Journal of Hydrology 538 (2016) 33–48

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Evidence for changes in the magnitude and frequency of observed rainfall vs. snowmelt driven floods in Norway

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ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form 21 March 2016
Accepted 31 March 2016
Available online 8 April 2016
This manuscript was handled by Andras Bardossy, Editor-in-Chief, with the assistance of Vazken Andreassian, Associate Editor

Keywords:
Peak flow trends
Peak-over-threshold
Flood generating processes
Rainfall floods
Snowmelt floods
Climate change

SUMMARY

There is increasing evidence for recent changes in the intensity and frequency of heavy precipitation and in the number of days with snow cover in many parts of Norway. The question arises as to whether these changes are also discernable with respect to their impacts on the magnitude and frequency of flooding and on the processes producing high flows. In this study, we tested up to 211 catchments for trends in peak flow discharge series by applying the Mann–Kendall test and Poisson regression for three different time periods (1962–2012, 1972–2012, 1982–2012). Field-significance was tested using a bootstrap approach. Over threshold discharge events were classified into rainfall vs. snowmelt dominated floods, based on a simple water balance approach utilizing a nationwide 1×1 km^2 gridded data set with daily observed rainfall and simulated snowmelt data. Results suggest that trends in flood frequency are more pronounced than trends in flood magnitude and are more spatially consistent with observed changes in the hydrometeorological drivers. Increasing flood frequencies in southern and western Norway are mainly due to positive trends in the frequency of rainfall dominated events, while decreasing flood frequencies in northern Norway are mainly the result of negative trends in the frequency of snowmelt dominated floods. Negative trends in flood magnitude are found more often than positive trends, and the regional patterns of significant trends reflect differences in the flood generating processes (FGPs). The results illustrate the benefit of distinguishing FGPs rather than simply applying seasonal analyses. The results further suggest that rainfall has generally gained an increasing importance for the generation of floods in Norway, while the role of snowmelt has been decreasing and the timing of snowmelt dominated floods has become earlier.

1. Introduction

Climate change is expected to intensify the global hydrological cycle which potentially leads to a general increase in the intensity and frequency of extreme climate events. This will, in turn, have direct implications for hydrological extremes such as flooding (IPCC, 2013). However, the impacts of climate change on hydrological extremes are expected to vary across different regions due to the prevailing hydrometeorological regimes and the nature of climate change in specific regions (Burn et al., 2010). For mountainous and northern regions, where the role of snowmelt vs. rainfall is highly relevant for the seasonal flood regimes, the impacts of climate change on runoff and flooding are expected to be more severe than in other regions (Barnett et al., 2005; Viviroli et al., 2011). With respect to floods, climate change may, therefore, result in increases or decreases in the magnitude and frequency of events as a consequence of changes in the hydrometeorological processes that generate flood events. In addition to projecting likely future changes, it is crucial to understand recent changes in flooding and flood generating processes (FGPs) due to observed changes in the hydrometeorological triggers (Hall et al., 2014). This paper studies recent changes in the magnitude and frequency of floods in Norway distinguished by their dominant FGPs which helps to detect consistencies and inconsistencies with respect to observed changes in hydrometeorological drivers.

Over the last century, and particularly since the end of the 1970 s, mean precipitation has increased in the whole of Norway by about 18% (Hanssen-Bauer et al., 2015). The same study reports that the largest increase is found for autumn precipitation in southern and south-eastern Norway and for spring precipitation in western and northern Norway (each by 2–3% per decade). The smallest increases are associated with summer precipitation across the whole of Norway. According to Dyrrdal et al. (2012), there has

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http://dx.doi.org/10.1016/j.jhydrol.2016.03.066
0022-1694/

also been an increase in the intensity of heavy precipitation events over the period 1957–2010 in most parts of Norway, except in small zones within central and northern Norway. These patterns of increasing extreme precipitation refer to annual maximum 1-day precipitation and the spatial patterns become even more apparent for longer-duration precipitation (5-day, and 10-day) due to reduced spatial variability. Furthermore, the frequency of moderate and heavy precipitation has increased in most parts of the country, particularly in southern and western Norway and in some coastal areas in northern Norway (Dyrrdal et al., 2012). Dyrrdal et al. (2013) and Skaugen et al. (2012) studied trends in snow depth (SD) and snow water equivalent (SWE) and found significant positive trends for both variables in the colder inland and northernmost regions of Norway. Despite an observed increase in mean annual temperature by about 0.8 °C during the last century, which is projected to accelerate in the coming decades, it is likely that some inland and high-altitude areas will still accumulate more snow during winter until the end of the 2050 s (Hanssen-Bauer et al., 2015). However, other parts of the country which are characterized by comparatively warmer winter climates already show negative long-term trends in observed SD and SWE. The projections also indicate that such trends will affect larger regions and higher altitudes towards the end of the 21st century.

