Observation of Spatial and Temporal Variability of Snowmelt Energy Balance Factors and Runoff Sources During Rain on Snow Events

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Introduction to Rain On Snow

Rain on snow (ROS) conditions often produce substantial floods in regions with a seasonal snow cover. Projected climate change is likely to further increase the frequency and area that such events can occur. Unfortunately, ROS floods are notoriously hard to predict due to the complexity of the processes involved and their large spatial and temporal heterogeneity. To improve the ability to simulate ROS floods, a study aimed at observing the spatial and temporal variability of the snow cover and the individual terms of the snowmelt energy balance and specifically how this variability impacts ROS floods was initiated. The study was carried out in the „Black Forest" region of southwestern Germany, a medium elevation (350 - 1500 m asl) mountain range with a temperate climate. The study used the approach of deploying numerous (up to 100) relatively low cost „Snow Monitoring Stations" measuring snow depth, surface temperature, incoming global radiation, windspeed, total precipitation, atmospheric pressure, and air temperature and - humidity. The data enables the calculation of a complete snow surface energy balance for any location.

Datum	Rainfall mm	SWE mm	% Snow
Brugga			
1	58	49	46
2	27	40	60
3	44	37	46
4	28	35	56
5	63	88	58
6	25	43	64
7	50	20	29
Breg			
8	55	20	27
9	56	63	53
10	60	25	29
11	58	66	53
Kinzig			
12	25	38	60
13	77	36	32
14	36	56	61
15	15	18	55

Table 1: Contributions of rain and snow to ROS floods

The instrument locations were chosen to cover a wide range of slopes, elevations, and expositions. Furthermore, "paired stations" located in close proximity to each other, one in the open andone underneath various forest canopies, were set up to investigate the influence of vegetation on snow dynamics. More information on the study setup and results are given in Pohl et al. (2014).

Rain on Snow Floods

For the study, a ROS flood was defined as having more than 3 mm rain, a pre-event basin wide average snow water equivalent exceeding 10 mm, and an initial snow covered area of larger than 33%. Over three winters, 15 ROS events in the three basins used as study areas were observed (Table 1). The contribution of snowmelt water to the overall runoff volume was substantial for all floods ranging from 27 to 64 %. This proves that the meltwater contribution enhanced the floods considerably, resulting in much more dangerous floods than if only precipitation water would have been able to contribute to the flooding event.

Introduction to ROS Events

Two ROS events in December of 2012 in the „Brugga" research basin were analyzed intensively. The Brugga basin has a fairly strong relief with elevations ranging from 400 to 1500 m asl. 70 % of the basin is covered by forest, 25 % are open (mostly pasture) meadows and 5 % are human settlements. The two events occurred over a relatively short time span with only six days between the events. However, the conditions prior to and during the two events were very different, making them ideal for a study on ROS runoff generation. The first ROS event (ROS 1) was preceded by a prolonged cold period that allowed a fairly substantial snow cover with a basin average SWE of 198 mm to accumulate. Thus the snow cover at the beginning of ROS 1 was fairly deep and cold. The climatic conditions were dominated by a low intensity but long lasting rainfall and temperatures just above 0°C throughout the area. These conditions led to a long lasting high runoff plateau. ROS 2 can be characterized by a warm, moist pre-event snow cover, a short but intense rainfall event and temperatures of well above 5°C. This led to a sharp increase in runoff with with a quick runoff peak and a flood level equal to a 20 year return period flood at the basin outlet. Figure 1 shows the basin average conditions during the study period.

