuterium content" and "deuterium concentration" throughout the revised manuscript.**

Eq 4: where does this Eq and the tan in it come from?

Equation 4 is a newly introduced formulation and represents an assumption on how the reference isotopic signature could change due to the piston flow effect (Fig.2). The tan function governs the shape of the gradual change of the deuterium reference value. It demonstrates that the reference value change is not a step function, but more likely S curve shape or reverse S curve shape, depending on initial snowmelt and snowpack signature.

Changes: **No changes.**

P7L1: the sentence 'Unlike our expectations' sounds like discussion

This sentence has been reformulated in the revised manuscript.

Changes: **Lines 11-12, Page 8.**

P7L3: the location of ‘only’ seems strange, reformulate to clarify what is referred to by ‘only’.

The sentence has been reformulated.

Changes: **See Lines 31, Page 10.**

While I am not a native speaker myself, I feel that there is some room for improvement with regard to the English. Among other things, the (not) use of ‘the’ seems not always correct and some sentences are a bit unclear to read (e.g. P2L19). The authors are also not fully consistent with the use of the tenses, and the tense used for reporting own work sometimes jumps between past and present.

The English style and grammar has been carefully checked by a native speaker.

Changes: **(Throughout the entire manuscript)**

Reply to general comments of J. Parajka:

The manuscript presents results of four experiments investigating rain percolation through the snowpack and snow melt runoff generation during rain-on-snow events. The rain was artificially generated by sprinkling deuterium enriched water. Contribution of rain and snowmelt on runoff generation was estimated by hydrograph separation technique. The results indicate that rain sprinkling on a colder snowpack had a different water transport dynamics compared to wet isothermal snowpack. Authors conclude that internal mass exchange is an important process for snowmelt runoff generation during rain-on-snow events.

This is an interesting study and worth to publish in HESS. However I also agree with the previous reviews that the clarity of the manuscript will benefit from some revision. I would suggest to make the formulation of title-objectives-results more consistent. The rainwater propagation/contribution/interaction does not have necessarily the same meaning and interpretation. Moreover I missed some more clear formulation of the research hypothesis. What is the main research question and how it can be accepted/rejected by performed experiments. Was there such a clear question prior to the setup of the experiment? Why and how were the four sites/dates selected? The last general comment is related to the discussion part – where it can be considered to add (I missed) some lessons learned section.

We would like to thank Dr. Parajka for his helpful comment.

We have carefully reassessed the uses of terms such as “propagation”, “contribution” and “interaction”. “Propagation” is used for describing the transport process of liquid water within the snowpack. “Contribution” refers to the volume of runoff originated in rainwater or meltwater, whereas “interaction” refers to melt/refreeze and displacement processes involving rainwater, liquid water content and ice matrix. Nevertheless, we suggest a new title of the paper “Rainwater propagation through snowpack during rain-on-snow sprinkling experiments under different snow conditions”

Changes: **The terms “propagation”, “contribution” and “interaction” were revised throughout the entire manuscript. We further changed the title of the paper.**

We intentionally avoided using research hypothesis, as the number of experiments is too small to allow for significance tests needed to accept/reject hypothesis. The main research idea is formulated in P3L9 and is further detailed in three research questions P3L12-14. All questions were formulated prior to the experiments and the experiments were designed according to these questions.

Changes: **The research question Nr. 2 was reformulated. See Lines 4-5, Page 4.**

The experimental sites were selected to guarantee sufficient snow depth to conduct the experiments towards the end of snow season. Additionally, reachability/safety reasons/technical feasibility for transport of the equipment limited the choice of possible sites.

Changes: **We extended Section 4.4, where also text on the "lessons learned" has been added. See Lines 5-9, Page 13.**

Overall I like the manuscript and enjoyed to reading it. I thus suggest some minor revision.

Reply to specific comments of J. Parajka:

1) Abstract, l.14: the term "advanced hydrograph separation" is not clear here. Please consider to be more specific.

The term "advanced" addresses that the approach employed in this paper additionally accounts for temporal changes in the isotopic signature of the reference values. We now specify this in the revised manuscript.

Changes: **The term "advanced" was replaced by "alternative". The alternative hydrograph separation is described by Eq. 4.**

2) Eq.4. The form of the relationship is not clear. Some reference or more specific information would be useful.

Equation 4 is a newly presented formulation and represents an assumption on how the reference isotopic signature could change during the piston flow effect (Fig. 2 in the manuscript). The tan function governs the shape of the gradual change of the deuterium reference value. It demonstrates that the reference value change is not a step function, but more likely S curve shape or reverse S curve shape (It depends on initial snowmelt and snowpack signature.).

Changes: **No changes.**

3) Tables/Figures. Please consider to show some more main messages of the paper (presented now in Tables) in the form of figures.

We have considered to present some results in form of figures instead of tables. While we find tables to be an efficient way of presenting the type of results that originate from this study, we have deleted one table (original Table 2) and added one figure (new Figure 4).

.

Changes: Deleted table 2, new figure 4.

4) Figure 4. Please consider to make the x axis longer, to show more clearly the timing. Perhaps the layout 1 column/4rows would be better.

Thanks for this comment which we have implemented as suggested (See Fig. b).

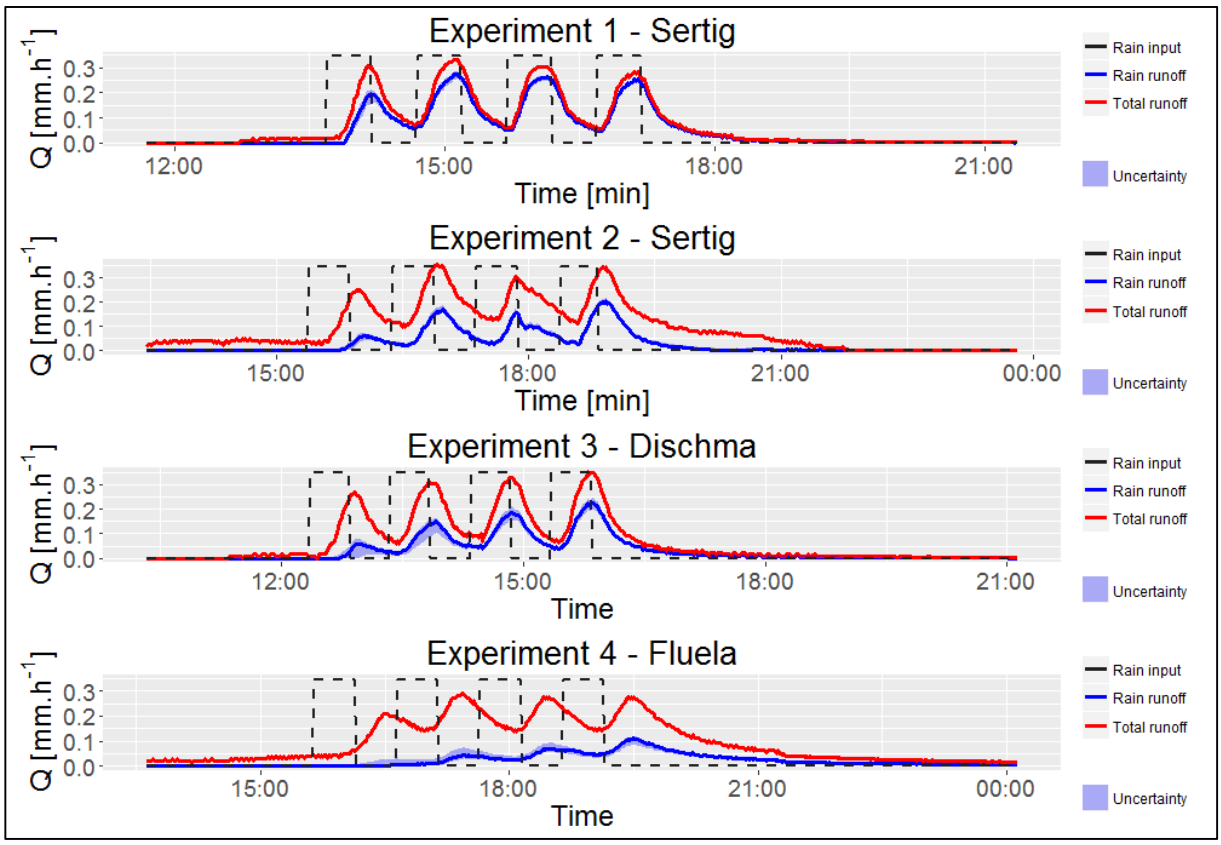

Fig. b – An updated plot of experimental runoffs.

Changes: ***New layout of*** **Figure 5 in the revised manuscript.**

Reply to general comments of J. Garvelmann:

The authors present a very interesting study about 4 sprinkling experiments with deuterium enriched water on natural snow covers with different initial conditions. The dynamics of snowpack outflow and the proportions of rainwater and melt water from the snowpack were analysed using a hydrograph separation approach based on the deuterium signatures of the sprinkled rainwater, the snow cover and the runoff from the snowpack. The results of the study provide some very interesting insights into the dynamics of water flow within the snowpack during the artificial sprinkling experiments and are therefore highly relevant for the process knowledge of runoff generation during ROS and consequently the improvement of hydrological models. The focus of the presented study is in the scope of HESS. I like the study very much. However, I recommend some revisions of the manuscript prior to a publication in HESS.

One of my main concerns about the submitted manuscript is the clear separation of experiment 1 from the other 3 experiments and the conclusions based on this one experiment having a cooler snow pack compared to the other experiments. From my point of view a snow pack described as "Snow temperature were mostly below the freezing point: : :" (page 6, lines 32 and 33) and the information from Table 3: Snow temperature -1.0°C with a standard deviation of 0.6°C cannot be called a cold snow pack. The use of the term "cool" would be probably better. The results of experiment 1 are of course distinctly different from the other experiments. However, it is just one experiment and the other three experiments show also individual behavior. A clear separation and the conclusions are therefore critical. The authors should think about focusing on the individual behavior of each experiment. This would include a more detailed discussion on the shape of the observed runoff hydrographs in Figure 4 is lacking and would improve the study considerably. Why are the peaks of experiment 1 decreasing from sprinkling period to sprinkling period, while the peaks in the other experiments tend to increase? Another point in that discussion may be the difference in the peak flows of total runoff and the rainwater fraction in total runoff. Furthermore, I highly motivate the authors to add a correlation analysis to further investigate the influences of snow pack properties (e.g. snow depth) on the observed hydrograph dynamics (e.g. lag times). This analysis would considerably improve the study and will provide further insight into the influences on different snow covers on the internal runoff generation.

The differences in total amounts of rainfall and runoff from the snowpack (page 9, lines 6 and 7 for example and Figure 5) are the reason why ROS events have the potential to generate more runoff than rainfall or snowmelt alone. Although the study in its current form is focused on the snow internal flow processes, please add a few more comments and think about extending the discussion on that aspect of the study.

There is missing a few words on the scale issue (the experiment was performed on a square meter of snow. What can be expected on a larger scale, what literature is available on the runoff generation during ROS on larger scales?) as well a few words on the effects at the edges of the sprinkled snow block. Please provide also some discussion on the snowmelt energy balance during ROS and the influences this energy (that was certainly not available during the sprinkling experiments may have on the runoff generation within the snowpack. Furthermore, there is missing at least one figure in the results section showing the deuterium signatures during the sprinkling experiments.

