Daily streamflow trends in Western versus Eastern Norway and their attribution to hydro-meteorological drivers

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Abstract
Regional warming and modifications in precipitation regimes has large impacts on streamflow in Norway, where both rainfall and snowmelt are important runoff generating processes. Hydrological impacts of recent changes in climate are usually investigated by trend analyses applied on annual, seasonal, or monthly time series. None of these detect sub-seasonal changes and their underlying causes. This study investigated sub-seasonal changes in streamflow, rainfall, and snowmelt in 61 and 51 catchments respectively in Western (Vestlandet) and Eastern (Østlandet) Norway by applying the Mann–Kendall test and Theil–Sen estimator on 10-day moving averaged daily time series over a 30-year period (1983–2012). The relative contribution of rainfall versus snowmelt to daily streamflow and the changes therein have also been estimated to identify the changing relevance of these driving processes over the same period. Detected changes in 10-day moving averaged daily streamflow were finally attributed to changes in the most important hydro-meteorological drivers using multiple-regression models with increasing complexity. Earlier spring flow timing in both regions occur due to earlier snowmelt. Østlandet shows increased summer streamflow in catchments up to 1100 m a.s.l. and slightly increased winter streamflow in about 50% of the catchments. Trend patterns in Vestlandet are less coherent. The importance of rainfall has increased in both regions. Attribution of trends reveals that changes in rainfall and snowmelt can explain some streamflow changes where they are dominant processes (e.g., spring snowmelt in Østlandet and autumn rainfall in Vestlandet). Overall, the detected streamflow changes can be best explained by adding temperature trends as an additional predictor, indicating the relevance of additional driving processes such as increased glacier melt and evapotranspiration.

KEYWORDS
attribution, climate change, hydrological change, hydro-meteorological driver, streamflow trend, trend analysis
INTRODUCTION

Hydrological changes as a consequence of global warming and climatic change (Hartmann et al., 2013) are important for human society since these changes have the potential to impact water supply, hydropower generation, and agriculture (e.g., Jiménez Cisneros et al., 2014). The impacts of climate change on hydrological conditions vary across different regions due to the hydro-meteorological regimes and the local character of climate change (Burn et al., 2010). Mountainous and cold-climate regions, where snow and ice are an integrated part of the hydrological cycle, are particularly vulnerable to global warming since the cryosphere in these regions is rapidly declining (Hock et al., 2019; Mote et al., 2005). Moreover, this trend will likely accelerate in the coming decades (Hamlet & Lettenmaier, 1999; Hock et al., 2019; Huss et al., 2017). In two geographical regions of Norway, Vestlandet and Østlandet (Western and Eastern Norway), snowmelt and rainfall are the dominant streamflow processes. The impacts of regional warming in interaction with changes in annual, seasonal, and sub-seasonal precipitation in these regions will be reflected by changes in the amount and timing of runoff (Bates et al., 2008). This paper explores sub-seasonal changes in streamflow regimes in Vestlandet and Østlandet in relation to changes in hydro-meteorological drivers, and attributes observed changes in streamflow to these driving processes.

Over the last century, and particularly from the mid-1970s, mean annual temperature and mean precipitation in Norway have increased by 0.8°C and 18% respectively (Hanssen-Bauer et al., 2015). There are, however, seasonal and regional differences: the largest increases in both temperature and precipitation are found for winter/spring and autumn, and these increases are more pronounced in Østlandet than in Vestlandet. In contrast to other mountainous regions (e.g., Marty et al., 2017; Mote, 2003) areas above 850 m a.s.l. and in colder inland regions in Norway have experienced positive trends in snow water equivalents and snow depth (Dyrrdal et al., 2013; Skaugen et al., 2012). At lower altitudes and in comparatively warmer regions these trends are negative. Future projections indicate that such trends will affect larger regions and higher altitudes (Hanssen-Bauer et al., 2015; Stewart, 2009).

Changes in the hydro-meteorological drivers will translate to streamflow changes via their direct influence on the most important streamflow generation processes in Norway, that is, rainfall and snowmelt. Like in other mountainous regions, snow accumulation and -melt are integral parts of the hydrological cycle and important factors determining the hydrological regime in various catchments (Gottschalk et al., 1979). However, due to the location at the west coast of the Scandinavian Peninsula, Vestlandet receives large amounts of precipitation, especially during autumn, while precipitation sums in Østlandet are considerably lower with seasonal peaks during summer. Typically, streamflow regimes in Vestlandet and Østlandet are characterized by a low-flow period during winter which is followed by a prominent snowmelt induced high-flow period during spring and early summer, and another low-flow period during summer is followed by a secondary high-flow period during autumn and early winter. There are, however, regional variabilities ranging from pronounced pluvial to fully nival regimes mainly determined by latitude, altitude, and topography. In turn, the question arises whether the outlined changes in the hydro-meteorological drivers have led to changes in the relative importance of the streamflow generation processes and in streamflow regimes in Vestlandet and Østlandet over the last decades.

Most studies of hydrological change focus on detecting and attributing hydro-meteorological trends at annual (e.g., Durocher et al., 2019; Hulley et al., 2019; Lindgren et al., 2017), seasonal (e.g., Birsan et al., 2014; Déry et al., 2016; Lindgren et al., 2017) monthly time scales (e.g., Makarieva et al., 2019; Stahl et al., 2010; Xu et al., 2020), or focus on changes in timing of certain events, for example, first annual spring snowmelt (Westmacott & Burn, 1997). Studies that have focused on streamflow changes in the Nordic countries found positive annual as well as seasonal streamflow trends (Lindgren et al., 2017; Lindstrøm & Bergstrøm, 2004; Stahl et al., 2010; Wilson et al., 2010), and trends in Norway are often consistent with the observed increases in mean precipitation outlined above (Wilson et al., 2010). Most notably, winter and spring streamflow has increased in the southern half of Norway, while summer streamflow has decreased. The significance and magnitude of these trends, however, vary considerably with the time period considered. The drawback of annual and seasonal trend analyses in general is that they will not detect changes at finer temporal scales. However, changes in precipitation and temperature that affect streamflow often occur at the sub-seasonal scale (Kormann et al., 2014), and therefore, examining trends at shorter time steps may provide additional insight beyond annual, seasonal, or monthly (Déry et al., 2009; Kim & Jain, 2010; Kormann et al., 2015; Leith & Whitfield, 1998). Where no significant annual change is found, significant sub-seasonal changes can be detected (Skålevåg, 2019). Examination of trends at finer time steps may help explain underlying causes for streamflow changes (Kormann et al., 2015). When trends in the most important streamflow generation processes (i.e., rainfall and snowmelt) are available for the same temporal resolution, and the same period of time, linkages can be assessed directly. Furthermore, information on hydrological changes at finer temporal resolution may be highly beneficial for water management strategies in terms of climate change adaptation and hydropower production.