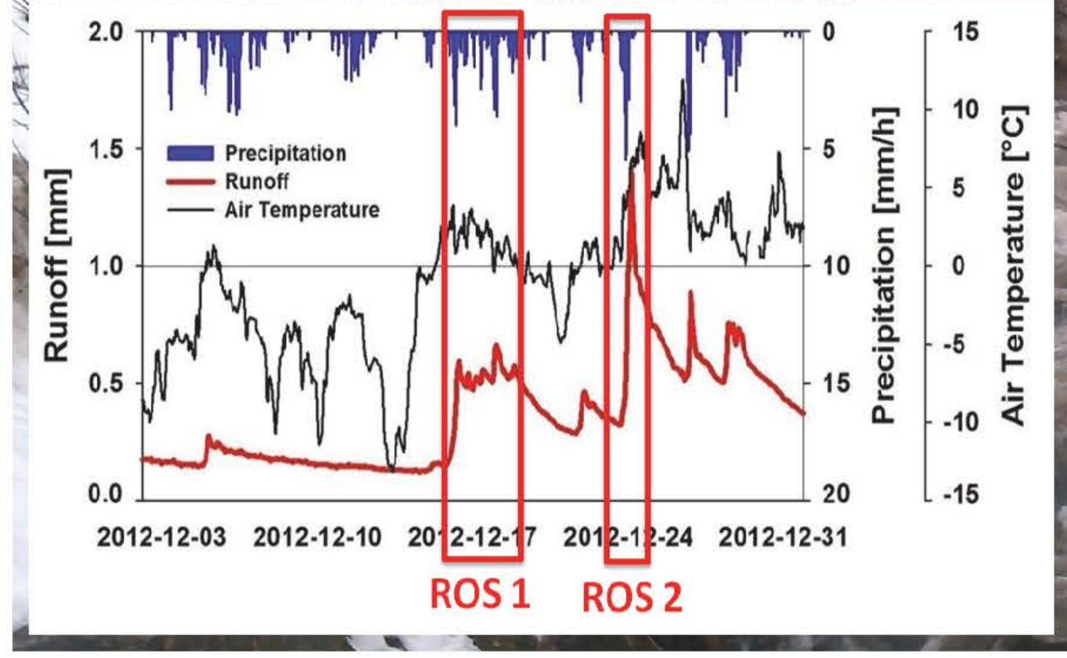

Figure 1: Basin average precipitation, air temperature and discharge in the Brugga catchment during December 2012

Where does the energy come from?

	Directly measured with SnoMoS	Additional information
SW in	Global radiation	
SW out		Albedo measured/calculated
LW in		after Satterlund (1979), additional LW under forest canopy after Essery et al. (2008)
LW out	Surface temperature	Stefan Boltzmann Equation
Sensible heat	Air temperature, Wind speed, surface temperature, air pressure	Bulk Aerodynamic Formula
Latent heat	RH, Wind speed, air temperature, surface temperature, air pressure	Bulk Aerodynamic Formula
Q_{Ground}		Constant
Q_{Rain}	Precipitation, Air temperature	

Table 2: Determination of energy balance components from SnoMoS measurements

Calculation of Snowmelt Energy Balance

The amount of energy available for snowmelt was defined by:

$$Q_{melt} = Q_{net\ SW} + Q_{net\ LW} + Q_{Sensible\ heat} + Q_{Latent\ heat} + Q_{Ground} + Q_{Rain}$$

The individual terms of the snow surface energy balance were measured or calculated from simple empirical formulae. The calculations were done on an hourly basis for all the SnoMoS locations to show the spatial variability within the study basin.

Snowmelt Energy Balance for Different Melt Conditions

Figure 2 shows hourly averages of different components of the snowmelt energy balance during ROS conditions and a clear sky spring period. The overall energy balance was consistently positive (even at nighttime) for both land covers during ROS conditions. Additionally, both land covers show fairly similar amounts of available melt energy. These conditions impact flood formation as the entire basin is continuously producing meltwater available for flood runoff. The clear sky conditions are characterized by large differences in meltrates between the two land covers and a clear diurnal cycle with open parts of the basin not producing meltwater at all during nighttime. The breakdown of the respective contributions of the individual terms of the energy balance indicates that, as expected, turbulent fluxes of sensible and latent energy drive the ROS melt energy balance while solar radiation dominates during clear sky periods. Advective energy only plays a role very early on during ROS events, when the snow cover is still cold and the falling rainwater refreezes.

