Driving processes of daily streamflow trends in the central Norwegian mountains

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Abstract

Mountainous and Nordic regions are experiencing more rapid temperature increases compared to regions at lower altitudes and latitudes, which will impact the hydrology in these regions.

We analysed daily-resolved streamflow trends for 112 catchments in Western and Eastern Norway for the period 1983-2012, and compared them with daily-resolved trends in hydro-meteorological drivers. Additionally, the relative contribution of snowmelt and rainfall to daily streamflow for each catchment were estimated and trends therein identified. This process-orientated approach at high temporal resolution allows for a better identification of (in)consistencies with changes in the hydro-meteorological drivers than simple seasonal comparisons. Lastly, we aim to attribute observed changes in daily streamflow to the most dominant hydro-meteorological drivers by applying seasonal multiple-regressions.

The major findings of this study are as follows:

- The high-resolution trend analysis allows for in-depth seasonal-specific insights into the hydrological response of catchments with different hydrological regimes to changes in the hydro-meteorological drivers.
- Increasing (decreasing) contributions of rainfall (snowmelt) to streamflow generally agree with prior expectations. The trends, however, show differences in magnitude and timing, depending on the geographical location (Vestlandet vs. Østlandet) and altitude.
- The seasonal multiple regression approach suggests that daily streamflow changes can be explained best by adding temperature as an additional predictor to snowmelt and rainfall, which may indicate the changing relevance of evapotranspiration particularly during summer.

1 Introduction

Context

It has been unequivocally confirmed that the world has warmed since the 19th century (Hartmann et al., 2013). How this warming has and will affect hydrology has been a focus of much research. Mountainous and cold-climate regions, where snow and ice plays an important role in the hydrological cycle, are thought to be especially vulnerable. As a result of global warming, possibly amplified by elevation dependent warming effects (Pepin et al., 2015), the cryosphere in mountainous regions are in a rapid decline, which will likely accelerate in the coming decades (Huss et al., 2017). Global warming is also changing the hydrological cycle. With each degree warming, the water holding capacity of the air increases with 7%, meaning changes are particularly evident in precipitation and potential evapotranspiration (Jiménez Cisneros et al., 2014; Trenberth, 2011). Furthermore, how runoff and groundwater will change in cold regions in a warmer climate has been identified as an unresolved questions in hydrology (Blöschl et al., 2019).

As hydrological predictions by global climate models on the catchment or seasonal scale are associated with high uncertainties (Shen et al., 2018; Todd et al., 2011), the analysis of already observed hydrological changes can give a valuable additional indication of expected future changes (Burn et al., 2012; Cramer et al., 2014).

Issue

Global streamflow trends display spatially complex patterns, which prevents simple generalisations of regional changes at the global scale (Gudmundsson et al., 2019). However, a global analysis of extreme and mean annual streamflow trends indicates that in a respective region, the entire flow distribution either increases or decreases, i.e. high-, mean- and low-flow generally all increase or decrease (Gudmundsson et al., 2019). The major rivers of the world show large interannual and decadal variations in streamflow (Dai et al., 2009).

There are currently several well established methods for detecting hydrological trends, most of which determine the trend significance and magnitude of a variable over a certain period. Attributing detected changes to climate change, however, is not straight forward.

Streamflow rates are the result of several interconnected catchment scale processes as well as variation in hydro-meteorological variables determined by prevailing climate patterns and variability. Various drivers acting simultaneously and some driver-effect mechanisms not being well understood complicates the attribution of hydrological trends, while high natural variability, low signal-to-noise ratio, and complex behaviour (in hydrological time series) can make trend detection difficult (Merz et al., 2012; Blöschl et al., 2007). "describe a reasonably coherent picture of short-term hydroclimatic change; however, trend detection and attribution remain difficult because of the length and quality of the available data, and the complex relationship between changes in temperature and precipitation and their combined effect on snowpack and snowmelt-dominated runoff."(Stewart, 2009)

"As hydrological variability is driven by climate and modified by catchment characteristics and changes in land cover, it is difficult to attribute hydrological change to the different driving forces" (Fleig et al., 2013). Furthermore, catchment characteristics can be altered over time by human activities such as land use change, or by hydrological alterations. "In order to predict and prepare for changes in hydrological characteristics under a changing climate, good knowledge about observed hydrological changes and their causes is necessary" (Fleig et al., 2013). "There is clearly a need to diagnose and better understand the causes and mechanisms underlying the observed pattern in flow regime and its variability over the region if projections of future change (and associated societal impacts) are to be made with any confidence."(DeBeer et al., 2016)

What is driving the detected streamflow change? The first step in attributing streamflow changes/trends to climate change is to identify which hydrological processes/variables are driving the change.

Literature review

Globally, precipitation is the main driver of streamflow trends and decadal to interannual variability (Dai et al., 2009). In the world's largest rivers, climate change has a larger effect on annual streamflow than human activities (Dai et al., 2009).

Observed changes in the hydroclimate of cold and mountainous regions have mainly focsed on analysing trends in ... Mountainous regions around the world show marked changes in timing and amount of snowmelt, snow accumulation etc. etc. ... "Mountains in many parts of the world are susceptible to the impacts of a rapidly changing climate, and provide interesting locations for the early detection and study of the signals of climatic change and its impacts on hydrological, ecological, and societal systems." (Beniston, 2005) "The assessment of climatic change and of its related impacts in mountain regions has been shown to be particularly difficult because of the complexity of a number of interrelated factors in regions where topography is a dominant feature of the environment." (Beniston, 2005)

Based on projections of future hydrological conditions in Norway, streamflow changes are driven by both temperature and precipitation, with temperature changes having the largest impact (Beldring et al., 2008, 2006).