Finally, I recommend removing or extending the analysis discussed in section 4.4. In its current form this part is too isolated from the rest of the study. However, the results of using a traditional hydrograph separation approach with snow or snowmelt isotope signature compared to the results with the presented approach would be highly interesting. The signature of the runoff observed prior to the actual sprinkling experiments (that is clearly visible in Figure 4 for all experiments) should be used, since Taylor et al. (2001 and 2002) recommend using the melt water stable isotope signature of the snowpack for an accurate isotope based hydrograph separation.

We would like to thank Dr. Garvelmann for his detailed review. We appreciate his comments and suggestions. Please find our reply to all his comments below.

The experiments were divided according to different snow properties, at first place the snow density and further the thermal state. Ex 1 was conducted during "mid-winter" condition, whereas Ex2-4 were conducted during melting period, when the snow density was already high. These differences are also reflected in the results. We agree that referring to the first experiment as "cold" experiment may not be ideal. We suggest to use the term "non-ripe" instead, which describes the overall snow state better.

Changes: **We changed the term "cold snowpack" for "non-ripe snowpack" throughout the manuscript.**

Thanks further for the excellent suggestions for a more detailed discussion of the result, which we hope delivers better insight in the differences between the four experiments.

Changes: **We have extended the discussion on the individual experiments, see particularly sections 4.2 and 4.3.**

We did further conduct a correlation analysis of initial snowpack properties (snow height, density, LWC) and the measures of runoff response (lag time, velocity) as suggested (Fig. c). However, we are convinced that the number of experiments is not sufficient to inform such an analysis thoroughly; In particular given that one of the experiments is distinctively different from the others, the analysis will result in high but ill-founded correlations. Even if we appreciate the general idea of such an analysis, we suggest – for the above reasoning - not to present data as those exemplarily shown below.

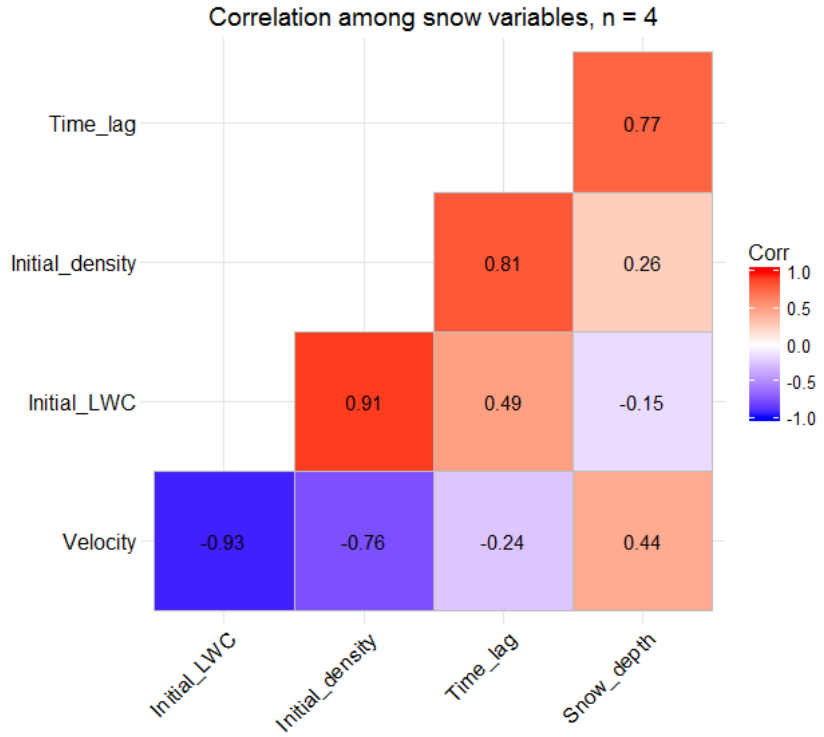

Fig. c - Correlation analysis between snow properties (Initial LWC, Initial density, Snow depth) and runoff data (Flow velocity, Time lag)

Changes: **No changes**

We have further expanded the discussion on the possible implications of the study results on the catchment scale. We argue that some of the described mechanisms in the point scale have implications on the catchment scale, however processes such as overland flow or lateral flow in snow further add to the complexity of runoff generation if concerned with the catchment scale. The presented hydrograph separation technique is transferable to larger scale, if the natural rain has constant isotopic signature (McDonnell et al., 1990). The results are now further discussed and compared with earlier studies (Dinçer et al., 1970; MacLean et al., 1995) *which have addressed runoff composition within snow covered catchments.*

Changes: **We extended Section 4.3, where the transferability between results from the point scale to the catchment scale is discussed (Lines 13-21, Page 12).**

Unfortunately the energy balance could not be meaningfully calculated because of missing short and longwave irradiation data inside the rainfall simulator. But we have prepared the plot of the deuterium signals as recommended which can be seen below in Fig. d.

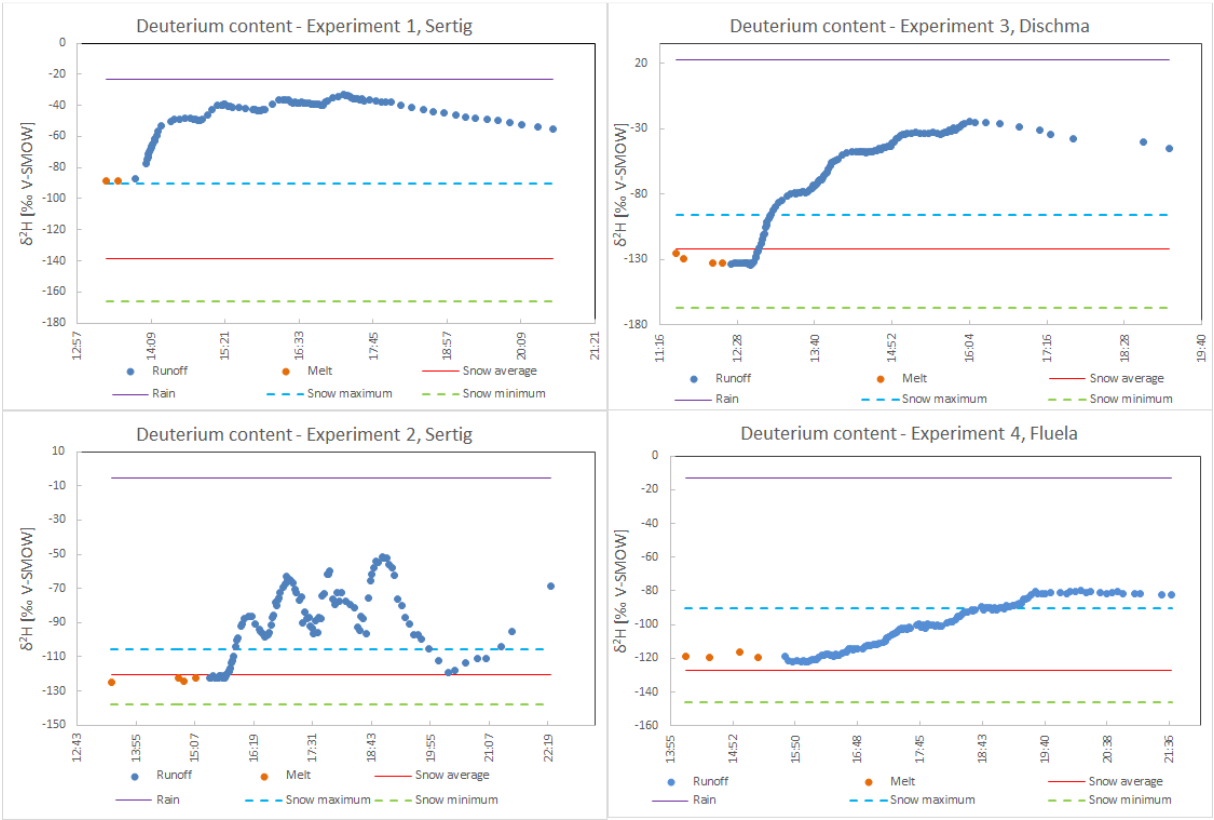

Fig. d – Suggestion of deuterium signature plot from all experiments.

Changes: **The new Figure 4 was added to the revised manuscript**

We agree that chapter 4.4 should be extended since the new approach was introduced. The main message of this chapter is that using the pre-experimental meltwater deuterium content as a reference value for Eq. 1 only entail negligible differences in time lags. But noticeable difference may

occur in the amount of rainwater in the total runoff. We have accentuated these findings in the chapter and also refer to Taylor et al., (2002) *in the context of our results summarized in Tab. 7.*

Changes: **Section 4.4 was extended and the results of the new hydrograph separation approach is now discussed in more detail. Please see Lines 5-9, Page 13.**

Reply to specific comments of J. Garvelmann:

I recommend the revision of the title of the presented study. Currently it is misleading, since the results of a number of artificial sprinkling experiments are shown and not the findings during a real ROS event.

We agree that the title could refer to the sprinkling experiments more specifically. We suggest changing the title to: "Rainwater propagation through snowpack during rain-on-snow sprinkling experiments under different snow conditions"
Changes: **The title in the revised manuscript was changed.**

In the introduction section there is missing more information about the previous modelling work (page 2, lines 9-12) as well as more details about the different flow concepts (page 2, lines 28-31).

We have revised the introduction accordingly.

Changes: **Please see Lines 7-16, Page 3.**

There is missing some important literature (page 3, lines 1-5). Taylor et al. (2001 and 2002) point out that for hydrological applications (in their case isotope based hydrograph separation too) a correct representation of the snow pack is absolutely crucial. They recommend using the melt water stable isotope signature of the snowpack for that purpose.

We have add more information and refer to corresponding studies.

Changes: **Lines 29-34, Page 3.**

From my point of view the use of "deuterium content" (page 4, line 9 for example) or "deuterium concentration" (page 4, line 30 for example) are not appropriate. Please use "deuterium signature" or "deuterium value" instead and correct throughout the whole manuscript.

Thank you for this notice. We now use the term "deuterium signature" as suggested.

Changes: **We changed the nomenclature throughout the revised manuscript.**

Please provide a few more words about the melt runoff and its isotopic signature that was recorded already before the actual experiment started (page 4, line 9).

We have added more information about the isotopic signature of pre-experimental meltwater.

Changes: Extended **information in Section 2.2 (Lines 4-5, Page 5). Specific pre-experimental signatures are further displayed in the Figure 4 in the revised manuscript.**

There are missing the information about the meteorological conditions prior and during the sprinkling experiments carried out.

A short comment about the meteorological situation during the experiment is included in the description of individual experiments.

Changes: **Extended Table 1.**

Is c-solid (page 5, line 32) the average deuterium signature of the pre-experimental snowpack? Please specify. More information about the isotope signature (page 6, line 25) of the sampled snow profile would be very helpful.

Indeed, c-solid represents the average deuterium signature of the pre-experimental snowpack. More information has been be added.

Changes: **Term "c_{solid}" was changed to "c_{snow}", which represents the deuterium signature of the snow sample, which can contain solid and liquid phase at the same time. The explanation of Eq. 4 is rewritten. Please see Line 32, Page 6.**

Why was the deuterium value of the sprinkling water +22.61 per-mille VSMOW during experiment 3?

It was important to maintain a minimum difference of 60 per-mile between sprinkling water and the solid snow. This difference was considered appropriate for a suitable rainwater separation. Setting of a maximal difference was not necessary, therefore it was not necessary to maintain identical isotopic values of the sprinkling water for all four experiments.

Changes: **No changes.**

The paragraph on page 8 on lines 8 to 14 is very confuse and hardly understandable. Please revise for more clarity.

We are sorry if this section caused any confusion. The paragraph has been revised for better reading.