Attributing detected trends to their specific causes is valuable for the understanding, prediction, and adaptation to expected future changes (Burn et al., 2012; DeBeer et al., 2016). Therefore, trend attribution has received much attention in recent years (see Bindoff et al., 2013; Cramer et al., 2014). Hydrological trend attribution goes beyond identifying (in)consistencies between trends in streamflow and trends in potential hydro-meteorological drivers. It rather involves quantifying the evidence for a causal link between external drivers and changes in streamflow (Bindoff et al., 2013). Various natural and human-induced drivers acting simultaneously, interactively, and even over different time scales, makes the linkage of possible drivers to detected changes in streamflow a challenging task (B. Merz et al., 2012). In this regard, a good spatial coverage of quality controlled streamflow data for a large set of pristine and near-natural
catchments is beneficial and available in Norway. It ensures that detected streamflow changes result either from climate change or natural variability. Generally, two different types of attribution approaches are currently established: (i) model-based approaches, in which the underlying causes for detected trends are inferred from (physically-based) hydrological models that are able to reproduce trends in streamflow observations (e.g., Kormann et al., 2016; Zhai & Tao, 2017), and (ii) data-based approaches, which aim at establishing statistical relationships between detected changes in streamflow and their particular drivers (e.g., Duethmann et al., 2015; Kormann et al., 2015). Data-based approaches can be data-intensive, and the credibility of detected statistical relationships being due to physical cause-effect relationships needs to be assessed individually. However, the advantage of data-based approaches against model-based approaches is that they are quick and less affected by uncertainties resulting from model structure, parameterisation, and simplifications (Duethmann et al., 2015).

Our study aims at better understanding the dominant processes driving sub-seasonal streamflow changes in the regions of Vestlandet and Østlandet in Norway. In this regard, we examine highly-resolved (i.e., daily 10-day moving averaged) trends in streamflow in 112 near-natural to pristine catchments in Vestlandet and Østlandet over three decades (1983–2012). Furthermore, we analyse trends in rainfall and snowmelt as the most important streamflow generation processes in both regions at the same temporal resolution. As such, these trends should to a large extent explain the detected changes in streamflow. In this perspective, we also analyse trends in the relative contribution of snowmelt and rainfall to daily streamflow to investigate changes in the relative importance of both streamflow generation processes. Finally, we perform a data-based trend attribution approach based on multiple-linear regression to assess the extent to which detected changes in streamflow can be explained by trends in the hydro-meteorological conditions. Four specific research questions are addressed by this paper:

i. What are the trends in streamflow, snowmelt and rainfall in Vestlandet and Østlandet between 1983 and 2012 at the sub-seasonal scale?

ii. How has the relative contribution of rainfall and snowmelt to daily streamflow changed in this period?

iii. What are the differences between these trends in Vestlandet and Østlandet?

iv. Can changes in the hydro-meteorological drivers explain observed trends in streamflow?

2 | STUDY AREA AND DATA

2.1 | Hydro-climatological and runoff conditions

The study area spans a geographical range of 5°–12°E and 59°–63°N, and an altitudinal range of 0–2500 m a.s.l. (Figure 1a). The area is divided into two regions, Vestlandet and Østlandet, which are located west and east of the water divide of the central Norwegian mountains, and correspond to the runoff region boundaries used in the national science basis for climate change adaptation in Norway (see Hanssen-Bauer et al., 2015). These runoff regions refer to watershed boundaries which are closely connected to administrative units as they are used for operational hydrological work by the Norwegian Water Resources and Energy Directorate (NVE) (Pettersson, 2012),

![Figure 1](image-url) Location of streamflow gauging stations and topography of southern Norway (a) and the dominant contributor to daily streamflow for catchments in Vestlandet (b) and Østlandet (c) sorted by median catchment altitude from high (index 0) to low. A streamflow contributor is dominant if on average more than two third of the runoff volume at a certain day over 1983–2012 stem from rainfall (blue) or snowmelt (red) respectively (see Section 3.1). Baseflow (grey) is dominant where the sum of snowmelt and rainfall contribution is less than two thirds. The rest is classified as mixed (beige).
although the regions reflect general hydrological differences in terms of streamflow regimes in the this portion of Norway.

Due to their location west and east of the Scandinavian Mountains, Vestlandet and Østlandet have marked hydro-climatological differences. In Vestlandet annual precipitation is large and may exceed 4000 mm, while annual precipitation in Østlandet is much lower and may drop down to 300–400 mm in some valleys that are located inland in the rain shadow of the Scandinavian Mountains. Vestlandet receives the largest precipitation volumes during autumn and winter, while summer precipitation is dominant in Østlandet. Mean annual temperature varies from about 6°C at the west coast to about –3°C in in the high-altitude areas in Østlandet. Due to the location at the west coast of Norway, annual temperature amplitudes in Vestlandet are considerably lower than in Østlandet, leading to mild and humid winters. Summer temperature is highest in Østlandet, and winters are cold and comparatively dry.

Mean annual runoff generally reflects the patterns of annual precipitation, and runoff coefficients tend to be high due to high precipitation and low evapotranspiration. The differences in the seasonal and altitude-dependent temperature regimes, however, have impacts on snowpack volumes and the snow season. This in turn leads to differences between and within the two regions in the relative importance of snowmelt as a runoff generating process. In higher altitude areas and east of the Scandinavian Mountains, snowmelt during spring and early summer is particularly important for the regional streamflow regime. The role of snowmelt decreases towards the west coast, and rainfall generated peak flows during autumn and winter are more prominent in Vestlandet. Still, both snowmelt and rainfall are relevant runoff contributors in both regions (Figure 1b,c), though with differences in their relative importance.

### 2.2 Streamflow records

Daily streamflow records from 112 streamflow gauging stations belonging to NVE’s hydrometric observation network formed the basis for the trend analyses in this study. Out of these 112 stations, 61 catchments are located in Vestlandet, and 51 are located in Østlandet. Furthermore, 70 of these catchments are part of the Norwegian Hydrological Reference Network (HRN) and have been assessed as suitable for studying the effects of climate variability and hydrological change in Norway (Fleig et al., 2013). These catchments were selected according to the criteria defined by Whitfield et al. (2012), meaning that they are pristine or near-natural, with less than 10% of the area affected by basin development and the absence of significant hydrological alterations. The streamflow data from many of these stations have previously been used in hydrological trend studies both of Europe, the Nordic countries and Norway (Hisdal et al., 2001; Stahl et al., 2010; Vormoor et al., 2016). Further 42 streamflow records were added to those of the HRN. These catchments are affected by land use to a small degree, but still unaffected by major hydrological alterations so that they are suitable for the purpose of this study. A total of 22 (13) catchments have a glaciated area larger than 5% (10%). The streamflow data of the HRN has been quality checked (Fleig et al., 2013), and we further ensured that only streamflow records from catchments with less than 10% days missing in the chosen period were included in the analysis.

