Rain-on-snow is the main cause of flooding in a cold maritime city

H. Ó. Andradóttir*, A.R. Arnardóttir & T. Zaqout

[1]Department of Civil and Environmental Engineering, University of Iceland, Hjarðarhagi 2-6, IS107 Reykjavík, Icleand

*Corresponding author email: hrund@hi.is

Highlights

- 80% of water related insurance claims in greater capital region of Iceland are filed in winter.
- Rain-on-snow and frozen ground generates more severe flooding than intense precipitation
- Rain-on-snow events are becoming more frequent and voluminous with climate change

Introduction

One of the sustainable development goals is that cities become more resilient to changing climate (https://sdgs.un.org). Much research has focused on the increased flood risks associated with more frequent high intensity precipitation (e.g., Kundzewicz et al., 2005; Lane, 2008). Yet, medium intensity, long-duration and high volume spring snowmelt is known to fill up entire wastewater networks and cause devastating urban damage (Bengtsson and Westerström, 1992; Valeo and Ho, 2004; Moghadas et al., 2018). Rain-on-snow events are known to generate voluminous floods that threaten infrastructure in rural catchments (Beniston and Stoffel, 2016). Moreover, the development of infiltration inhibiting frost can augment flood risk (Zaqout and Andradóttir, 2021a). The fact that winter flooding involves the co-action of two to three independent meteorological conditions with different extreme value distributions make them particularly difficult to understand and predict. The goal of this research was to assess which meteorological condition(s) pose(s) the greatest urban flood risk in cold maritime climate, characterized by frequent freeze thaw cycles; and to determine the future outlook of these conditions in the context of climate change. For this purpose, a historical data set of flood severity was compiled based on filed insurance claims within the capital region of Reykavík, Iceland. Our poster will provide a short summary of our recently published article in Hydrological Processes (Andradóttir et al. 2021).

Methodology

Data

The capital region of Iceland (220 thousand inhabitants, 64°N) is located on a peninsula by the North Atlantic Ocean. The climate is wet (1000 mm total annual precipitation), mild (5°C annual average air temperature and characterized by frequent freeze-thaw cycles in winter. Insurance claims associated with intense rainfall or snowmelt were acquired from the three largest insurance companies in Iceland, representing 88% of the market share. Historical daily weather, snow depth and soil temperature from the principal measurement station in Reykjavik were obtained from the Icelandic Meteorological Office. Auxiliary information during flooding dates were compiled from local media, and interviews with local utility operators.

Analyses

Statistics of water related insurance claims in winter (November throughout April), and summer (May through October) were calculated. Annual 24-h and 48-h block maxima of singular- and co-acting hydrological winter parameters (rain, rain during snow, snow during rain and rain-on-snow). Theoretical snowmelt was estimated based on energy available for melt (Assaf, 2007). Twelve urban flooding events were identified on the basis of number of insurance claims, representing the top 90% of events. The hydro-meteorological conditions during each event were analysed in the context of return periods of winter parameters. Indicators of flooding were assessed based on linear regression analyses. Statistical trends in temperature, precipitation, and rain-on-snow were assessed using Mann-Kendall tests. Further descriptions are provided in Andradóttir et al. (2021).

Results and discussion

Approximately 80% of water related insurance claims were filed in the six months of winter. Winter floods were more frequent, generated more claims and affected a greater number of neighbourhoods than summer floods. All but one of the twelve large flood events were associated with the passage of weather systems from the south, bringing warm (>4°C) air at high wind speeds. Only two of the large events were intense summer rainfall (Table 1). The remaining ten events all occurred in the months of November through March, involving over 20 mm of rainfall. Nine of the ten winter events were rain-on-snow that could be classified into two groups: medium intensity precipitation (2-3 year return period) that evolved from snow to rainfall on bare, frozen ground; and medium to low intensity rain on varying degree of snow (>5 cm). None of large urban flooding events were radiation driven spring snowmelt.

Table 1. Classification of large urban flood events in Greater Reykjavík in 2006-2018.

Flood event type	Nr. of events	Max. hourly precipitation [mm; return period in years]	Soil temp at 10 cm depth [°C]	Total runoff volume [rain + melt; mm]	Duration [hrs]	Nr. of insurance claims
Intense summer precipitation	2	10-13; ≥10	13-14	17-49	5-12	21-24
Rain on non-frozen ground	1	3.0; <2	4.8	30	13	10
Precipitation on frozen ground	3	4.7-6.9; 2-3	-0.1 to -1.1	20-34	7-15	9-69
Rain-on-snow	6	2.6-6.1; 1-2	0.9 to -1.6	22-76	13-25	7-51