These changes in the hydrometeorological triggers will, most likely, impact runoff and flooding in Norway via their direct effect on the relative importance of rainfall vs. snowmelt in runoff generation. Currently, about 30% of the annual precipitation in Norway falls as snow, and snow storage and melting play an important role in the hydrological regime of many catchments in the country (Gottschalk et al., 1979). In these catchments, a low flow period during winter is followed by a prominent snowmelt induced high-flow period in spring and early summer, and another low flow period during summer is followed by occasional floods occurring during autumn. Other catchments, however, exhibit pronounced pluvial regimes with prominent rainfall induced high flow events particularly during autumn or fully nival regimes with prominent high flows only during a snowmelt period in late spring to early summer. Therefore, the obvious question that arises is whether or not the observed changes in the hydrometeorological triggers outlined in previous paragraph have led to changes in flooding in Norway as a consequence of changes in the FGPs.

Previous studies considering trends in high flows with mixed populations (i.e. rainfall and snowmelt generated floods) reveal that changes in regional flood regimes largely depend on changes in FGPs. For instance, Burn et al. (2010) studied trends in hydrological extremes for Canadian watersheds and found decreasing patterns of annual and snowmelt-associated spring maximum flows that tend to occur earlier while at the same time the number of rainfall-associated flood events is increasing. There are, however, no clear patterns regarding trends in the magnitude of these rainfall-associated flood events. The same study, as does Burn and Whitfield (2015), emphasizes the benefit of studying trends in floods with respect to prevailing flood regimes. For the European Alps, Bard et al. (2012) found significant trends towards higher snowmelt-related spring (peak) flows and an onset for these flows during the snowmelt period. They also noted an increase in the length of the snowmelt season. An earlier timing of spring peak flows is the most robust climate change signal that has been detected in runoff observations from all over the world where snowmelt is an important FGP, as has also been reported in earlier studies (e.g. Hodgkins et al., 2003; Korhonen and Kuusisto, 2010; Reihan et al., 2012).

For the Nordic countries, a coherent picture of positive annual as well as seasonal streamflow trends has been linked to the observed increases in mean precipitation outlined above (Stahl et al., 2010; Wilson et al., 2010). With respect to flood discharge, however, neither trends towards higher winter floods, nor systematic trends towards higher spring flood magnitudes, despite increasing precipitation, have been detected (Wilson et al., 2010). Some catchments along the west coast, however, have shown slight decreases in autumn flood magnitudes. For small catchments in Norway (<60 km^2), Wilson et al. (2014) found a few positive trends in the frequency and magnitude of high flow events in southern Norway, though the majority of catchments considered showed no trend. Moreover, trends in the frequency were stronger as compared with trends in the magnitude. For Sweden, Arheimer and Lindström (2015) found oscillating changes in floods between dry and wet periods, but no significant trends in flooding over the last century. However, they found some tendencies towards a seasonal shift in flooding (decreasing spring flood magnitudes, increasing autumn flood magnitudes), suggesting a growing importance of rainfall as a FGP.

The majority of the studies mentioned above show that seasonal analyses are usually applied for establishing links between discharge trends and hydrometeorological drivers that have a high degree of seasonality (e.g. cyclonic precipitation, convective storms, and snowmelt). This, however, can only provide clues and inferences regarding the underlying causes for the detected changes. For example, increasing spring flood magnitudes might be attributed to increased snowmelt based on their seasonality, although they may actually be the result of increased precipitation intensities during spring (as has been observed in some regions in Norway). This underscores that seasonal analyses do not necessarily give a clear picture of changes in flood generation in catchments where FGPs do not have a unique correspondence with peak flow seasonality. Thus, by distinguishing between rainfall and snowmelt as the dominant FGPs and analyzing trends for both groups of events separately, one can generate a sounder physical basis for linking trends in peak discharge to changes in hydrometeorological drivers. Moreover, such an approach will assist in identifying regions where rainfall dominated and snowmelt dominated peak flows show opposite trends, such that trend analyses which combine all flows independent of their FGPs may indicate the lack of a trend.

Changes in flooding can be seen as the integrated response of a catchment to different natural and human-induced drivers that may act in parallel, interactively, and sometimes even over different time scales (Merz et al., 2012). This is one of the reasons which make the linkage of possible causality to detected changes a challenging problem. Norway has a good spatial coverage of quality controlled streamflow records representing a large set of pristine and near-natural catchments with a minimum of human interventions. This ensures that detected changes in flooding in these catchments are either the result natural variability or (human-induced) climate change.

In this study, we analyze trends in the daily peak flow series of a comprehensive set of pristine and near-natural catchments in Norway. Furthermore, we apply an event-based approach in order to distinguish rainfall and snowmelt generated peak flow events. By analyzing trends in rainfall and snowmelt generated floods separately, we aim to gain insight into the changing role of these processes on peak discharge in general, and to consider possible linkages between the outlined changes in the hydrometeorological triggers and the high flow regimes in Norway. Such knowledge regarding changes in recent years will also be helpful in interpreting possible future changes due to climate warming (Hall et al., 2014). In particular, four research questions are addressed by this paper: (i) Have floods increased in magnitude or frequency in Norway during the last five decades? (ii) Which FGPs are responsible for the detected changes? (iii) What are the primary consistencies and inconsistencies between changes in the magnitude and frequency of floods and reported changes in hydrometeorological