### 2.3 Hydro-meteorological data

Daily data for the hydro-meteorological drivers, rainfall, snowmelt and temperature for each catchment stem from daily 1 × 1 km gridded datasets (seNorge data) covering the whole of Norway. The seNorge grids provide data for a range of hydro-meteorological variables starting in 01 September 1957. The gridded data is available for display at www.seNorge.no (Engeset, 2016). Daily temperature, rainfall and snowmelt time series were extracted from the seNorge grids for each of the 112 catchments by taking the spatial mean. The time series data were available up to 2012.

Precipitation and temperature data in the seNorge dataset used in this study (version 1.1.1) are interpolated from meteorological stations measurements, using triangular irregular networks and detrended residual kriging respectively (see Mohr & Tveito, 2008). Precipitation is exposure and altitude corrected assuming a 10%/5% increase in precipitation per 100 m below/above 1000 m a.s.l. (Førland, 1979). Detrending temperature accounts for the dependency of temperature on altitude and continentality (see Vormoor & Skaugen, 2013, for a summary of details). Regarding precipitation, we only consider rainfall in this study, which was defined as precipitation on days with temperatures above 0.5°C.

The daily snowmelt grids are modelled with the seNorge snow model (version 1.1.1) (Saloranta, 2014). The model uses daily temperature and precipitation grids as input, and simulates various variables including snow depth, snow water equivalents, and snowmelt, employing a degree-day approach with an additional term related to the seasonal and zonal variation in incoming short-wave radiation (Saloranta, 2014).

### 3 METHODS

#### 3.1 Determination of the relative contribution of rainfall and snowmelt to daily streamflow

To determine the relative contribution of rainfall and snowmelt, respectively, to streamflow at each single day in the year, we applied the approach described in Vormoor et al. (2015, 2016). The approach allows a high flow event to be classified according to its dominant generating process (i.e., rainfall or snowmelt) using the time of concentration and recession of a large flood event within a specific catchment. Here, we focus on the catchment specific recession times (RT) of such large flood events. RT covers the time span a specific catchment needs to drain from full saturation to baseflow conditions. If we now consider this time span before a specific day in the year, we account for the time in which all runoff generation and routing processes can theoretically contribute to streamflow at this particular day. Hence, by accounting for rainfall and snowmelt dynamics over RT
before a specific day, we are able to estimate the relative contribution of rainfall and snowmelt to discharge at this day. This is formalized in the following way:

\[ R_{X,t} = \sum_{i=1}^{t} X_i \]  

(1)

The runoff \( R \) contributed by the variable \( X \) (either snowmelt or rainfall) at time \( t \) describes the amount of water that theoretically can be contributed by \( X \) over the RT at any given day. The contributions of \( X \) are estimated from the gridded rainfall and snowmelt data, using the mean of the grid point values for a given catchment. \( RT \) is catchment specific and range between 2 to 20 days for most of the catchments, while four comparatively large catchments show a \( RT \) of more than 35 days. The numbers of days for \( RT \) are taken from Vormoor et al. (2016) who have investigated the rainfall (\( RF \)) and the mean of the grid point values for a given catchment. \( RT \) of more than 35 days are available leading to a total of 6 (variables) \( \times 112 \) (catchments) \( \times 365 \) (10-dayMA values) = 245 280 DOY time series which were analyzed for significant trends. Note, that although we will continue referring to trends in DOYs, this actually refers to the smoothed daily time series. These have slightly different statistical characteristics than the original daily time series, which affects some aspects of the trend detection and significance estimation (see next step).

That is, streamflow at any given day can be separated into components of rainfall- and snowmelt contributions (fractions between 0 and 1). On days where neither snowmelt nor rainfall contributed to streamflow (both \( C_{RF} \) and \( C_{SM} \) are zero), which is common during the winter months, it is assumed that baseflow is the dominant source of streamflow.

### 3.2 Ten-day moving average trend analysis

To analyse hydro-climatological changes at the sub-seasonal scale we opted for an approach developed and applied by Kormann et al. (2014) for catchments in the Austrian Alps. The idea of this approach is to determine trends for each day of year (DOY), that is, trends in time series that consists of only, for example, January 1st values. However, due to large inter-annual variability in daily values, which impacts the ability of trend detection methods to identify trends, some kind of smoothing the DOY time series is necessary to reduce noise. Thus, we analyzed trends on 10-day moving averaged (10dMA) time series of streamflow (Q), rainfall (RF), relative rainfall contribution (RFC), snowmelt (SM), relative snowmelt contribution (SMC), and temperature (T) for each of the 112 catchments. Trends were analyzed for the period 1983–2012. This period was chosen to ensure the best spatial and altitudinal coverage while covering a climate normal period of at least 30 years. Figure 2 shows the workflow of the 10dMA trend analysis for streamflow as an example. Each step can be described as follows:

a. The original daily time series were smoothed with a centred 10dMA filter (Figure 2a). In addition to reducing the variability in the DOY time series, this filtering approach may minimize the effect of transient storms on precipitation fluctuations and obtain similar hydrological responses from catchments of varying sizes (Dévy et al., 2009). Kormann et al. (2014, 2015) used a 30dMA filter, but similar applications have applied a 3dMA filter (Kim & Jain, 2010), or used 5-day sequent averages (Dévy et al., 2009; Leith & Whitfield, 1998). We opted for a 10dMA filter as a well-balanced compromise between a reasonable degree of smoothing and preserving intra-annual variability.

b. From the 10dMA time series, individual time series for each DOY over the period 1983–2012 were extracted. In the example shown in Figure 2b, this is illustrated for DOY 140 (i.e., May 20th). That is, for each catchment and variable, 365 DOY time series over 30 years are available leading to a total of 6 (variables) \( \times 112 \) (catchments) \( \times 365 \) (10dMA values) = 245 280 DOY time series which were analyzed for significant trends.