The two strongest predictors for flood risk were frost in the top soil and the total volume of liquid available for runoff. In general, the rainfall volume was more influential in contributing to flooding. But a steady, low intensity (1-2 mm/hr) snowmelt played an important role in sustaining runoff for a longer time, and connecting two discrete rainfall events in one longer event. In particular, it was noted that the peak runoff generation occurred in the second half of the large rain-on-snow events, at which time soils would be soaked and all initial storage volumes in the catchments filled. The solid-liquid texture of the rain-on-snow also appears to be important. For example, events that evolved from snowfall to rainfall tended to generate flooding on major highways by clogging inlets. Similarly, the formation of super-saturated snow (Figure 1) after rainfall can cause fully inhibiting frost, so called concrete frost, if shortly followed by a freezing period. Lastly, winter events affected indiscriminately new and old neighbourhoods, independent of whether the wastewater collection system was combined or separate.

Figure 1. Super-saturated snow after rainfall can clog inlets and is vulnerable for generating concrete frost. (Photo: Hrund Andrdóttir, February 2019).

Trend analyses highlighted that winter air temperature were warming, snow depth was increasing, and the rain-on-snow frequency and volume were increasing. Further description of the results can be found in Andradóttir et al. (2021).

Conclusions and future work

This study concludes that rain-on-snow is the primary cause of flooding in the cold maritime city of Reykjavík. This research highlights the need for better understanding flooding generated by rain-on-snow in an urban setting. Most of the current research is based on a rural setting, focusing on deep snow (> 10 cm snow). We show, however, that the snow depth is not a strong predictor for urban runoff potential in maritime climate characterized by frequent snow and frost cycles. Rather, snowmelt aids high precipitation to generate runoff, by clogging street inlets; and by elongating runoff and connecting two shorter duration rainfall events into a longer runoff event. More focus needs to be on measuring surface cover characteristics, such as the density of the snow and surface frost, in order to better understand runoff during winter rain-on snow. Both water content and temperature near the surface is needed in order to establish if soil is porous or not (see e.g. Zaqout and Andradóttir, 2021b).

Acknowledgments

This research was funded by the Icelandic Research Fund (Icelandic: Rannís), grant number 185398-053. Data from the local insurance companies (Sjóvá, Tryggingamiðstöðin and Vátryggingafélag Íslands) and the Icelandic Meteorological Office is acknowledged.

References

Andradóttir, H.Ó., Arnardóttir, A.R. and Zaqout, T. (2021). Rain-on-snow induced urban floods in cold maritime climate: Risk, indicators and trends, Hydrological Processes, 14298

Assaf, H. (2007) Development of an energy-budget snowmelt updating model for incorporating feedback from snow course survey measurements. Journal of Engineering, Computing and Architecture, 1, 1-25.

Bengtsson, L., & Westerström, G. (1992). Urban snowmelt and runoff in northern Sweden. Hydrological Sciences Journal, 37(3), 263–275. https://doi.org/10.1080/02626669209492586

Beniston, M., & Stoffel, M. (2016). Rain-on-snow events, floods and climate change in the Alps: Events may increase with warming up to 4 °C and decrease thereafter. Science of The Total Environment, 571, 228–236. https://doi.org/10.1016/j.scitotenv.2016.07.146

Kundzewicz Z. W., Ulbrich U., Brucher T., Graczyk D., Kruger A., Leckebusch G. C., Menzel L., Pinskwar I., Radziejewski M. and Szwed M. (2005). Summer floods in central Europe - Climate change track? Natural Hazards, 36(1-2), 165-189.

Lane S. N. (2005). Climate change and the summer 2007 floods in the U.K. Geography, 93(2), 91-98.

Moghadas, S., Leonhardt, G., Marsalek, J., & Viklander, M. (2018). Modeling urban runoff from rain-on-snow events with the U.S. EPA SWMM model for current and future climate scenarios. Journal of Cold Regions Engineering, 32(1), 04017021. https://doi.org/10.1061/(ASCE)CR.1943-5495.0000147

Valeo, C., & Ho, C. L. I. (2004). Modelling urban snowmelt runoff. Journal of Hydrology, 299(3), 237–251. https://doi.org/10.1016/j.jhydrol.2004.08.007

Zaqout, T., & Andradóttir, H. Ó. (2021a). Hydrologic performance of grass swales in cold maritime climates: Impacts of frost, rain-on-snow and snow cover on flow and volume reduction. Journal of Hydrology, 597, 126159. https://doi.org/10.1016/j.jhydrol.2021.126159

Zaqout, T., & Andradóttir, H. Ó. (2021b). Infiltration capacity in grass swales during frequent freeze-thaw cycles and intermittent snowmelt in a cold maritime climate, 15th International Conference on Urban Drainage, Melbourne, October, 2021.