Changes: **Lines 30-31, Page 9.**

Do you refer to a certain experiment or to all experiments on Page 8, line 18?

Here, we refer to all experiments. The sentence has been revised for better clarity.

Changes: **Line 3, Page 10.**

Please mention clearly that the preferential flow may be due to the rapid development of fast flow paths in the snowpack when rainwater is infiltrating for more clarity (page 9, line 10). Please provide a more comprehensive discussion on the hydrological response of the snow pack (section 4.2). Please provide more details about the Colbeck (1975) study.

Here some examples that may be relevant, among others of course, in order to improve the discussion on this aspect: Average liquid water holding capacity of 7% of an isothermal snowpack (Singh et al., 1997). Liquid water retention storage between 2% and 52% depending on snowpack conditions (Anderson, 1973). Kattelmann (1997): water outflow from 1 to 2 m snowpack between 4 and 6 hours after onset of rainfall.

Thank you for these suggestions which we considered when revising the discussion.

Changes: **The discussion was extended and more details were added. Please see Lines 35-37, Page 10.**

The description of the methods are confuse at some points. Please provide the information on the methods used in the study in a very clear way. There are mixed some results and discussion (page 7, lines 15-17 for example). I recommend a careful proofreading of the final version of the revised manuscript prior to re-submission.

We have followed the above suggestions and revised the manuscript carefully, including an English language check.

Changes: **The sentence was rewritten accordingly (Lines 29-32, Page 8), language / grammar was checked by a English native speaker (throughout the manuscript). .**

Technical notes:
Page 3, Line 23: average winter air temperature and mean annual winter precipitation for example.
The basic nomenclature has been unified.

Changes: **The sentence was rewritten (Lines 14-15, Page 4).**

Page 4, Line 30: Was the deuterium signature of snow melt water or sampled solid snow later melted in the lab prior to analysis?
All frozen samples in the plastic bottles were melted in the lab prior to the analysis.

Changes: **Additional information were added. Please see Line 7, Page 6.**

Page 5, Line 11: Date analysis would be the more adequate title of this section.
Thank you for the suggestion.

Changes: **We changed the title of Section 2.5 to "Data analysis".**

Page 6, Line 9: Please revise equation 5 (Q-rain-in).
Thank you for the notice. The subscript $Q_{rain\text{-}in}$ has been revised.

Changes: **Revised equation 5.**

Page 5, Line 19: "was" instead of "were".
We could not find any "were" in P5L19, but on P6L19. We use the plural form of the word "data" and the related plural verb form "were".

Changes: **No changes.**

Page 8, Line 20: rain water
We would prefer to keep "rainwater" as it is through the entire manuscript.

Changes: **We use only the term "rainwater" through the revised manuscript. Similarly we use term "meltwater".**

Page 8, Line 30: deficit instead of deficiency
Corrected. Thank you.

Changes: **Line 16, Page 10.**

Page 8, Line 32: ": : :rainwater contribution, however, increased …"
Done
Changes: **Line 18, Page 10.**

Page 9, Line 8: The title of section 4.2 is confused. Please revise.
We changed the title of Section 4.2 to "Rainwater transport within different flow regimes".

Changes: **Changed title of Section 4.2 (Page XXX, line YYY)**

Page 9, Line 22: Please provide some literature at this point.
Some relevant references have been added.

Changes: **The sentence was rewritten and relevant literature was added. Please see Lines 17-18, Page 11.**

Page 9, Line 29: The point at the end of the sentence is missing.
In our version of the manuscript, the punctuation is used correctly. This might be a technical problem with the pdf viewer?

Changes: **No changes.**

Page 9, Lines 31 and 32: This sentence is too vague. Be careful with statements on the energy exchange processes within the snow pack based on the results of the study. Please revise this sentence.
The sentence has be reconsidered but not changed.

Changes: ***N*****o changed.**

Page 9, Line 32: Space too large.
Done

Changes: **Line 30, Page 11.**

Page 10, Line 3: "… refrozen or stored as liquid water in the snow pack." Please revise.
The sentence has been revised.

Changes: **Line 38, Page 11.**

Page 10, Line 9: This sentence is too vague. Please revise.
The sentence has been deleted.

Changes: **sentence deleted.**

Page 10, Line 11: Please provide information about were (section) the discussion on piston flow can be found in the manuscript.
This information can be found in chapter 4.1.

Changes: **Added reference to Section 4.1 in Line 30, Page 11.**

Page 15, Table 1: Please revise the dates in table 1 (missing point, space).
The dates in table 1 have been revised.

Changes: **Revised Table 1.**

Page 15, Table 2: Is this table really needed? Please check if the content can be included to the text or added to another table.
We have decided to delete table 2.

Changes: ***(Deleted*** **Table 2).**

Page 16, Table 3: Please provide SWE of the snowpack in the table. Please provide the information of the structure analysis (grain size etc.) as mentioned in the methods section. Please revise unit of bulk density (kg*cm-3 instead of kg.cm-3). Please provide percentages to allow a better comparison of the different experiments.
We think that SWE would only provide a redundant information, because density and snow depth are already in the table. We do not have comprehensive information about the grain size from all experiments. The density unit will be corrected – (kg m^{-3}).

Changes: ***Revised*** **Units of the snow density in Table 2.**

Page 16, Table 4: Please provide units (per-mille VSMOW) in the table. Should it be different instead of difference in the header of the table? However, please revise the header text for more clarity.
The units are now provided. Also the header of the table has been revised.

Changes: **Revised Table 3.**

Page 16, Table 3 and Table 3: Please thick about combining the two tables.
This comment was probably meant to combine Tables 5 and Table 6. We think that a combination of these tables would not be beneficial for the paper, because it would contain too much information. In

the current manuscript Table 5 represents the results of hydrograph times and water velocity. On the other hand Table 6 represents results of water volumes within the hydrographs.

Changes: **No changes.**

Page 17, Table 5: ": : :events" in the table caption. The peak times (10 min) for sprinkling period 3 and 4 in experiment 3 seem to be wrong. Please check.
Done. The peak times were checked and confirmed as correct.

Changes: **Revised Table 4.**

Page 20, Figure 1: A real picture of the set-up of experiments would be nice to see.
Unfortunately, we do not have an appropriate picture of the entire set-up to add.

Changes: **No changes.**

Page 21, Figure 2: The influence of rainwater isotope signature is missing. Is this figure really relevant and needed for the study?
The Figure represents the new hydrograph separation concept. It is a graphical representation of formula 4, which we think is helpful.

Changes: **No changes.**

Rainwater propagation through snowpack during rain-on-snow sprinkling experiments under different snow conditions~~Rainwater propagation through snowpack during rain-on-snow events under different snow condition~~

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Abstract. The mechanisms of rainwater propagation and runoff generation during rain-on-snow (ROS) are still insufficiently known. Understanding ~~the behaviour~~storage and transport of liquid water ~~within the~~in natural snowpacks is crucial especially for forecasting of natural hazards such as floods and wet snow avalanches. In this study, propagation of rainwater ~~percolation~~ through snow was investigated by sprinkling experiments with deuterium enriched water ~~on snow~~ and applying an ~~advanced~~ alternative hydrograph separation technique on samples collected from the snowpack runoff. This allowed quantifying the contribution of rainwater, ~~and~~ snowmelt and initial liquid water ~~in the water~~ released from the snowpack. Four field experiments were carried out during ~~the~~ winter 2015 in the vicinity of Davos, Switzerland. ~~For this purpose, large~~ B~~b~~locks of natural snow were isolated from the surrounding snowpack to inhibit lateral exchange of water and~~. These blocks~~ were exposed to artificial rainfall using deuterium-enriched water ~~with 41 mm of deuterium enriched water~~. The experiments were composed of~~sprinkling was run in~~ four 30 minutes periods of sprinkling, separated by three 30 minutes ~~non sprinkling periods~~breaks. The snowpack runoff ~~from the snow block~~ was continuously gauged and sampled for the ~~deuterium concentration~~deuterium signature. At the onset of each experiment ~~initially present~~antecedent liquid water ~~content~~ was first pushed out by the sprinkling water. Hydrographs showed four pronounced peaks corresponding to the four sprinkling bursts. The contribution of rainwater to snowpack runoff consistently increased over the course of the experiment but never exceeded 86 %. An experiment conducted on a ~~cold~~non-ripe snowpack suggested the development of preferential flow paths that allowed rainwater to efficiently propagate through the snowpack limiting the time for mass exchange processes to take effect. On the contrary, experiments conducted on ripe isothermal snowpack showed a slower response behaviour and resulted in a total runoff volume which consisted of less than 50 % of the rain input.

Keywords: *hydrograph separation, stable isotopes, sprinkling experiment, preferential flow, flood forecasting*

1 Introduction

Rain-on-snow (ROS) events are a natural phenomenon which has been in the focus of hydrological research in the past decades, particularly because of their high potential to cause natural hazards. ROS initiated severe floods in the past in many European countries such as Germany (HND Bayern, 2011; Sui and Koehler, 2001),

Switzerland (Badoux et al., 2013; Rössler et al., 2014), Czech Republic (Čekal et al., 2011) or ~~US~~ North America (Ferguson, 2000; Kattelmann, 1997; McCabe et al., 2007; Pomeroy et al., 2016). Rainwater also affects snowpack stability which can initiate formation of wet snow avalanches (Ambach and Howorka, 1966; Baggi and Schweizer, 2008; Conway and Raymond, 1993) or trigger slushflows (Hestnes and Sandersen, 1987; Nyberg, 1989; Onesti, 1987). In addition to natural hazards, ROS events are also relevant from a geochemical point of view. Rainwater affects transport of ions (Jones et al., 1989) and solutes (Feng et al., 2001; Harrington and Bales, 1998; Lee et al., 2008; Waldner et al., 2004) through snow which affects the pH and chemical compositions of adjacent streams (Casson et al., 2014; Dozier et al., 1989; MacLean et al., 1995).

The presence of liquid water in snow fastens the metamorphism processes such as snow settling, snowpack warming (Conway and Benedict, 1994) and grain coarsening (Gude and Scherer, 1998; Tusima, 1985). These processes entail a higher hydraulic conductivity and snow permeability which lead to faster water flow (Calonne et al., 2012; Conway and Benedict, 1994). Rainwater introduced to the snowpack during ROS represents an important additional source of liquid water besides snowmelt which can contribute to the generation of snowpack runoff.

Predicting snowpack runoff for an upcoming ROS event requires the understanding of water transport processes ~~through~~ in snow. Water input from heavy rainfall ~~flows~~ typically flows faster through a snowpack than meltwater outside ~~of~~ rain periods, which is why ROS situations may entail an augmented flood risk (Singh et al., 1998). Interactions between the liquid and solid phase of water make the water flow modelling in snow more difficult compared to other porous media like soil or sand where the solid phase is ~~supposed~~ considered to be stable. ~~Existing water flow models for snow have rarely been specifically tested for ROS scenarios, nevertheless Würzer et al. (2016b) have recently introduced a new approach integrated within the SNOWPACK model (Bartelt and Lehning, 2002; Wever et al., 2015).~~

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There is still a lack of knowledge regarding how rainwater ~~is propagating~~propagates through a snowpack and in particular, ~~to generate snowpack runoff and what runoff portion can rainwater represent under various snow conditions~~how this process is affected by various snowpack properties. Previous studies have shown that water ~~can flow through~~transport in snow ~~in~~occurs in two different regimes, matrix flow and preferential flow, which are both governed by specific snow properties (Schneebeli, 1995; Waldner et al., 2004). In the matrix flow regime, snow is wetted top down uniformly with all snow being wet above the wetting front (Schneebeli, 1995; Techel et al., 2008). Preferential flow, on the other hand, is characterised by spatially heterogeneous wetting patterns with horizontally isolated wet and dry zones often referred to as flow fingers (e.g. Techel et al., 2008; Waldner et al., 2004). The area involved in preferential flow has been shown to increase with inflow intensity and to decrease with grain size~~These patterns grow with percolation intensity and grain size~~ (Hirashima et al., 2014). During dye tracer experiments in a non-ripe snowpack with temperatures below the freezing point, matrix flow was observed in the uppermost layers of the snowpack whereas preferential flow was observed in deeper

layers only (Würzer et al., 2016b, Techel et al., 2008). Various approaches of water flow transport in snowpack~~Concepts of water flow behaviour in snowpack~~ were further investigated which~~in various approaches~~ included~~ing~~ rainfall simulation (Conway and Benedict, 1994; Eiriksson et al., 2013; Juras et al., 2013; Singh et al., 1997), artificial wetting (Avanzi et al., 2015; Katsushima et al., 2013; Yamaguchi et al., 2010) or numerical modelling (Hirashima et al., 2010, 2014, Wever et al., 2014a, 2015).

