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Centurial changes in the augmentation of low flows by snow and glacier melt in the River Rhine

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Low flows can have severe consequences for river ecosystems, energy production, navigation and other river water uses. In the mid- and downstream reaches of the River Rhine late-summer low flows are augmented by the ice melt component from the glaciated mountain headwaters upstream. As the glaciers are retreating fast, the quantification of this augmentation has become a highly relevant question. Based on results from a long-term modelling experiment, this study explores the contributions of snow and ice melt to the River Rhine's daily streamflows in extreme low flow events since 1900 from a downstream perspective. While the glacier ice melt component only contributes a few percent to the average annual flow of the Rhine downstream of Switzerland, its contribution is much higher during drought events such as those that have caused extreme low flows in the late summers of 1921, 1947, and 2003. In these situations, over 30% of the low flow downstream of Basel was comprised of ice melt and this fraction remains rather similar further along the Rhine to the Netherlands. Despite the loss of glacier volume and area in the headwaters over the course of the 20th century, an increasingly negative mass balance appears to have compensated for the glacier retreat, resulting in little long-term change to the ice melt component in summer streamflow. However, for an extreme event such as that in 2003, the ice melt component would have contributed a third more flow if it had occurred in the early 1900s. We use the modeled long-term coupled changes in glaciers and hydrology to quantify the low flow hazard that may loom ahead as the glaciers continue to decline.