c. The trend for each DOY was estimated by separately analysing each DOY time series. Figure 2c shows the example for DOY 140. The Mann–Kendall (MK) test (Kendall, 1975; Mann, 1945) was used for the detection of trends and for the determination of the significance of these trends both at the local \( \alpha_{local} \) and the global (field) level \( \alpha_{field} \). The MK test is a non-parametric trend test for the detection of monotonic trends (Chandler & Scott, 2011; Helsel & Hirsch, 2002) and widely applied in hydrology for the detection of significant trends in time series (Burn et al., 2012). Potential autocorrelation (serial correlation) in the time series may lead to a disproportionate rejection of the null hypothesis, that is, that no trend is detected by the MK test (Yue et al., 2002). However, due to the independency of the individual DOY values over the study period (i.e., separated by a year), autocorrelation was found to be negligible since only 4%–9% of the time series showed significant serial correlation (\( \alpha = 0.05 \)). Therefore, no prewhitening has been performed. The MK test was applied to all DOY time series and the significance of a trend at the \( \alpha_{local} = 0.1 \) level was determined. Hydro-climatological data from different sites located in the same geographical area are often cross-correlated (Renard et al., 2008; Wilks, 2006). The field significance can be used to determine whether detected trends at multiple sites are significant at the field (global) significance level \( \alpha_{field} \), and not purely detected by chance (Burn & Hag Elnur, 2002). Where a field significant trend is detected, it is assumed that a significant change has occurred across the region. The field significance (\( \alpha_{field} = 0.1 \)) for each DOY in a region was calculated using a bootstrapping approach proposed by Burn and Hag Elnur (2002). Bootstrapping shuffles the temporal structure of the individual DOY time series, but preserves any cross-correlation in the original dataset. The MK test was then applied to the bootstrapped time series. This procedure was repeated \( N \) times, and the percentage of catchments with a
significant trend in each resampling was combined to create a distribution \( N = 600 \). The critical value \( p_{\text{crit}} \) is defined as the \( 1 - \alpha \) field percentile of this distribution. If the percentage of catchments with significant trends exceeded \( p_{\text{crit}} \), the trend was deemed to be field significant, that is, likely not caused by randomness and not significantly impacted by cross-correlation. The MA smoothing has some influence on the field significance through how it affects significant trend clusters (see Skålevåg, 2019, p. 52), mainly by slightly widening the DOY range where trends are field significant. Trend magnitudes were estimated using the Theil–Sen (TS) estimator (Sen, 1968; Theil, 1950), which is the median of the slopes of all data point pairs. As a non-parametric approach, the TS estimator is robust against outliers and works better than linear regression on heteroscedastic and skewed data (Wilcox, 2010), of which the latter is common in environmental data.

d. The trend magnitude for each DOY time series was then aggregated into a yearly trend cycle, that is, daily 10dMA resolved trends throughout the year. Figure 2d shows the trend estimated for DOY 140 (\(-8.51 \text{ m}^3\text{s}^{-1}\text{yr}^{-1}\); step c) in relation to the trends estimated for all other DOYs through the year.

e. These daily 10dMA trends of each catchment are then compiled to a regional trend array ordered by median catchment altitude (Figure 2e). That is, in Figure 2e, we are looking from above at the daily resolved trend curve (Figure 2d) for each investigated catchment, while positive and negative trends are colour coded in blue and red respectively.

3.3 | Data-based trend attribution with multiple linear regression

Due to the large number of catchments, a data-based attribution approach using ordinary least squares multiple regression was chosen,
rather than a model-based approach. Such a multiple-regression approach establishes a quantitative relationship between trends and their possible drivers (Duethmann et al., 2015). We assessed to what degree various combinations of daily 10dMA trends in snowmelt (SM), rainfall (RF) and temperature (T) explains daily 10dMA trends in streamflow (Q) for each of the 112 catchments. The relationship between the trends was assessed for the entire annual cycle, but also per calendar seasons, that is, winter (DOY 335–359; Dec–Feb), spring (DOY 60–151; Mar–May), summer (DOY 152–243; Jun–Aug), and autumn (DOY 244–333; Sep–Nov). Such a separation is somewhat artificial due to the variability of seasons lengths in the catchments caused by differences in local climate. However, we chose to include a seasonal trend attribution since these calendar seasons do reflect large parts of general temporal variability of the hydro-meteorological drivers (1a,b). All daily 10dMA trends, both significant and nonsignificant were included in the attribution analysis.

The streamflow trend in each DOY time series is assumed to be proportional to the trend in the hydro-meteorological drivers (Equation (3)). Since RF and SM are the most important runoff generation processes, trends in these variables should explain a large part of the Q trends. Trends in T may serve as a proxy or give an indication for other temperature dependant drivers of streamflow change like glacial melt and evapotranspiration (ET). We gradually increased the number of predictors to investigate which drivers explain best the detected (seasonal) trends in daily 10dMA streamflow (Table 1). That is, we first established the relationship between trends in Q with trends in only RF and SM, respectively. Then we established the relationship of trends in Q with temperature dependant drivers of streamflow change like glacial melt trends. Trends in T may serve as a proxy or give an indication for other proportional to the trend in the hydro-meteorological drivers [Equation (3)] were included in the attribution analysis.

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The extent to which trends in hydro-meteorological drivers explain trends in streamflow was evaluated with the coefficient of determination R^2. The significance of R^2 was determined with the F-test comparing the multiple regression model with an ‘intercept-only’ model, that is, all regression coefficients are equal to zero (for details, see e.g., Handl & Kuhlenkasper, 2017). To ensure that any improved results from including more independent variables in the multiple regression are not the result of overfitting, we compared the Akaike Information Criterion (AIC) of the models.

All analyses and visualizations were performed with code written by the authors to run under 3.7 (Python Software Foundation, 2018). The code for the MK test and TS estimator were obtained from United States Geological Survey python module ‘trend’ (Hodson, 2018).

### TABLE 1  Overview of attribution models

| Model abbreviation | Model equation |
|--------------------|----------------|
| QSMRFT             | Qtrend ~ SMtrend + RFtrend + Ttrend |
| QSMRF              | Qtrend ~ SMtrend + RFtrend |
| QSM                | Qtrend ~ SMtrend |
| QRF                | Qtrend ~ RFtrend |

### RESULTS

#### 4.1 Trends in streamflow

Figure 3 displays the detected significant trends in Q for Vestlandet (a) and Østlandet (b). The lower row (Figure 3c,d) shows the same results but additionally plots detected nonsignificant trends which are masked by a white hatch pattern (all further results will be presented in this style). For both regions, field and local significant positive Q trends can be observed between DOY 70–110. These positive trends in daily 10dMA Q with magnitudes of more than 40% (up to 78% Østlandet; 57% Vestlandet) per decade is detected for almost all catchments at every altitude level (y-axis), except for the lowest elevated catchments. Following the positive trends is a band of negative trends between DOY 105–170 in both regions. These negative trends are more pronounced, more significant (in terms of number of catchments), and of larger magnitude in Østlandet than in Vestlandet (on average 21% per decade vs. 14% per decade). Trend magnitudes are also larger in lower elevated catchments as compared to high-altitude catchments. In Østlandet, some altitude-dependency regarding the timing of this positive-negative trend sequence is detected, with an earlier onset of this sequence at low altitudes. In Vestlandet, this altitude-dependency is not visible.