Water transport was first quantitatively described by a gravity drainage water transport model for isothermal, homogeneous snow (Colbeck, 1972). Later, Illangasekare et al. (1990) introduced a 2-D model describing water transport in subfreezing and layered snow including capillary forces. With the implementation of the full Richard's equation (RE) described by Wever et al. (2014b), the influence of capillary forces on the water flow was finally represented in an operationally used 1-D SNOWPACK model. A multi-dimensional water transport model, which allows for the explicit simulation of preferential flowpaths has been introduced by (Hirashima et al., 2014). Since multi-dimensional models are computationally intensive and lack the description of processes such as snow metamorphism and snow settling, they have not yet been shown to be suitable for hydrological or operational purposes. Recently, a new dual domain approach of modelling water transport considering preferential flow was implemented in the 1-D SNOWPACK model (Wever et al., 2016; Würzer et al., 2017).

Due to the common different isotopic signature of rain and snow, hydrograph separation can be applied to differentiate rainwater from the meltwater in the total runoff from the snowpack.~~The fact that rain and melting snow feature a different isotopic content can be used to differentiate between both components in the snowpack runoff analogically to hydrograph separation, which~~ This is a widely used technique especially in watershed hydrology (Buttle et al., 1995; Dinçer et al., 1970; Unnikrishna et al., 2002). Snowpack usually features a heterogeneous vertical isotope composition (Lee et al., 2010; Zhou et al., 2008) which is partially homogenized over the course of the winter season by a combination of moisture exchange, meltwater presence and rain infiltration (Krouse et al., 1977; Unnikrishna et al., 2002). Isotopically lighter meltwater is produced at the beginning of snowmelt and becomes heavier as melt progresses. This change is augmented by isotopic enrichment of the meltwater through the late spring rainfalls (Unnikrishna et al., 2002). Several authors (Feng et al., 2002; Hashimoto et al., 2002; Unnikrishna et al., 2002) reported a typical difference of $\delta^{18}O$ ~~around~~ of approximately 2‰ between solid snow and liquid water in snow which is mostly caused by the isotopic fractionation. Taylor et al. (2002) pointed out that a systematic error can occur if the isotopic signature of the snowpack is used instead of snowmelt for hydrograph separation purposes. ~~Feng et al. (2002) reported that a difference of 1 ‰ in $\delta^{18}O$ is equivalent of 8 ‰ change in $\delta^{2}H$.~~ Nevertheless the study considered only daily time resolution when fractionation between ice and liquid water plays an important role. Studies estimating uncertainties of hydrograph separation within sub-hourly or hourly time resolution, which is typical for ROS events, are, to the best of the author's knowledge, unavailable. ~~Although this discrepancy can lead to some uncertainties in hydrograph separation, only little work has addressed the effects of the time variant isotopic content of the non-rain water.~~

Juras et al. (2016) demonstrated in a feasibility study that they could quantify the contribution of rainwater in snowpack runoff during a sprinkling experiment using hydrograph separation techniques. However, their experiment was conducted with very high sprinkling intensities well beyond typical rain intensities. In this paper, we extend their study to investigate the propagation of liquid water through snowpack under conditions

representative of natural ROS events and for different types of snowpack. Our data analysis ~~allows answering~~answers the following questions:

1. How much does ~~rain water~~ rainwater contribute to the total snowpack runoff during ROS?
2. ~~What is the interaction between rain and ripe or cold snowpack?~~Is there evidence of mass transfer processes between rainwater and ripe or non-ripe snow?
3. How do initial snowpack conditions of ~~cold~~non-ripe and ripe snow influence liquid water transport in snow?

In addition, we present a new approach to deal with isotopic differences within the initial snowpack, and test it against standard procedures.

2 Material and methods

2.1 Study site

Four sprinkling experiments were carried out in the vicinity of Davos, Switzerland. The ~~E~~elevation of the experimental sites ranged between 1850 and 2150 m a. s. l. Details of all sites and experiments are summarised in T~~t~~able 1. All sites were located in open flat terrain. The winter season 2014/2015 was characterized by lower snow cover height and higher mean air temperature compared to the long term averages ~~below average snowcover and above average mean air temperatures~~. Davos climate has a subalpine character with mean air winter temperature of -2.18°C and cumulative winter precipitation of 371 mm (Nov - Apr).

[Table 1]

2.2 Experimental procedure

Four ROS experiments were conducted in this study. During each experiment, deuterium enriched water was sprinkled on an isolated block of snow, consisting of natural and undisturbed snow of 1m² surface area. Each experiment was conducted within three subsequent days: The first day, an experimental snow block of natural snow was prepared. To inhibit lateral exchange of water the snow block was carefully cut out and isolated from adjacent snow using 4 sheets of Ethafoam® of 2cm thickness. A metal tray was pushed through the bottom section of the snow block ~~in~~at a slight angle enabling ~~to collect~~the collection of liquid water from the lowest corner. The tray featured a rim of 5cm height on three of the four sides. The outlet channel was then attached to the fourth side, but only after the tray had been pushed through the snow block. The outlet was connected to a tipping bucket gauge, which also served to sample water for the laboratory analysis. The rainfall simulator was then placed above the snow block with a wind protection cover (Fig. 1) rolled up to ensure ambient thermal conditions. ~~Even if mechanical and thermal disturbances were kept to a minimum the setup was allowed to settle over night before sprinkling experiments commenced the next day.~~

[Figure 1]

During the second day, the actual sprinkling onto the snow block was performed. Pre-experimental snow properties were measured in undisturbed snow within a few meters from the experiment at the time that the

sprinkling started. ~~We~~ The authors recorded vertical profiles of snow temperature, liquid water content (LWC), grain size and density. LWC was measured using a "Denoth meter" (Denoth, 1994). In addition snow samples were taken to analyse the δ^2H content. Snowpack runoff was recorded from two hours before the first sprinkling burst till five hours after the last sprinkling burst. The meltwater, preceding the sprinkling, was sampled to investigate how its mean isotopic signature differs from the isotopic signature of the entire snowpack. The snowpack runoff was further sampled for δ^2H content during the entire experiment. The sampling interval varied according to the snowpack runoff rate, ranging from one minute during the peak flow to 20 minutes during periods with marginal flow only. During the sprinkling, the wind protection cover was put in place to enable spatially homogenous sprinkling results. The cover was shortly opened during the non-rain period to prevent the possible accumulation of warm air. On D~~d~~ay 3, approximately 20 hours after the last sprinkling burst, post-experimental snow properties were measured analogously to ~~day~~ Day 2, with the exception that the sampling was conducted within the snow block that was sprinkled. Again, snow samples were taken to determine how much sprinkling water remained in the snowpack.

2.3 Rainfall simulation and monitoring

An enhanced version of the rainfall simulator described in Juras et al. (2013, 2016) was designed to achieve rain intensities close to observations during natural ROS (Osterhuber, 1999; Rössler et al., 2014; Würzer et al., 2016a). The new device was equipped by a ~~nozzle~~ Lechler 460.368.30.CA nozzle which was precisely calibrated in the laboratory and again on site. The nozzle was placed 160 cm above the snow cover ensuring a spatially uniform rainwater distribution for the inner $1m^2$ of the sprinkling area, i.e. over the snow block.

Each of the four experiments consisted of four sprinkling periods lasting 30 minutes, separated by a 30 minute break (See Fig. 4). During each experiment, 41 mm of deuterium enriched water was sprinkled on the isolated snowpack resulting in a mean rainfall intensity of 10.25 mm per hour and 20.5 mm per burst, respectively. This approach was chosen to be able to investigate the temporal progression of response times to signals in the sprinkling input as the snowpack conditions changed over the course of the experiment. ~~During each experiment about 41 mm of deuterium enriched water was sprinkled in four sprinkling periods of 30 min each, separated by 30 min non sprinkling periods, resulting in a mean rainfall intensity of 10.25 mm per hour, per burst respectively.~~

The ~~deuterium content~~deuterium signature is expressed as a difference relative to the Vienna Standard Mean Ocean Water (V-SMOW). For the purposes of an efficient hydrograph separation, tap water was enriched with deuterium to reach a difference of at least δ^2H = 60 ‰ V-SMOW between the snowpack and the sprinkling water. The ~~S~~sprinkling water deuterium ~~concentration~~ signature ranged between δ^2H –23.11 to +22.61 ‰ V-SMOW and the initial snowmelt ~~deuterium concentration~~deuterium signature ranged between δ^2H –132.47 to -88.64 ‰ V-SMOW. The barrels containing the enriched sprinkling water were buried into snow to cool down the water temperature. The mean ~~rain water~~ rainwater temperature after pumping varied between 4.3 – 7.5°C (measured over the snow), which is considered representative of temperatures during natural rain on snow events in the area.

2.4 Sampling and laboratory analysis

Water samples collected during the experiments were stored in 10 or 20 ml plastic bottles. To minimize isotopic fractionation, air gaps in the samples were avoided and samples were subsequently frozen until the laboratory analysis. Snow samples were taken along three vertical profiles at 10 cm spacing before and after each experiment. Additionally, three samples of the entire snow profile were taken at the same time. All snow samples were melted at room temperature, filled into 10 ml plastic bottles and frozen until the laboratory analysis. The frozen samples were then melted in the laboratory prior to the analysis.

The analysis were carried out using a laser spectroscopy by LGR Inc. LWIA v2 facility of the Czech Technical University in Prague (Penna et al., 2010). The ~~S~~standard deviation of the results is δ^2H 0.58 ‰ V-SMOW and the 95 % confidence interval is δ^2H 0.33 ‰ V-SMOW.

2.5 Data ~~interpretation~~analysis

The hydrograph separation technique was used to separate rainwater from the non-rain water in the total runoff:

$$Q_{total}(t) \times c_{total}(t) = Q_{rain}(t) \times c_{rain} + Q_{non-rain}(t) \times c_{non-rain}(t) \quad (1)$$

$$Q_{total}(t) = Q_{rain}(t) + Q_{non-rain}(t), \quad (2)$$

where Q [mm·min^{-1}] is the flow rate, c [‰ δ^2H in V-SMOW] is the ~~deuterium concentration~~deuterium signature and the subscripts *total*, *rain* and *non-rain* represent the total gauged snowpack runoff, the rainwater runoff and water originating~~originates~~ from pre-experimental LWC and snowmelt respectively.