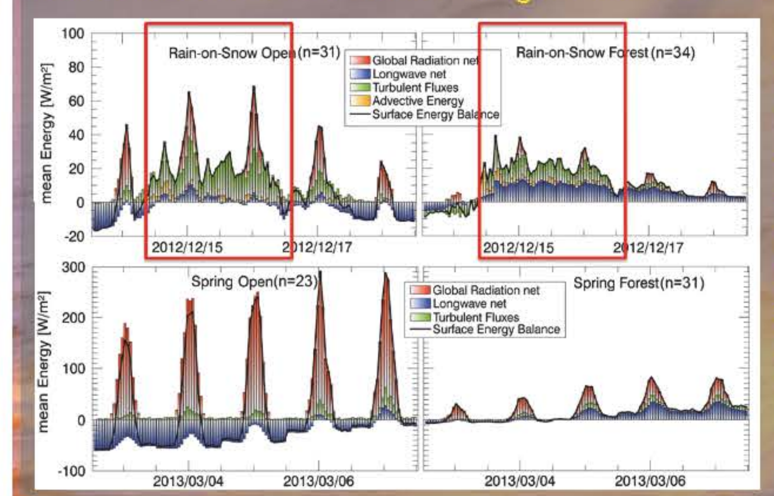

Figure 2: Average hourly meltrates of different snowmelt energy balance components for a ROS and a clear sky melt event for open and forested locations

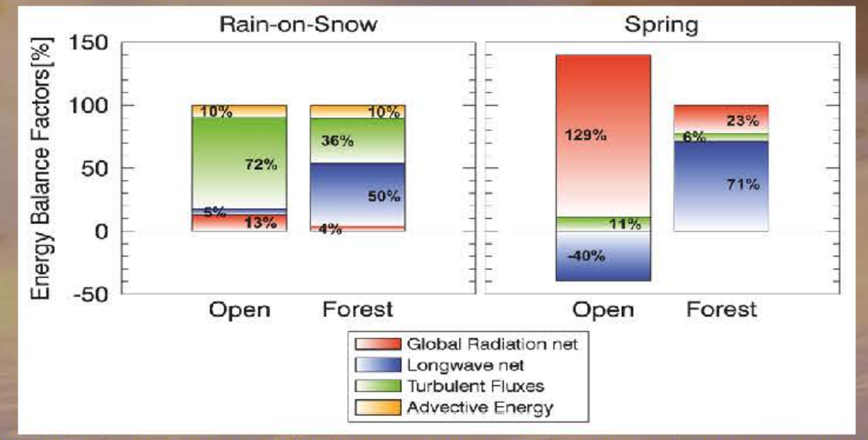

Figure 3: Average contributions of snowmelt energy balance components to overall melt for a ROS and a clear sky melt period