During the rest of the year, the regions differ from each other. In Østlandet, there is a clear and mostly significant increase in 10dMA streamflow during DOY 180–250 by up to more than 30% per decade for catchments with altitudes up to 1071 m a.s.l. Above this altitude, the positive trends are considerably smaller and mostly nonsignificant. For about 50% of the catchments in Østlandet, mostly above 781 m a.s.l., significant positive trends can also be observed roughly between DOY 330–370 (winter period), while the other catchments show no trends or some small trends in the opposite direction.

The streamflow trends in Vestlandet for the rest of the year are less coherent than in Østlandet. During the second half of the year (DOY 200–320), there are two alternating periods of significant decreases and increases across all altitudes, each with a period of 30 days. In magnitude these trends vary between ~25% per decade to +30% per decade, while the significance is larger (more catchments) for the negative trends than for the positive trends. Field significance is given for almost all described trend patterns that show a large degree of local significance (see orange bars in the top row of each plot), except for the trends in Østlandet between DOY 330–370.

Another difference between both regions is found with regard to trends throughout the year. The colour bars at the very right of each plot in Figure 3 indicate that the sum of significant daily 10dMA trends over the year are positive (green), as it is dominantly the case for Østlandet, or negative (magenta), as it is dominantly the case for Vestlandet.
4.2 Trends in rainfall and snowmelt and their contribution to streamflow

Figure 4 shows the detected trends in (i) absolute snowmelt and (ii) in the relative contribution of snowmelt to streamflow in Vestlandet (Figure 4a,c) and Østlandet (Figure 4b,d). Detected trends in absolute rainfall and in the relative contribution of rainfall to streamflow are displayed in the same configuration for both regions in Figure 5.

Regarding changes in SM, a clear, consistent and largely significant signal towards earlier snowmelt is detected for both regions (Figure 4a, b, DOY 70–110), which coincides with the timing of positive streamflow trends in both regions as shown in Figure 3 (DOY 70–110). In both regions, this increase in snowmelt is detected for the same period where we also found significantly positive temperature trends (not shown). Regarding altitude dependency, both regions show that the onset of this trend occurs with a temporal delay towards higher altitudes. The lowest elevated catchments in both regions, however, do not show any trend during this time span. Another common pattern for both regions is found around DOY 280, where small but significant negative snowmelt trends occur in catchments above 700 m a.s.l. (Vestlandet) and 1000 m a.s.l. (Østlandet). Overall, the sum of significant daily 10dMA trends in snowmelt over the entire year are negative for most of the catchments in both regions.

Focusing on changes in SMC, the patterns in Figure 4c,d reflect the impact of earlier snowmelt on streamflow (DOY 70–100). Significant negative trends in SMC between DOY 100 and 200 are more pronounced in Vestlandet than in Østlandet and in lower elevated catchments (both regions). These changes are also field significant in both regions. In Vestlandet, in most catchments across all altitudes, the number of days with significant negative trends in SM and SMC is larger than the number of days with significant positive trends. In Østlandet, in contrast, the period of significant positive trends in SMC (DOY 70–100) is more pronounced in terms of duration and trend magnitude as compared to Vestlandet. This results in an increasing role of snowmelt contribution to streamflow in about 50% of the catchments, particularly at altitude levels between 600 to 1000 m a.s.l. Another remarkable difference between both regions is that significant positive trends in snowmelt contribution are found for some catchments below 1200 m a.s.l. between DOY 0–40) in Vestlandet. These trends are rarely present in Østlandet.

With reference to trends in daily 10dMA RF (Figure 5a,b), the two regions show clear differences. In Vestlandet there are short periods with both significant positive and negative trends in RF almost throughout the entire year, with overall slightly positive trends in the first half of the year, and dominantly negative trends in the second half of the year (particularly between DOY 270–300 by more than
The difference between days with significant increases and decreases in daily 10dMA RF trends are mixed for Vestlandet; about one third of the catchments show negative and about two thirds show positive differences, respectively, without any particular altitude-dependent pattern. In Østlandet, significant trends in daily 10dMA RF of are mainly detected between DOY 150–210. A short period (<10 days; from DOY 100) of decreases is followed by slightly longer period (15–30 days; from DOY 180) showing significant increases in daily 10dMA RF (up to $+1.5$ mm per decade) across all altitudes. Trends appearing between DOY 210–250 with alternating periods of increases and decreases are mostly nonsignificant. There are more days with significant increases in RF than days with significant decreases in most catchments in Østlandet. In contrast to snowmelt, altitude-dependencies regarding the timing of daily 10dMA RF trends are not detected.

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In Vestlandet, rainfall contribution is significantly decreasing around DOY 340, particularly in catchments above 800 m a.s.l. This matches with the negative trends in rainfall sums during this time period (Figure 5a). In Østlandet, the relative contribution of rainfall to streamflow increases significantly between DOY 325–350 in catchments below 1000 m a.s.l., although no significant trends in rainfall sums have been detected. Note, however, that the detected changes are still small ($\pm 10$ percentage points per decade).

### 4.3 Attribution of streamflow trends to hydro-meteorological drivers

Figure 6 presents the spatial distribution of the results achieved by the annual and seasonal multiple regressions (columns); the complexity of the regression models increases from bottom to top (rows). Note, that significant $R^2$ values are shown as filled symbols; nonsignificant $R^2$ values as hollow-symbols. Table 2 provides a summary of the results according to the number of catchments that achieved a certain significant $R^2$ score for the respective regression models at the annual scale.

Focusing on the two simplest models (QRF and QSM; see Table 1), we generally see that neither trends in rainfall nor snowmelt alone can explain the detected trends in streamflow very well at the
annual scale ($R^2$ dominantly below 0.2; Table 2). Trends in rainfall, though, explain the detected streamflow trends considerably well during autumn for many catchments in Vestlandet ($R^2$ up to 0.8; Figure 6). Trends in snowmelt, on the other hand, explain considerably well the detected streamflow trends during spring for many catchments in Vestlandet and for the most mountainous catchments in Østlandet ($R^2$ up to 0.8). Combining trends in snowmelt and rainfall as predictors (QSMRF) leads to improved $R^2$ at the annual scale ($R^2$ mostly between 0.2–0.8; Table 2). Still many catchments, particularly in the very east of Østlandet show low significant $R^2$ scores around 0.2.