The non-rain water was considered as a mixture of two components pre-event liquid water content in the snowpack (pre-LWC) and the additional ~~snowmelt water~~meltwater within the experimental snow block:

$$Q_{non-rain} = Q_{melt} + Q_{pre-LWC}. \quad (3)$$

Q_{melt} represents additional ~~melt water~~ meltwater produced during the experiment and $Q_{pre\text{-}LWC}$ represents pre-experimental liquid water content in the snowpack. Since the isotopic ~~content~~ signature of the snowpack varies within the vertical profile, ~~we~~ the authors assume that the reference value of non-rain water is not constant, but time variant. According to previous investigations (Juras et al., 2016), rainwater appears ~~in the~~as snowpack runoff only after a certain delay. ~~We~~ It can therefore be assumed that at the beginning of runoff the non-rain water ~~consisted~~ consists mostly of pre-LWC water ($Q_{pre\text{-}LWC}$). After some time contribution of pre-LWC retreats and additional ~~melt water~~ meltwater (Q_{melt}) ~~starts~~ begins to dominate within the non-rain runoff water volume. This water originating instantly from the solid phase has different isotopic ~~content~~ signature compared to pre-LWC (Feng, 2002; Hashimoto et al., 2002; Unnikrishna et al., 2002). As a result, the authors introduce a new approach to non-rain water isotopic signature calculation. The partitioning of the non-rain water in the snowpack ($c_{non\text{-}rain}$ in ~~eq.~~ Eq. 1) can be expressed as:

$$c_{non-rain} = \tan^{-1}\left(\frac{\frac{(T-t)\cdot 20\pi}{S}}{\pi} + 0.5\right) \cdot (c_{~~solid~~snow} - c_{melt}) + c_{melt}, \quad (4)$$

where T is the time vector, t [min] is the time hypothetically needed to release all pre-LWC water, S is a dimensionless parameter governing the shape of the curve, $c_{snow~~solid~~}$ is the mean ~~deuterium content~~deuterium signature of ~~solid phase~~snow samples from ~~of~~ the entire pre-experimental snowpack, and c_{melt} is the ~~deuterium~~

~~content~~deuterium signature of pre-experimental meltwater. Parameter *t* was derived as the time when the volume of non-rain water equalled pre-LWC (Fig. 2). The temporal smoothing parameter S was set to ~~an arbitrary~~ a value of 45 and values of parameter *t* were set individually for each experiment as follows: Ex. 1= 20 min, Ex. 2 = 95 min, Ex. 3 = 88 min, Ex. 4 = 215 min. These values were chosen to best match the times estimated for the given pre-LWC volume to be released from the snowpack, c.f. S~~s~~ection 4.4 for a discussion on the sensitivity of alternative approaches regarding E~~e~~q. (4). ~~All fitted parameters are listed in Table 2.~~ An illustration of the mixing curve is displayed in Fig.~~ure~~ 2.

~~Table 2~~[Figure 2]

The isotopic value of the pre-LWC non-rain water was derived from the sampling of the pre-experiment melt outflow and the isotopic value of the additional melt was derived from the sample of the entire snowpack. The isotopic value of the rainwater was derived from the sampling of the water in the barrel. In view of the short duration of the experiment, ~~we don't~~the authors do not assume any fractionation between solid and liquid phase during the sprinkling.

Rainwater storage in the snow cube was estimated as:

$$Q_{stored} = Q_{rain-in} - Q_{rain-out}. \quad (5)$$

~~We~~ The authors define the LWC deficit as the non-rain water contribution to the snowpack runoff that cannot be satisfied from the initial LWC storage. Hence, values above zero indicate the minimal snowmelt that must have occurred to provide LWC for the snowpack runoff. The LWC deficit is calculated as a cumulative deficit from the water balance as:

$$LWC_{deficit}(t) = \max\left(\sum_0^t V_{non-rain} - LWC_{init}, 0\right), \quad (6)$$

where LWC_{init} refers to initial total LWC summarised in Table ~~3~~ 2 $V_{non\text{-}rain}$ refers to the volume of non-rain water in the runoff. Hydrograph data were analysed for time lag and peak times of each hydrograph component (Fig. 3). ~~We~~ The authors define rainwater time lag as a time when rainwater runoff rate reaches 0.01 mm·h^{-1} (according to Eq. 1, 2). Total water time lag is defined as a time difference between the onset of the rain and the first significant increase of total water runoff above the base flow (consisting of melt) (Eq. 2). Peak time is defined as a time difference between the onset of the rain and the time of runoff maximum of each hydrograph component.

Uncertainties ~~of~~ in rainwater runoff contribution were estimated ~~from~~ using the spread between individual samples from the vertical snow profiles at 10 % and 90 % percentiles. The isotopic signature of the pre-experimental snowpacks vertical samples from all experiments ranged between -166.64 ‰ to -90 ‰.

[Figure 3]

3 Results

3.1 Snowpack changes

Table ~~3~~ 2 shows an overview of the pre-experimental and post-experimental snowpack conditions. The three snow blocks in Ex. 2-4 consisted of snow with similar conditions which included characteristics such as~~being~~ isothermal, well ripened with bulk densities above 400 kg·m^{-3} and ~~contained~~ containing considerable initial liquid water. These snowpack conditions are referred to in the text as "ripe snow". Pre-experimental snowpack conditions in ~~Ex1~~Ex. 1 differed from the other three. Snow temperatures were mostly below ~~the~~ freezing point and the bulk density was ~~around~~ approximately 250 kg·m^{-3}. Despite this, a small amount of pre-experimental LWC was found in the top 5 cm, where the snow temperature was around the freezing point (~~Ex1~~Ex. 1). Nevertheless, these snowpack conditions are referred to as "~~cold~~non-ripe snow".

Ripe snowpacks resulted in greater density changes compared to the density changes in the non-ripe snowpack~~Unlike our expectations, the experiments resulted in greater density changes in ripe snow compared to the changes in cold snow~~. The total bulk density increased by ~~between~~ 17 ~~and~~ to 54 kg·m^{-3} in Ex. 2-4 compared to a 4 kg·m^{-3} increase only in Ex. 1 (Table ~~3~~2)~~.~~. On the contrary, LWC increased in all experiments by very similar values of approx. 2 %.

[Table ~~3~~2]

An increased ~~deuterium content~~deuterium signature of snow, caused by the isotopically enriched sprinkling water, indicated additional storage of ~~rain water~~ rainwater. ~~Our~~ The results showed a considerable increase in ~~deuterium content~~deuterium signature (Table ~~4~~3) only for ~~ex~~Ex. 2-4 (ripe snow conditions). In comparison, ~~Ex. 1~~ Ex. 1 (~~cold~~non-ripe snow) showed a more ambiguous picture, indicating that only little rainwater volume remained in the snow after the experiment; if at all, the ~~deuterium content~~deuterium signature even decreased slightly (by -0.88 ‰). Details of the ~~deuterium content~~deuterium signature of the main components before and after the experiments are listed in Table ~~4~~3 and Fig. 4, which also complete the deuterium signature development in the runoff.

[Table 3~~4~~]

[Figure 4]

3.2 Snowpack runoff

All experiments showed a quick response in snowpack runoff within 10 min (~~Ex1~~Ex. 1) to 27 min (~~Ex4~~Ex. 4) after the start of sprinkling (Fig. ~~4~~5). However, the first significant increase of ~~deuterium content~~deuterium signature ~~(signalizing the appearance of the rainwater)~~ was detected in the runoff somewhat later. ~~which indicates that rainwater initially pushed out the pre-event LWC and only then started to contribute to the runoff with some delay.~~ Time lags and peak flow times of main hydrograph components are summarised in Table ~~5~~4. The difference between rainwater time lag and total water time lag indicates the delay with which rainwater appears in the snowpack runoff relative to other source of LWC. Interestingly, this delay was considerable in

~~experiments~~ Ex. 2-4 (at least 12 minutes), but only minor (6 minutes) in ~~experiment~~ Ex. 1 which was the only one conducted on ~~cold~~non-ripe snow.

~~Also~~ Additionally, the difference between total runoff and rain runoff demonstrate that water from other sources than rain such as pre-experimental LWC dominated snowpack runoff at the beginning of the sprinkling experiment. Again, it is ~~experiment~~ Ex. 1 that deviates from the others by featuring a higher rain contribution in the total runoff already during the first sprinkling period~~s~~ (Fig. ~~4~~5). Towards the end of the experiment (sprinkling period 4), rain contributed only 27 % in ~~Ex4~~Ex. 4 but 82 % in ~~Ex1~~Ex. 1.

The total water time lag was similar between the four sprinkling periods of each experiment, with the exception of ~~Ex1~~Ex. 1 that featured a considerably longer time lag in the first sprinkling period compared to all subsequent periods, which may hint at the development of preferential flow paths early on during the experiment.

[Figure ~~4~~5]

[Table ~~5~~4]

3.3 Water balance

All experiments showed a negative snowpack mass balance (Table ~~6~~5), which is characterized by cumulative total runoff (output) exceeding the cumulative rain input (Fig. ~~5~~6). This required that additional melt occurred during all experiments. Cumulative event runoff computed according to Eq. 1 and 2 consisted of between 22.0 % (~~Ex4~~Ex. 4) and 76.4 % (~~Ex1~~Ex. 1) of rainwater (Table ~~6~~5, Fig. ~~5~~6). The storage of rainwater was calculated according to ~~Eq.~~ Eq. 5 which revealed that, averaged over the entire experiment the snowpack retained 21.6 % (~~Ex1~~Ex. 1) to 69.6 % (~~Ex4~~Ex. 4) of the original rainwater volume. However, the rainwater storage ratio varied over the course of the experiment. After the first sprinkling period, the ratio was always highest and decreased with subsequent sprinkling periods (Table ~~6~~5), and even depleted almost completely towards the end of ~~Ex1~~Ex. 1.

[Figure 6]

The pre-LWC represented an important source of non-rain water in the snowpack runoff, especially during the first sprinkling period. The LWC deficit for each sprinkling period is shown in ~~table~~ Table ~~6~~5. For example, in ~~Ex1~~Ex. 1 only 0.9 mm of pre-LWC was available (Table ~~3~~2), but 4.1 mm of non-rain water appeared in the outflow after the first sprinkling period (Table ~~6~~5), resulting in a LWC deficit of 3.17 mm that must have been satisfied by snowmelt. In contrast, the initial snowpack in ~~Ex2~~Ex. 2 -4 contained sufficient pre-LWC to fully explain the non-rain component to the runoff from the first sprinkling period. ~~But also towards the end of these experiments some meltwater is required to explain the observed snowpack runoff.~~ On the other hand, towards the end of these experiments, some snowpack runoff must occur due to meltwater.

[Table ~~6~~5]

4 Discussion

4.1 Rainwater interaction with the snowpack

All ~~S~~samples from snowpack runoff at the beginning of ~~the~~ all sprinkling experiments revealed~~,~~ that the first water to ~~exfiltrate~~ extract from the snowpack originated from pre-LWC, and not from the rain. Only with a certain time lag did rain start to appear in the runoff samples. Obviously, rainwater introduced to the snowpack pushed existing pre-LWC water out of the snow block during the onset of the runoff generation. The ~~F~~first water samples taken from the runoff featured a similar ~~deuterium content~~deuterium signature as the pre-LWC, ~~we may thus assume~~leading to assumption that pre-LWC predominated in the non-rain water at the beginning of the experiment, but as the pre-LWC storage depleted, meltwater ~~took over~~superseded. The process where rainwater shifted the pre-LWC out of the snow matrix ~~has been~~can be described as piston flow (Feng et al., 2001; Unnikrishna et al., 2002). The piston flow effect probably played a role not only at the beginning of runoff generation, but also during the entire sprinkling experiment. Time shifts in peak flow times suggest that rainwater pushed non-rain water even beyond the initial phase, although the effect weakened over the course of the experiment (Table ~~5~~4). A similar ~~behaviour~~ process was also described in Juras et al. (2016).