Spatial Variability of Energy Balance

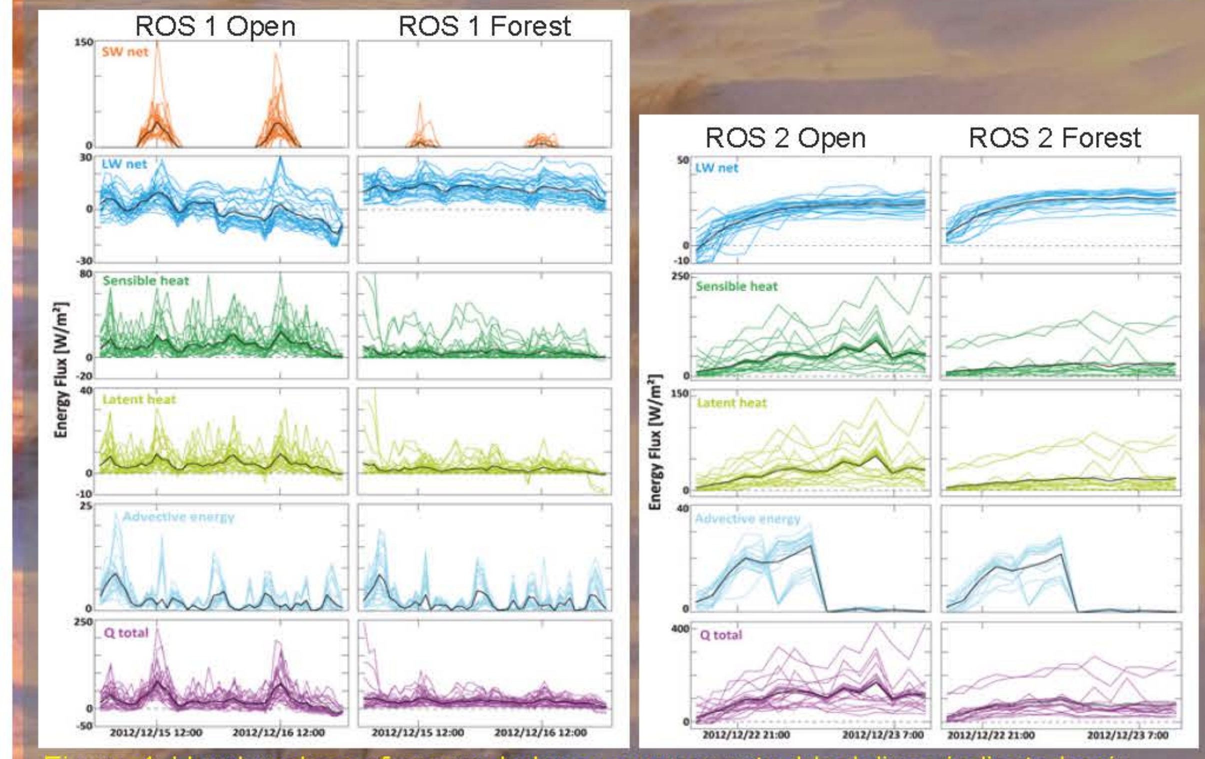

Figure 4: Hourly values of energy balance components, black lines indicate basin average (adapted from Garvelmann et al. 2014)

Figure 4 shows that short and long wave input was spatially relatively homogeneous over the basin. This can attributed to the fact that during ROS conditions overcast skies dominate, thus limiting the effect of slope and exposure on direct short wave radiation and providing a constant long wave input from the cloud cover. The most spatially variable energy terms were the turbulent fluxes of sensible and latent energy especially during the second ROS event which was characterized by high wind speeds. The strong influence of the forest vegetation on wind speed and therefore the turbulent energy fluxes becomes obvious as the turbulent fluxes underneath the forest canopy are lower than in the open areas and overall more variable with some outliers. This can be related to the vastly different forms of forest vegetation as especially open deciduous forest locations were such outliers. Similar observations were made for open locations where a few very exposed locations show much higher values of turbulent energy fluxes.

Where does the water come from?

Retention Storage of the Pre-Event Snow Cover

The retention storage of the snow cover was calculated from spatially distributed values of snow water equivalent and snow temperature. The snow prior to ROS 1 can be characterized as a fairly deep, dry snowpack. Figure 5 shows the distribution of the total retention storage of the snowpack in the study catchment. Total available retention storage before ROS 1 was between 0 mm in the lowest parts with no snow and up to 14.2 mm in the highest parts of the catchment. For ROS 2 the pre-event snow cover was relatively warm and moist at all elevations and therefore had a very low total retention storage. In fact the pre-event basin average basin retention storage of the snowpack was just 0.5 mm. This shows how important the condition of the snow cover is for the potential of a large rain on snow flooding event.