The highest significant $R^2$ scores both at the annual and seasonal scale are achieved by adding temperature as an additional predictor to the previous regression model (QSMRFT; Table 1; top row in Figure 6). For most of the catchments the $R^2$ scores still range from 0.2–0.8. However, the number of catchments within the group of lowest $R^2$ scores at the annual scale has been reduced by 50% (Table 2). The improvements by adding temperature as an additional driver are also illustrated in Figure 7. The largest improvements at the annual scale are found for catchments in the North of Vestlandet close to the border between both regions (Figure 6). These catchments show comparatively large glacier coverages (by more than 10%). Figure 7 illustrates the improvement in $R^2$ scores for the QSMRFT model as compared to QSMRF, and underlines that the largest improvements are observed in most of the catchments with glacier coverage of >10%. Still the predictability of the most complex regression model for these catchments is comparatively low (0.38–0.68), and the improvements in $R^2$ scores for catchments with smaller glacier coverage (<5%) is less pronounced. Improvements of similar magnitudes as for catchments with small glacier coverages are also found for many unglaciated catchments in both Vestlandet and Østlandet. A comparison of the AIC between the models including/excluding temperature trends as additional drivers reveals little to no difference, which indicates that the detected improvements by adding temperature trends is not the result of overfitting the multiple regression models. The catchments with the lowest $R^2$ scores are found for catchments in the very east of Østlandet, irrespective of the season and model complexity considered.

5 | DISCUSSION

5.1 | Trends in daily 10dMA streamflow, rainfall, and snowmelt

Trends in daily 10dMA streamflow show large consistencies with the trends in daily 10dMA snowmelt and rainfall. The most obvious and mostly significant pattern in daily 10dMA streamflow trends,
observed in both regions, is related to changes in the timing of snowmelt. Earlier snowmelt leads to an earlier onset of the spring freshet; negative streamflow trends immediately afterwards are then due to a reduction of the snowpack by earlier snowmelt. However, these negative trends are generally of larger magnitude than the increases earlier in the year, and may be attributed to an overall reduction of snow cover at the end of the snow season (Rizzi et al., 2018). Earlier timing snowmelt and associated runoff has been detected in several mountainous and cold-climate regions around the world (Clow, 2010; Déry et al., 2009; Maurer et al., 2007; Morán-Tejeda et al., 2014; Stewart, 2009; Vincent et al., 2015) and can be considered as the most robust signal of climate change impacts on streamflow in such environments (Hock et al., 2019; Jiménez Cisneros et al., 2014).

**Figure 6** Results of the data-based trend attribution. The coefficient of determination $R^2$ value is indicated by colour, and $R^2$ significance by filled (significant) and hollow (nonsignificant) circles. The first two rows show the differences between the two main models (QSMRFT and QSMRF), with RF trend, SM trend (and T trend) as drivers, for the entire yearly trend cycle (annual) and for each season (winter, spring, summer and autumn).

**Table 2** Overview of attribution results for the entire yearly trend cycle (annual)

| Model    | $R^2 < 0.2$ | $R^2 = 0.2-0.4$ | $R^2 = 0.4-0.6$ | $R^2 = 0.6-0.8$ | $R^2 > 0.8$ |
|----------|-------------|-----------------|-----------------|-----------------|-------------|
| QSMRFT   | 12 (4;8)    | 39 (21;18)      | 35 (23;12)      | 25 (13;12)      | 1 (0;1)     |
| QSMRF    | 24 (14;10)  | 36 (18;18)      | 27 (17;10)      | 24 (12;12)      | 1 (0;1)     |
| QSMT     | 40 (24;16)  | 53 (32;21)      | 14 (4;10)       | 5 (1;4)         | 0 (0;0)     |
| QRFT     | 57 (20;37)  | 36 (23;13)      | 16 (15;1)       | 2 (2;0)         | 0 (0;0)     |

Note: Number of catchments within the $R^2$ range, with the distribution between the two regions indicated in brackets (Vestlandet; Østlandet).
The altitude-dependency of these streamflow trends during spring and early summer, meaning the temporal delay of earlier snowmelt in catchments at higher altitudes as compared to lower altitudes, is not as pronounced as one might have expected. For catchments in the Alps, Alps, Kormann et al. (2015) found much more pronounced altitude-dependent streamflow patterns during spring and summer. However, due to the different altitude ranges of the Alps and the Scandinavian Mountains, the catchments they considered cover much higher altitudes (up to >3100 m a.s.l. mean catchment altitude) than the catchments considered in this study (up to 1546 m a.s.l.). Still, the altitude-dependency of snowmelt trends during spring is more pronounced than the altitude-dependency of streamflow trends for the same season. This might be explained by ‘snowmelt-compensation-effects’ as described by Rottler et al. (2021). They argue that, at a certain day, meltwater in streamflow which previously stem from lower elevation bands is now replaced by meltwater from higher elevation bands. This explains why altitude-dependent trends in the timing of snowmelt itself are more prominent than trends in the timing of snowmelt-dominated streamflow.

The prominent and mostly significant increasing streamflow trends during summer in Østlandet (DOY 180–250) are consistent with detected positive trends in summer rainfall which agrees with reported seasonal precipitation trends in this region (Hanssen-Bauer et al., 2015). It disagrees, though, with seasonal streamflow trends reported by Wilson et al. (2010) who did not find any trends for catchments in Østlandet for the period 1961–2000. However, although rainfall trends are positive in all catchments throughout the entire altitude range, positive streamflow trends were only found for catchments up to 1100 m a.s.l. Above this altitude, the increasing relevance of rainfall does not translate to positive streamflow trends due to the decreasing relevance of summer snowmelt in many of these high-altitude catchments.

In Vestlandet, most trends outside spring are nonsignificant (for all variables). Still, the pattern of narrow alternating bands with significant positive and negative trends in rainfall and streamflow might be explained by a ‘stochastic drift’, caused by natural variability or simply by the random occurrence of autumn storms, which heavily impacts precipitation in this region. Therefore, this pattern is not necessarily connected with climate change. In addition, these patterns do not emerge prominently when considering trends for longer time periods (1963–2012) (Skålevåg, 2019). Unlike as in Østlandet, the difference in days with significant increases and decreases in daily 10dMA rainfall trends are mixed and catchment dependent. This agrees with regional observations for annual precipitation, which show the lowest percentage changes (slight increase) during recent decades and the largest uncertainties (Hanssen-Bauer et al., 2015). Seasonally, large decreases in autumn rainfall are also reflected by our results. However, large increases in spring precipitation in Vestlandet as shown by Hanssen-Bauer et al. (2015) are not fully reflected by our results based on daily 10dMA trend analysis. This may be due to our focus on rainfall instead of general precipitation, so that we have missed intra-seasonal increases in snowfall during early spring, particularly in the high-altitude catchments.