Comparing the volume of retained rainwater within the first sprinkling period with the amount of released non-rain water (Table ~~6~~5) reveals that, in all experiments, the initial snowpack had a liquid water ~~deficiency~~deficit. Available pore space in the snowpack was filled after the beginning of the sprinkling, which also resulted in relatively little rainwater runoff during the first sprinkling period. The rainwater contribution, however, increased during subsequent sprinkling periods, as available storage capacity for liquid water depleted and pre-LWC water ~~exfiltrated~~was removed. During all experiments, the ratio of rainwater in the total snowpack runoff was well below 100 % at all times (Fig. ~~4~~5). This indicates that some rainwater is constantly retained in the snowpack (refrozen or as LWC) over the entire course of the sprinkling within both, ~~cold~~non-ripe ~~as well as~~and ripe snow.

Differences in the results from ~~Ex1~~Ex. 1 relative to results from the other experiments demonstrated that the contribution of rainwater to the runoff is influenced by the initial snowpack conditions. ~~Cold~~Non-ripe snowpack containing low pre-LWC volume allowed a high contribution of rainwater to the runoff (~~Ex1~~Ex. 1). On the other hand, ripe snowpack with considerable pre-LWC volume showed a stronger indication of piston flow, which resulted in mostly non-rain water to appear in early snowpack runoff. Adding rain, pre-LWC and additional melt resulted in total cumulative runoff volumes exceeding the cumulative rain input ~~on average~~ by 27 % on average for the experiment with ripe snow (~~Ex2~~Ex. 2 -4). To the contrary, runoff from the ~~cold~~non-ripe snowpack exceeded rain input ~~only~~ by only 3 %.

4.2 Rainwater transport within different flow regimes~~Hydrological response of snowpack with different snow conditions on ROS~~

~~Our~~ The results showed that rainwater was transported much faster in ~~cold~~non-ripe snow (Table ~~5~~4) which indicated the presence of preferential flow (Section 3.2). The preferential flowpaths probably developed rapidly after the rain onset due to microstructural transitions observed within the snow profile. This is supported by studies which investigated the formation of preferential flow (Hirashima et al., 2014; Katsushima et al., 2013;

Techel et al., 2008). On the other hand, experiments with ripe snow, resulted in a much slower transport of ~~rain water~~ rainwater and showed evidence of the matrix flow regime. These findings are in agreement with previous studies, ~~-~~where liquid water transport was monitored by dye tracer (Schneebeli, 1995; Würzer et al., 2017). ~~of Schneebeli (1995) and Würzer et al. (2016b), but see Colbeck (1975) who reported long time lags to be typical for rain on coldnon ripe snowpacks. Preferential flow is mostly observed in layered snow, where microstructural transitions can be found in the density profile (Hirashima et al., 2014; Techel et al., 2008).~~ The presence of capillary barriers supports water ponding and horizontal water movement (Avanzi et al., 2016), but also the generation of fast preferential flow paths (Eiriksson et al., 2013). During preferential flow, the wetting front is disaggregated into many smaller flow fingers, within which the hydraulic conductivity can be very high (Waldner et al., 2004) allowing water to be transported ~~faster~~quickly. Given the experimental procedure, the preferential flow could not be observed visually, but its presence was shown in a supplementary study using dye tracer instead of deuterium enriched water (Würzer et al., 2017).

The hydraulic conductivity is ~~-~~connected to the intrinsic permeability of snow ~~(Calonne et al., 2012) and varies with the snow grain size and density (Hirashima et al., 2014). The intrinsic permeability~~ , which increases as the snow density decreases (Calonne et al., 2012)~~, which is in agreement with our results~~. The snow in ~~Ex1~~Ex. 1 was characterized by a lower density and therefore supported the faster generation of snowpack runoff compared to ~~Ex2~~Ex. 2 ~~-Ex4~~Ex. 4. On the other hand, ripe snow typically features ~~rounded snow grains and~~ initial saturation which ~~are~~is associated with higher intrinsic permeability (Colbeck, 1972)~~hydraulic conductivities~~. ~~This opposing effect may have led to the findings of Colbeck (1975) cited above.~~ In our experiments however, the distinctly lower density of the snow in ~~Ex1~~Ex. 1 in combination with the occurrence of preferential flows seem to have prevailed other effects and caused a considerably faster transport of liquid water through the snowpack ~~if~~ when compared to the experiments in ripe snow.

~~Ex1~~Ex. 1 aside, ~~Ex2~~Ex. 2 -4 showed similar initial snowpack conditions with the exception of snow depth (Table ~~3~~2). This allowed to verify that rainwater time lags were expectedly sensitive to the transport distance. Time lags recorded during ~~Ex4~~Ex. 4 were markedly longer than those recorded during ~~Ex2~~Ex. 2 -3, which supports a positive correlation between snow depth and water transport times as also noted by Wever et al. (2014a) ~~Wever et al. (2014)~~.

4.3 Internal mass exchange

Our results provide an evidence of internal mass and energy exchange processes in the snowpack during the sprinkling experiments. Such processes represent refreezing of rainwater and generation of snowmelt (Avanzi et al., 2015; Wever et al., 2015), whereas mass has additionally been exchanged by the displacement of pre-LWC by rainwater.

After the first sprinkling period the ~~cold~~non-ripe snowpack in ~~Ex1~~Ex. 1 released more non-rain water than can be explained by available pre-experimental LWC. The corresponding LWC deficit even increases over the course of the sprinkling experiment (Table ~~6~~5). This leads to the conclusion that snowmelt must have occurred as one of the processes involved in runoff generation. Further, ~~rain water~~ rainwater retained in the snowpack at the end of the experiment was larger than the final LWC which suggests that, at the same time, some ~~rain water~~ rainwater has been refrozen or stored as a liquid water. Nevertheless, these processes may have been limited to

comparably small amounts of water since the LWC deficit, as well as the retained ~~rain water~~ rainwater volume, were relatively small compared to the runoff volume. This conclusion is also supported by the small difference between the ~~deuterium concentration~~deuterium signature of the snowpack before and after the experiment (Table ~~4~~3).

~~Ex4~~Ex. 4, to the contrary, started with sufficient LWC to explain the runoff originating from non-rain water until sprinkling period 4, even without additional snowmelt. ~~While snowmelt may or may not have happened during the entire experiment, it must at least have occurred during sprinkling period 4. But~~However, apparently pre-experimental LWC has dominated the runoff generated early on during the experiment (see discussion on piston flow regime, Section 4.1). The same applies to ~~Ex2~~Ex. 2 ~~and~~ 3, for which snowmelt was evidenced from at least sprinkling period 2 onwards. In all 3 experiments, the ~~deuterium concentration~~deuterium signature differed considerably in snow samples collected before and after the experiment. This suggests that mass exchange processes have had a larger turnover compared to ~~Ex1~~Ex. 1.

Runoff generation from the snowpack is a very important mechanism especially at the catchment scale. During rain, snow cover can either attenuate runoff formation by retaining rainwater in the snowpack, or augment runoff formation with water from snowmelt (Würzer et al., 2016a). The presence of snow can further lead to high antecedent soil moisture (Webb et al., 2015; Williams et al., 2015) and to the formation of basal ice layers (Bayard et al., 2005; Stähli et al., 2001), which can support rapid runoff formation processes like overland flow. Many of the mechanisms described in this work, although investigated at the point scale, also apply at the catchment scale. However, processes such as overland flow or lateral flow in snow further add to the complexity of runoff generation of entire catchments. The presented hydrograph separation technique is, however, transferable to larger scale, if the natural rain has a spatially constant isotopic signature (McDonnell et al., 1990).

4.4 Partitioning of non-rain water~~Using a variable non-rain water reference in eq (4)~~

The ~~deuterium concentration~~deuterium signature of pre-experimental ~~melt water~~ meltwater and samples taken from the entire snowpack profile differed within all experiments (Table ~~4~~3). This is caused when snowmelt is not produced over the entire snow profile (Ex. 1). Snowmelt prevails in the upper part of the snowpack. And indeed, the ~~deuterium concentration~~deuterium signature of pre-experimental melt in Ex. 1 was very close to values sampled from the top level of the snow profile.

~~We can~~It is expected that the pre-experimental melt (sourcing from pre-LWC) is continuously depleted and meltwater is also concurrently produced from the snowpack with a different isotopic ~~concentration~~signature. This is why ~~we~~ the authors introduced an enhanced approach of hydrograph separation between rainwater and non-rain water by allowing the non-rain water isotopic reference value to be variable in time. This method was compared to the more traditional approach (c.f. Juras et al., 2016) where a constant isotopic value is used from either pre-experimental meltwater or sampled from the entire snowpack. ~~Also~~ Furthermore, different parameters (t, S) in Eq.~~uation~~ 4 were tested. Table ~~7~~ 6 summarises ~~rain water~~ rainwater time lags, rainwater peak times and cumulative rainwater of all experiments that resulted from our sensitivity tests. While in general the differences between results from different approaches were small, notably different time lags resulted when using a constant isotopic value sampled from the entire snow column.

ParticularlyEspecially in Ex1Ex. 1 when the isotopic value from the snowpack is used, the resulting rainwater time lag of 0 is unrealistic. While differences between the approaches are minor, using a time variant non-rainwater reference value seems to be a reasonable approach to arrive at more accurate estimations of rainwater time lags and outflow volumes.

Implementing the new approach seems reasonable, especially when the isotopic signature of the pre-event liquid water and of the entire snowpack differ significantly (Taylor et al., 2002). The most notable benefit of our approach is seen in an increased accuracy of the mass balance estimates (i.e. when quantifying contributions of rainwater, melt, and antecedent liquid water in the snowpack runoff). However, with respect to time lags, using only the meltwater isotopic signature as reported in Feng et al., (2001, 2002) leads to very similar results.

Table 67

5 Conclusion

In this study we investigated liquid water transport behaviour through natural snow by means of sprinkling experiments. Using deuterated deuterium rich water enabled to determinate the movementdisentangle the fate of rain water rainwater and initial liquid water content. Furthermore, the approach provided evidence of rain water rainwater refreezing and meltwater generation to occur together over the course of the sprinkling experiments.

Interestingly, a sprinkling experiment on a coldnon-ripe snowpack resulted in markedly different water transport dynamics in comparison to experiments on melting snow. Snowpack runoff responded comparably quickly to the onset of sprinkling, and rainwater arrived in the runoff with a short delay only. The overall share of rainwater in the runoff was around 80 % indicating that internal mass exchange processes played a minor role. Data from this experiment further suggested the development of preferential flow paths that allowed rainwater to propagate increasingly efficient through the snowpack as the sprinkling continued.

On the other hand, experiments conducted on wet isothermal snowpack, showed a different behaviour. Snowpack runoff was considerably delayed relative to the onset of the sprinkling, and consisted of initial liquid water content only. Rainwater appeared in the runoff only with further delay and with a relatively low share, where the overall contribution of rainwater in the runoff did not exceed 50 %. At the same time, the total runoff volume exceeded rain input plus initial liquid water content which requires that additional water from snowmelt contributed to the runoff. Both findings demonstrate that internal mass exchange processes and the type of snowpack were important for substantially affect runoff generation during rain on a melting snowpack.