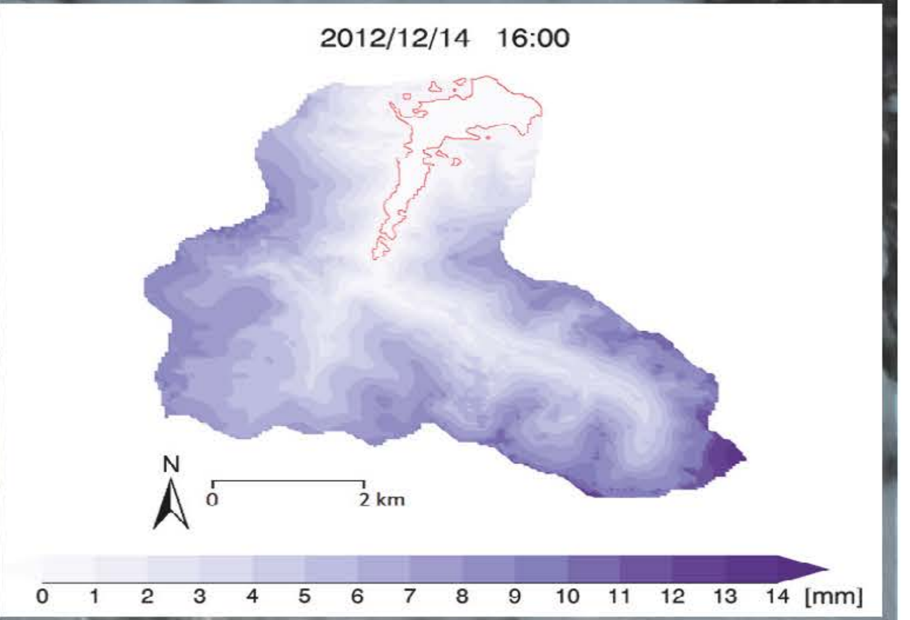

Figure 5: Spatial distribution of total retention storage prior to ROS 1

Potential Runoff Water

The total retention storage was used along with the rainfall input and snowmelt water taken from the SnoMoS observations to calculate the hourly amounts of water potentially available for runoff at the the snowpack soil surface interface. In this calculation the snowpack was considered as a variable storage system and once the total retention storage of the snowpack was reached, the excess water was considered the potential runoff. Figures 6 and 7 show that the highest amounts of potential runoff was generated in the upper areas of the catchment especially on open, south facing slopes. This can be attributed to the higher amounts of SWE present in the open, upper parts of the basin and the on average slightly warmer snow temperatures on south facing slopes prior to the event. The analysis also showed that forested areas produced less potential runoff. However, the reduction was only 10%, indicating that virtually the wholebasin area contributed significantly to runoff. The Figures also indicate that the spatial pattern of available runoff water was very similar for the two events. However, they also show that the range of potential runoff.