The results of this study demonstrate the benefit of high-resolution trend analyses. Assessing trends at a daily 10dMA resolution allows for the detection of sub-seasonal trend clusters, including changes in the timing of trends, and it enables a direct comparison of trends in streamflow and their dominant drivers. That is, it accounts for information that may not be perfectly caught by seasonal or monthly trend analyses. For instance, the detected trend patterns of earlier snowmelt (and related streamflow) across the elevation range would not have been correctly identified for all catchments by seasonal or monthly trend analyses. Instead, the trend patterns of earlier snowmelt compensates for the decreasing relevance of summer snowmelt in many of these high-altitude catchments.

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5.2 The changing relevance of rainfall and snowmelt on streamflow

Estimating the relative contribution of rainfall and snowmelt to daily streamflow allows for gaining deeper insights into the changing relevance of the most important runoff generating processes on streamflow in Norway. Our results point towards a generally increasing (decreasing) importance of rainfall (snowmelt) on streamflow contribution in both regions. This is in line with findings by Vormoor et al. (2016), who identified the increasing role of rainfall for flood generation in Norway over the last decades. It may also be seen as the onset of a development that will intensify in the future (Vormoor et al., 2015) and potentially lead to systematic shifts in streamflow
regimes in Norway (Beldring et al., 2008) as it is generally predicted for areas where much of winter precipitation currently falls as snow (Bates et al., 2008). Similar results on the decreasing importance of snowmelt induced event runoff have also been presented for catchments in other parts of the world where snowmelt is an important runoff generating process (e.g., Burn & Whitfield, 2016, 2017; Sikorska-Senoner & Seibert, 2020). In Norway, the increasing (decreasing) role of seasonal rainfall (snowmelt) may rearrange the relative importance of the peak flow periods during spring and autumn in many catchments which currently are characterized by mixed flow regimes.

Based on the sums of significant trends throughout the year, there have been identified catchments in Østlandet at altitude levels between 600–1000 m a.s.l. which show an increasing contribution by both rainfall and snowmelt. In these cases, the positive snowmelt contribution can be explained by generally positive trends in winter precipitation in Østlandet and temperatures that are still low enough to ensure considerable snow storage throughout winter (Hanssen-Bauer et al., 2015; Skaugen et al., 2012) which is then available for snowmelt between DOY70-100. The increasing streamflow contribution of rainfall in these catchments (DOY 110–150 and DOY 330–350) are either the result of positive trends in rainfall or the decreasing relevance of intra-seasonal snowmelt during early winter. This interpretation again exemplifies the benefit of analysing and comparing trends at finer than monthly temporal resolution.

Winter streamflow was found to increase in many catchments in both regions, although more pronounced in Østlandet (DOY 330–370) than in Vestlandet (DOY 0–90). However, these changes are small in absolute terms and often nonsignificant. This is particularly but not exclusively the case in catchments which are characterized by dominant winter baseflow conditions (i.e., none of both drivers is dominant; Figure 1b). The detected increase in winter streamflow is line with significant positive trends at the monthly scale for Norwegian catchments with winter low flow regimes (Stahl et al., 2010), and has also been observed in other cold climate regions (e.g., Moore et al., 2002; Paznekas & Hayashi, 2016; Ye et al., 2003; Zion et al., 2011). For some of our study catchments, the increase in winter streamflow can be explained by either increased winter rainfall contribution caused by a shift in the snow/rain ratio resulting from increasing temperatures (Hýntica & Huth, 2019; Paznekas & Hayashi, 2016) or intermediate snowmelt contribution due higher winter temperatures. Changes in winter baseflow rates due to interactions between frost depth, groundwater discharge and increasing air temperature (Moore et al., 2002) may also play a role. However, there is no obvious link between increased winter streamflow and changes in rainfall and snowmelt (contribution to streamflow) for most of the study catchments. This might also explain the comparatively low predictive skills of the multiple-regression approaches for the attribution of winter streamflow changes (Figure 6), which will be further discussed in Section 5.3.

To our knowledge, this is the first data-based attempt to evaluate changes in the contribution of rainfall and snowmelt as the most important runoff generation processes to daily streamflow in Norwegian catchments. This approach has originally been developed for the classification of peak flow events in Norway. The simple distinction between rainfall and snowmelt is comparatively straightforward since their contrasting roles for event runoff generation are very prominent compared to other regions where more complex event classification (e.g., R. Merz & Bîoschli, 2003) is necessary. For daily streamflow including low flow periods, however, additional drivers and catchment state variables are relevant as it has been indicated by the results of the statistical trend attribution. These have not been explicitly considered by this study. Still, this simple approach proved to be valuable to distinguish between rainfall and snowmelt as important contributors to daily streamflow and their changing relevance over time. However, the approach only allows to approximate the relative fraction of either rainfall and snowmelt contribution to measured streamflow volumes. It does not allow for the direct quantification of these runoff components in terms of volume.

5.3 Attribution of streamflow trends to hydro-meteorological drivers

The two simplest regression models (QRF and QSM; see Table 1) showed that rainfall and snowmelt as isolated drivers can explain streamflow changes to some degree in periods and regions where they are dominant (snowmelt: spring and Østlandet; rainfall: autumn and Vestlandet). The combination of both drivers into a more complex multiple-regression approach (QSMRF) improved the predictability of streamflow changes during all seasons and in both regions. This confirms the importance of both processes for the streamflow regimes in Vest- and Østlandet. Notably, detected streamflow changes can be best explained by adding temperature as an additional predictor.

Our results indicate that temperature trends may serve as a proxy for changes glacier melt in catchments that show some glacier coverage (particularly in Vestlandet). That is, glacial meltwater contribution to streamflow is indirectly considered by adding temperature as a predictor to the attribution approach. The fact that the largest improvements of the full regression model are observed for catchments with >10% glacier cover is interesting and may underline the relevance of temperature trends in this regard. However, it is important to note that the $R^2$ scores are still low (<0.5) and not all catchments with such large glacier cover show improvements of the same magnitude. At this point, alternative attribution approaches like dynamical process explorations based on physically-based hydrological models could be beneficial for gaining more insights into the role and interaction of trend drivers.