Data availability

All data are available on request.

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Table 1 - Details of the experiments

Site	Latitude	Longitude	Elevation	Label	Date	Meteo observation
Sertig 1	46.7227267N	9.8505897E	**1850 m**	~~Ex1~~Ex. 1	***17. – 19. 3. 2015***	Light rain and snow, wind , partially cloudy/sunny
Sertig 2	46.7227856N	9.8507236E	**1850 m**	~~Ex2~~Ex. 2	***22. – 24. 4. 2015***	Light wind, sunny
Dischma ~~Dürrbod~~	46.7209731N	9.9219625E	**2000 m**	~~Ex3~~Ex. 3	**29. 4. – 2. 5. 2015**	Wind and light rain, cloudy.
Flüela	46.7436736N	9.9812761E	**2150 m**	~~Ex4~~Ex. 4	**7. – 9. 5. 2015**	Sunny, very gentle wind

~~Table 2 – Parameters used in equation 4 for every single experiment.~~

~~**Experiment**~~	~~**t [min]**~~	~~**S [-]**~~
~~**Ex1**~~	~~20~~	~~45~~
~~**Ex2**~~	~~95~~	~~45~~
~~**Ex3**~~	~~88~~	~~45~~
~~**Ex4**~~	~~215~~	~~45~~

Table ~~3~~ 2 – Experimental snow block conditions before and after each experiment. Bulk density values were derived from the entire snow profile sample.

Snow properties	Pre-experiment		After-experiment		Difference
	Mean	St. Dev.	Mean	St. Dev.	
	~~Ex1~~Ex. 1 – Sertig, Snow pits 17. - 19. 3. 2015				
Bulk density [kg. ~~e~~m^{-3}]	247	4	251	8	4
Total LWC [%]	0.2	1.1	1.7	0.5	1.6
Total LWC [mm]	0.9	0.3	8.3	2.4	7.4
Snow depth [cm]	54.4	3.7	48.2	3.0	-6.2
Snow temperature [°C]	-1.0	0.6	0.0	0.0	1.0
	~~Ex2~~Ex. 2 – Sertig, Snow pits 22. - 24. 4. 2015				
Bulk density [kg. ~~e~~m^{-3}]	408	18	425	12	17
Total LWC [%]	3.7	0.1	5.3	0.7	1.6
Total LWC [mm]	11.0	0.3	13.9	1.1	2.8
Snow depth [cm]	29.7	2.2	25.8	2.1	-3.9
Snow temperature [°C]	0.0	0.0	0.0	0.0	0.0
	~~Ex3~~Ex. 3 – Dischma, Snow pits 29 .- 1. 5. 2015				
Bulk density [kg. ~~e~~m^{-3}]	403	33	457	14	54
Total LWC [%]	3.8	0.3	6.3	0.1	2.6
Total LWC [mm]	10.6	0.8	16.9	0.3	6.3
Snow depth [cm]	28.1	2.5	26.6	2.1	-1.6
Snow temperature [°C]	0.0	0.0	0.0	0.0	0.0
	~~Ex4~~Ex. 4 – Fluela, Snow pits 6.-8.5.2015				
Bulk density [kg. ~~e~~m^{-3}]	477	21	495	9	18
Total LWC [%]	3.5	0.5	5.6	0.3	2.1
Total LWC [mm]	28.7	4.3	45.8	3.7	17.1
Snow depth [cm]	88.4	2.1	81.6	2.4	-6.8
Snow temperature [°C]	0.0	0.0	0.0	0.0	0.0

Table ~~4~~ 3 – Overview of ~~deuterium concentration~~deuterium signature changes within each experiment. Reference values were used in ~~eq.~~ Eq. 1 and 4 for hydrograph separation. Snow samples were taken by extracting a vertical core from the entire snow profile.

	Pre-experimental reference value			Reference value after experiment	Difference
	Rainwater	***Melt water***	***Snow sample***	***Snow sample***	***Snow sample***
~~Ex1~~Ex. 1	-23.11	-88.64	-138.88	-139.76	-0.88
~~Ex2~~Ex. 2	-5.60	-123.49	-120.41	-116.32	4.09
~~Ex3~~Ex. 3	22.61	-132.47	-122.00	-105.84	16.16
~~Ex4~~Ex. 4	-13.16	-118.66	-127.48	-116.22	11.26

Table ~~5~~ ~~4~~ – Hydrograph analysis of different artificial rain-on-snow event~~s~~.

Sprinkling period	Time lag total [min]	Time lag rain [min]	Rainwater velocity [cm.min^{-1}]	Peak time total [min]	Peak time rain [min]
~~*Ex1*~~*Ex. 1* - ***Sertig 17. — 19. 3. 2015*** - *snow depth = 54.4 cm*					
1	10	16	3.40	27	33
2	4	4	13.60	22	27
3	4	4	13.60	20	27
4	5	5	10.88	25	25
~~*Ex2*~~*Ex. 2* - ***Sertig 22. - 24. 4. 2015*** -*snow depth = 29.7 cm*					
1	15	27	1.10	35	40
2	13	13	2.28	31	36
3	17	17	1.75	28	10
4	13	14	2.12	30	10
~~*Ex3*~~*Ex. 3* - ***Dischma 29. 4. - 1. 5. 2015*** - *snow depth = 29 cm*					
1	13	26	1.08	33	36
2	9	9	3.12	29	34
3	11	11	2.55	28	31
4	9	9	3.12	27	27
~~*Ex4*~~*Ex. 4* - ***Flüela 6. - 8. 5. 2015*** - *snow depth = 88.4 cm*					
1	27	∞*	na*	50	na*
2	27	27	3.27	47	49
3	27	27	3.27	46	53
4	32	32	2.76	47	51

***** rainwater was not recorded in response to the first sprinkling burst

Table 52 – Water balance computed from every outflow peak of the four experiments.

Sprinkling period	Input [mm]	LWC deficit [mm]	Total out [mm]	Rain out [mm]	Rain out [%]	Non-Rain out [mm]	Volume rain stored [mm]	Volume Rain Stored [%]
			~~Ex1~~Ex. 1 - Sertig 17.-19.3.2015					
1	10.39	3.17	8.14	4.04	49.65	4.10	6.35	61.10
2	10.39	5.36	11.48	9.29	80.95	2.19	1.10	10.56
3	10.39	6.87	10.52	9.01	85.62	1.51	1.38	13.31
4	10.39	9.15	12.53	10.26	81.85	2.27	0.13	1.29
Total	**41.56**		**42.67**	**32.60**	**76.40**	**10.07**	**8.96**	**21.56**
			~~Ex2~~Ex. 2 - Sertig 22.-24.4.2015					
1	10.13	0	8.98	1.76	19.63	7.22	8.37	82.60
2	10.13	4.66	14.00	5.57	39.76	8.43	4.56	45.04
3	10.13	11.55	11.49	4.60	40.04	6.89	5.53	54.59
4	10.13	24.76	20.02	6.81	34.03	13.21	3.32	32.75
Total	**40.52**		**54.49**	**18.74**	**34.40**	**35.75**	**21.78**	**53.74**
			~~Ex3~~Ex. 3 - Dischma 29.4.-1.5.2015					
1	10.39	0	7.20	1.58	21.89	5.62	8.81	84.83
2	10.39	0.25	10.44	5.14	49.21	5.30	5.25	50.55
3	10.39	4.98	11.14	6.41	57.55	4.73	3.98	38.30
4	10.39	11.55	16.22	9.64	59.46	6.58	0.75	7.17
Total	**41.56**		**45.00**	**22.77**	**50.60**	**22.23**	**14.25**	**45.21**
			~~Ex4~~Ex. 4 – Flüela 6.-8.5.2015					
1	10.39	0	4.62	0.00	0.00	4.62	10.39	100.00
2	10.39	0	12.38	1.89	15.28	10.49	8.50	81.79
3	10.39	0	12.08	3.16	26.14	8.92	7.23	69.61
4	10.39	16.13	28.40	7.60	26.75	20.80	2.79	26.87
Total	**41.56**		**57.48**	**12.65**	**22.00**	**44.83**	**28.91**	**69.57**

Table 63 – Different methods for estimation of reference non-rain water isotopic value were used in this table. 1. Constant value of a) entire snow sample, b) pre-experimental ~~melt water~~ meltwater and 2. Different parameters t, S in ~~equation~~ Equation 4, where a) parameter used from Table 2, b) modified parameter from Table 2; t = t/2, S = S, c) modified parameter from Table 2; t = 2t, S = S, d) modified parameter from Table 2; t = t, S/2 = S, e) modified parameter from Table 2; t = t, S = 2S.

	Non-rain reference isotopic source	Time lag rain [min]				Peak time rain [min]				Total rain output [min]			
		~~Ex1~~ Ex. 1	~~Ex2~~ Ex. 2	~~Ex3~~ Ex. 3	~~Ex4~~ Ex. 4	~~Ex1~~ Ex. 1	~~Ex2~~ Ex. 2	~~Ex3~~ Ex. 3	~~Ex4~~ Ex. 4	~~Ex1~~ Ex. 1	~~Ex2~~ Ex. 2	~~Ex3~~ Ex. 3	~~Ex4~~ Ex. 4
1	**a) Only snow**	0	29	31	39	30	42	38	62	34.2	18.2	21.6	16.2
	b) Only melt	16	27	26	87	33	40	36	-	28.1	19.1	23.2	12.7
2	**a) Mixing - used**	16	27	26	87	33	40	36	-	32.6	18.8	22.8	12.8
	b) Mixing - t/2	15	27	26	87	29	40	36	-	33.8	18.5	22.3	13.8
	c) Mixing - 2 t	16	27	26	87	33	40	36	-	31.4	19.1	23.2	12.8
	d) Mixing - S/2	16	27	26	87	33	40	36	-	32.5	18.8	22.8	12.8
	e) Mixing - 2 S	15	27	26	87	33	40	36	-	32.6	18.8	22.8	12.8

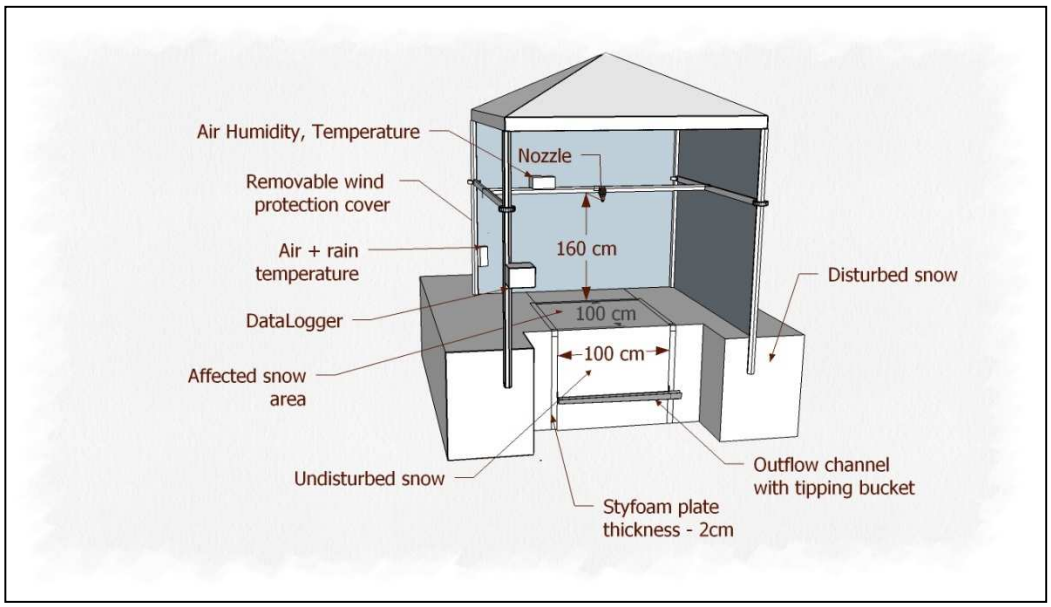

Figure 1 – Experimental setup of rainfall simulator.