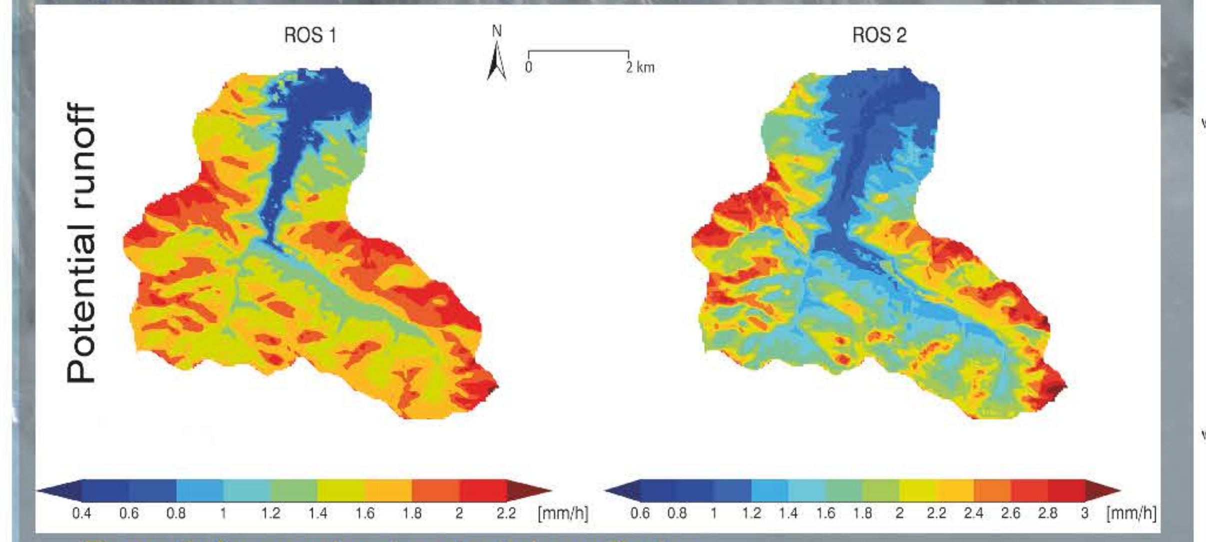

Figure 6: Average hourly potential runoff rates

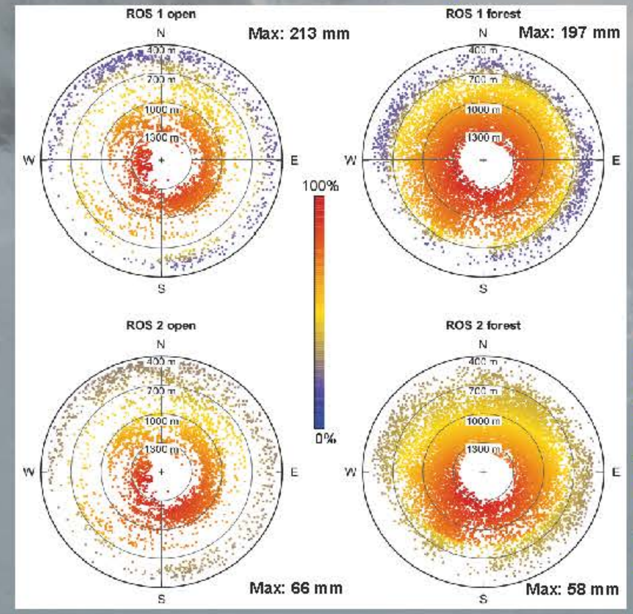

Figure 7: Average hourly potential runoff relative to the maximum

Conclusions

The observation of the temporal and spatial variability of the snowmelt energy balance factors and the runoff generating processes during rain on snow events has shown why these events often produce large flooding. The analysis of the obtained energy balance shows that the entire basin independent of land cover receives considerably continuously positive energy input that is used to melt the snow. Thus snowmelt water from the entire basin can continuously contribute to runoff. A comparison of the contributions of rain and meltwater to overall flood runoff has further revealed the great impact of the snow meltwater to flooding. The study has further shown that the initial conditions of the snow cover are absolutely crucial for the formation of a rain on snow flood. A cold deep dry snow cover may act as a buffer as it can retain large quantities of rainwater and can delay the activation of the basin considerably. On the other hand, a warm moist snow cover can accelerate the formation of a flood, as it will contribute significant amounts of snowmelt water almost immediately, thus leading to a quick rising, potentially very dangerous flooding.

Literature cited:

Garvelmann J, Pohl S, Weiler M. 2014. Variability of observed energy fluxes during rain-on-snow and clear sky snowmelt in a mid-latitude mountain environment. Journal of Hydrometeorology, DOI: 10.1175/JHM-D-13-0187.1.

Pohl S, Garvelmann J, Wawerla J, Weiler M. 2014. Potential of an innovative low cost sensor network to understand the spatial and temporal dynamics of a mountain snow cover. Water Resources Research. DOI:10.1175/JHM-D-13-0187.1.

Activation of the Basin

Runoff in the basin started at south facing slopes in the lowest elevations and proceeded upwards and to north facing slopes. Significant differences were observed as to how quickly the entire basin contributed to runoff. During ROS 1 it took 12 hours before the entire basin was contributing while it was only 1 hour during ROS 2.

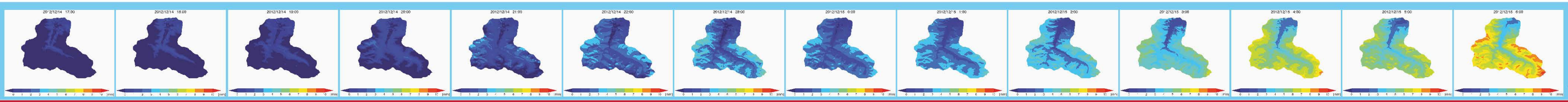

Figure 9: Hourly amounts of potential runoff

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