Improvements in $R^2$ scores by the full regression model were also found for unglaciated catchments in both regions. Here, it is assumed that temperature trends may serve as a proxy for increased ET, meaning that water losses to the atmosphere are also indirectly considered by the approach. This appears reasonable since the improvements are not only found for the summer season (glacier melt) but also for spring and autumn where ET may already/still impact the water balance of the catchments. A limitation of assuming temperature trends as proxies for both glacier melt and ET trends, is that an increase in each will
have the opposite effect on streamflow. Thus, it is possible that the effect of both drivers on streamflow are masked by each other in glaciated catchments. In this context, negative summer streamflow trends in Romania have been attributed to increased temperature and ET (Birsan et al., 2014), and in the Austrian Alps, Kormann et al. (2016) found positive ET trends during spring and summer, which however, could not be identified as a major driver for streamflow changes due to the dominance of other drivers. Trend analyses for different parts of the world reveal that ET has increased at many locations over the last decades (e.g., Duethmann & Blöschl, 2018; Ukkola & Prentice, 2013). Annual ET trends during the study period, estimated from water budget in unglaciated catchments, are generally positive to nonsignificant in Østlandet and negative to nonsignificant in Vestlandet (Skålevåg, 2019). Although the relative importance of ET on streamflow in Norway is small, it will probably increase in the future due to projected warming and (related) changes in vegetation characteristics like longer vegetation periods, upward migration of species in mountainous areas and land use changes (Bryn, 2008; Bryn & Potthoff, 2018). At the same time, water limitations (for ET) are not supposed to become a general issue in Norway due to an overall projected increase in precipitation in future years (Hanssen-Bauer et al., 2015).

Finally, we need to emphasize that even with our most complex multiple-regression model some streamflow changes could not be sufficiently explained. Regionally, this is particularly the case for some catchments in the high-mountain areas of Vestlandet and some catchments in the very east of Østlandet close to the Swedish border. Seasonally, it is particularly the case for winter streamflow changes, although potential drivers are known and have been discussed in Section 5.2. A general limitation of data-based attribution approaches is their inability to identify exact reasons for (poor) predictive performances. Regarding winter streamflow changes, one reason might be due to our classification of rainfall, which is defined as precipitation that falls at ≥0.5°C average catchment temperature. This approach is especially uncertain in winter; some of the precipitation at days with >0.5°C may still fall as snow, or rainfall may freeze on the ground. In both cases, the precipitation defined as ‘rainfall’ does not immediately contribute to streamflow. This may partly explain why rainfall and snowmelt trends explain streamflow trends during winter so poorly (Rizzi et al., 2018). A more general reason might be due to a missing predictor (i.e., driver) for the attribution of streamflow changes. However, since human interventions do not play any role in the study catchments, and since the attribution with the considered drivers works well for other catchments, it is hardly possible to identify any missing major driver in our statistical attribution approach. Uncertainty in streamflow, rainfall, and snowmelt data may be an issue that leads to poor attribution results for some catchments, particularly at the daily 10dMA scale and catchment-averaged snowmelt (modelled), rainfall and temperature (interpolated) values considered in this study. In this perspective, complementary hydrological model-based attribution attempts may (i) help identifying the influence of all these speculative reasons on the predictive performance of the multiple-regressions and (ii) possibly improve the attribution and understanding of meteorological drivers to detected changes in daily 10dMA streamflow where the statistical models perform poorly, (iii) identify trends in individual streamflow components (see Kormann et al., 2016). The adoption of a model-based approach would, however, require the adaptation, calibration and verification of a dynamic (physically-based) hydrological model in a multitude of catchments which larger data requirement.

6 | CONCLUSIONS

This study examined sub-seasonal trends (i.e., daily trends in 10-day moving averaged time series) in streamflow, rainfall and snowmelt in 112 catchments divided between two Norwegian runoff regions (Vestlandet and Østlandet) over a 30-year period (1983–2012). Moreover, this study also estimated the relative contribution of snowmelt and rainfall to daily streamflow in these catchments, and trends over the same time period reflect the changing relevance of both processes for streamflow generation at the sub-seasonal scale.

Results reveal the benefit of sub-seasonal trend analyses since the identification of significant sub-seasonal trends allows for (i) the detection of periods with positive/negative trends which might compensate each other at the seasonal or annual scale, and (ii) the direct comparison of streamflow trends with their most important hydroclimatological drivers. The most significant trends detected in this study for both regions refer to earlier snowmelt which causes an earlier onset of spring streamflow. This is in line with other studies from Nordic and/or mountainous regions and can be considered as the most robust climate change signal in streamflow response in such environments. The sub-seasonal perspective, though, allows to identify the exact timing of these trends which can be catchment specific and altitude dependent.

Otherwise, the detected trend patterns differ between both regions. Positive rainfall trends during summer in Østlandet coincide with increases in streamflow in catchments up to 1100 m a.s.l. Winter streamflow increases occurred in about 50% of the catchments in Østlandet which is also supported by other studies from cold regions. Trend patterns in Vestlandet are less coherent and less significant as compared to Østlandet. In general, the relative importance of rainfall (snowmelt) as a contributor to daily streamflow has increased (decreased) in both regions over 1983–2012, which will certainly continue in future.

Using a data-based trend attribution approach (i.e., multiple linear regression models with growing complexity), we found that trends in snowmelt and rainfall can to a certain extent explain observed streamflow trends, with considerable seasonal and inter-catchment differences. The improvement of the attribution by including temperature trends in the multiple linear regression, though, indicate that other temperature-dependant drivers such as glacier melt and evapotranspiration may also be important in driving recent streamflow changes in Norway. However, also the most complex regression model used in this study could not sufficiently explain/suggest the underlying causes for the detected changes in streamflow in all
catchments. This highlighted the limitation of such data-based attribution approaches. Dynamical (physically-based) hydrological modelling could be applied as an alternative to explore and attribute streamflow changes to changes in the atmospheric boundary conditions and streamflow generation processes.

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DATA AVAILABILITY STATEMENT
Runoff data for most of the catchments used in this study are freely available for scientific purposes via the Hydra II database (https://www.nve.no/hydrologi/hydrologiske-data/data-i-hydra-ii-database/bruk-av-hydra-ii/) maintained by the Norwegian Water Resources and Energy Directorate (NVE). For a few catchments, restrictions apply to the availability of these data, which were used with permission for this study. Gridded precipitation, temperature, and snowmelt data stem from the seNorge database (http://www.senorge.no).

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