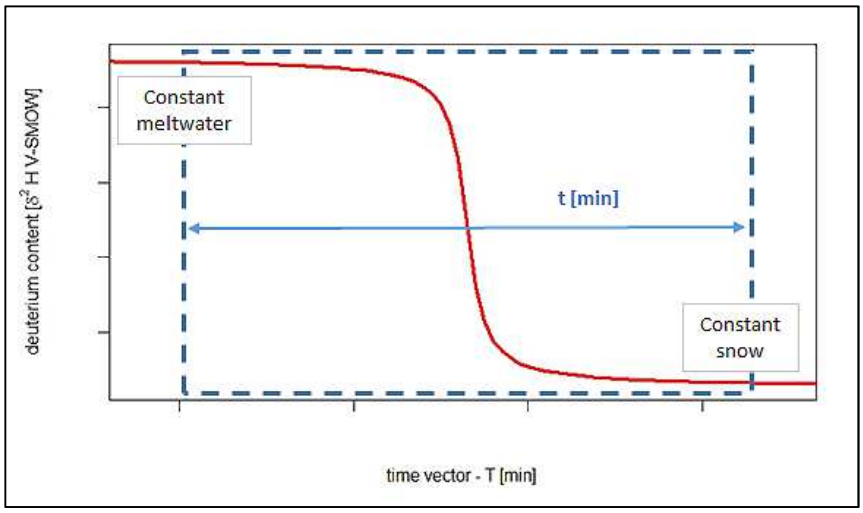

Figure 2 - Generalized mixing curve of non-rain water $c_{non\text{-}rain}(t)$ representing a transition from the ~~deuterium concentration~~deuterium signature of pre-experimental LWC to a value which is influenced by additional melt.

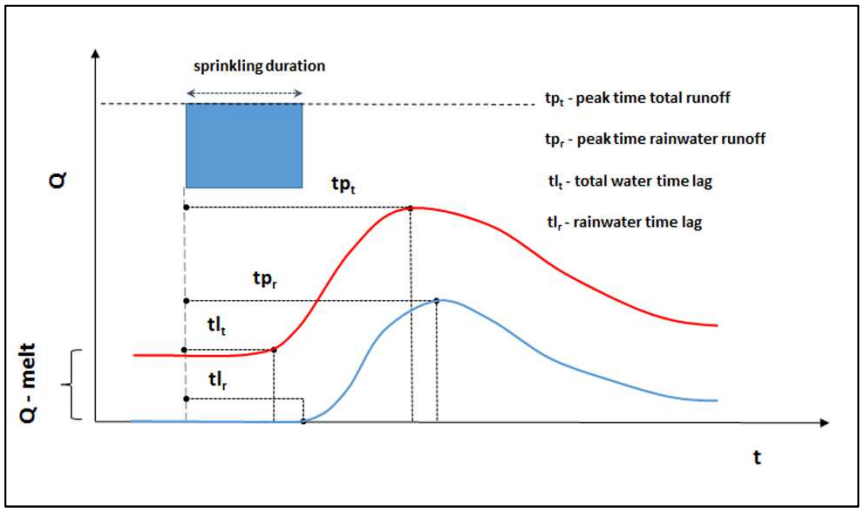

Figure 3 – Graphical definition of peak times and time lags.

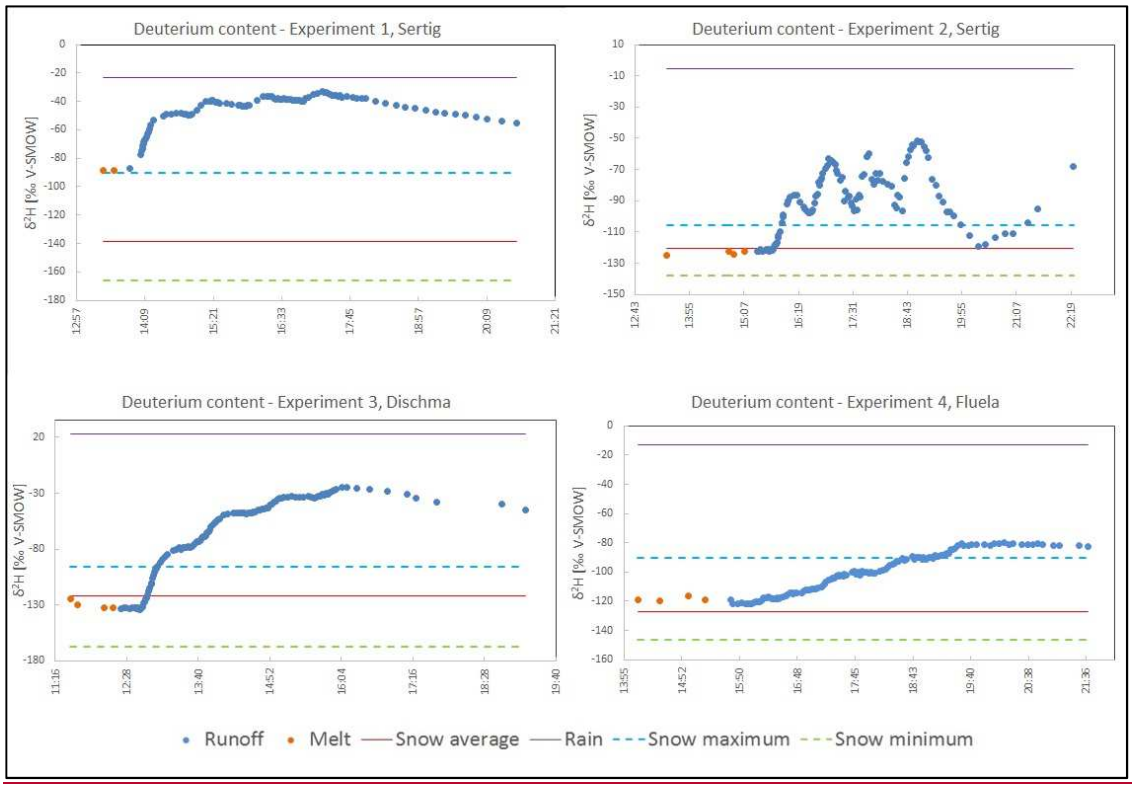

Figure 4 – Deuterium signature of the snowpack runoff during sprinkling (blue dots) or pre sprinkling meltwater (red dots). The lines represent the range (minimum and maximum) and averages of the deuterium signature derived for snow samples and the sprinkling water (Rain).

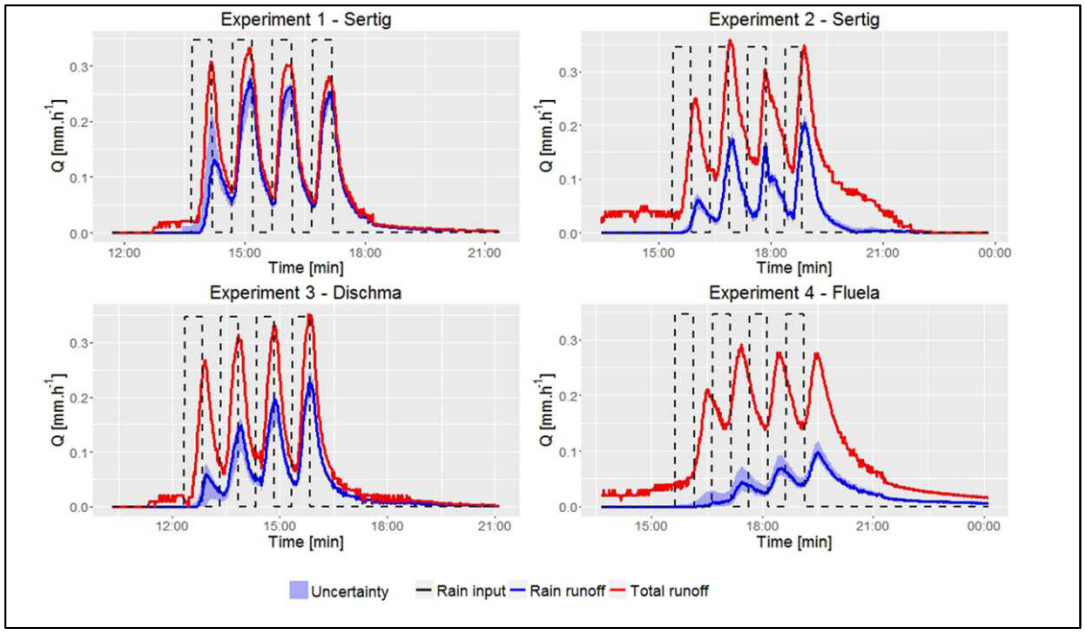

Figure 4-5 - Runoff from the experimental snow block during all artificial ROS.

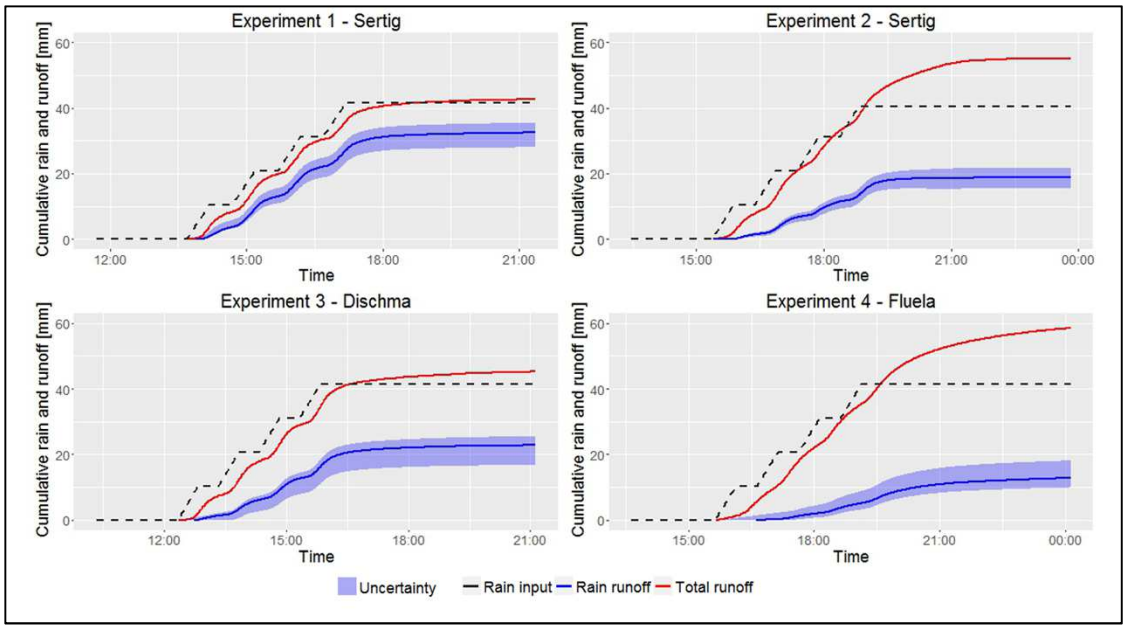

Figure 65 – Cumulative outflow from the investigated snow cube.