In two catchments on the Tibetan plateau, where snow and glacial melt plays important role in the hydrological regime, "The rainfall runoff was considered as the dominant factor driving changes of river discharge, which can be responsible for over 84% of changes in the total runoff over all focus catchments." (Zhang et al., 2019), but also found glacial melt to play an increasingly important role in compensating during dry periods.

"Since the early 1970s, and until 1996, the wintertime NAO index has been increasingly positive, indicative of enhanced westerly flow over the North Atlantic. This has led to synoptic situations in recent decades which have been associated with abundant precipitation over Norway, as cyclonic tracks enter Europe relatively far to the north of the continent (HURRELL, 1995)." (Beniston, 2005)

Earlier timing snowmelt and associated streamflow/runoff has been detected in many regions around the world (Clow, 2010; Maurer et al., 2007; Vincent et al., 2015; Stewart, 2009; Morán-Tejeda et al., 2014) and can be considered a consistent hydrological response to global warming. Although an earlier onset of snowmelt is expected in a warming climate, the rate of snowmelt will likely be reduced (Musselman et al., 2017; Wu et al., 2018).

"an air temperature increase from December to March had the largest impact on snow accumulation, while warming from April to June rather affected snowmelt onset, dynamics and melt-out (point in time at which all snowmelt out of the catchment) (Knowles et al., 2006; Feng and Hu, 2007)." (Jenicek et al., 2016)

"Snowpack takes on special significance in mountain regions where snow stores enormous quantities of water, altering the ecologic and economic balance of regions far down- stream by delaying the release of water months after precipitation events." (Brown and Mote, 2009) "The elevation response of snow cover and SWE varies with climate region, involves nonlinear inter- actions between snow cover duration and accumulated snowfall, and also depends on local factors, such as lapse rates, topography, and vegetation cover; these influences will complicate the interpretation of snow cover changes, particularly in mountain regions. The strongest elevation sensitivity of snow cover to climate change is most likely to be found in maritime climate regions."(Brown and Mote, 2009) "The strongest decreases in spring snow cover extent are observed around the coastal margins of NA, Scan- dinavia, northern Russia, and over the Himalayas. This follows the findings of the sensitivity analysis results, which indicated that snow cover in areas with larger precipitation amounts were likely to be more sensitive to warming." (Brown and Mote, 2009) "Snow cover duration was shown to have the strongest sensitivity to warming as measured by signal-to-noise ratio, with the largest relative changes in SCD and SWE over lower elevations of regions with a maritime winter climate— that is, moist climates with snow season temperatures in the range of -5°to +5 °C."(Brown and Mote, 2009)

"In watersheds receiving a mixture of winter rain and snow, the percentage of the watershed in the seasonal snow zone is the most important determinant of the seasonal streamflow distribution and the sensitivity to climatic warming. Trend analysis strongly indicates that the maritime PNW has seen a regional shift toward increasing winter discharge and decreasing summer discharge in seasonally snow dominated watersheds." (Jefferson, 2011)

"Data-based approaches are typically relatively fast to apply and less affected by model structural and parameter uncertainties. However, it is not always obvious whether the identified statistical relationships are due to physical cause-effect relationships. In the simulation-based approach, changes in streamflow are linked to changes in the drivers via process-based relationships implemented in the model. Furthermore, other data, such as the glacier mass balance data in this study, can be integrated within the modeling approach so that it may also be investigated whether the assumed causes for the changes are consistent with these data. Disadvantages of the simulation-based approach are the introduction of model parameter and structural uncertainties and the greater effort for setting up the model." (Duethmann et al., 2015)

"Trend attribution in mountain catchments is complex due to the fact that one has to consider the influences of variations in temperature and precipitation, in seasonal snow storage, and in glacier mass balance and area at different elevations [Molnar et al., 2011]." (Duethmann et al., 2015)

By comparing center timing trends modelled by VIC model with trends "estimated from a surface hydrology model driven by meteorology from a multicentury GCM control simulation", Maurer et al. (2007) found that observed center timing trends in 1950-1999 can't be significantly attributed to external forcing (as opposed to only natural climate variability).

Significant changes in the seasonal distribution of streamflow in Norway are expected (Beldring et al., 2006).

Several authors have suggested that examining seasonal and sub-seasonal trends may be more appropriate than annual trends, when it comes to hydrological change. Indeed, when both an annual and high-resolution trend analysis is performed, it is revealed that there may be significant seasonal change where no significant annual change is detected (Skålevåg, 2019). Additionally, high-resolution trends could help explain the underlying causes of any detected annual changes (Stahl et al., 2010). ”Streamflow trend analyses at a high temporal resolution, e.g., using annual time series of streamflow of each day of the year, are useful to investigate tem- poral shifts of the streamflow regime, which may then further be related to catchment properties [Dery et al., 2009; Kormann et al., 2015].” (Duethmann et al., 2015)

Norway is different in that high-elevation areas are showing a positive trend in SWE, although snow cover extent is reduced (Rizzi et al., 2018). Positive trends in SWE above about 850 m.a.s.l. were found by Skaugen et al. (2012). ”In regions characterized by colder winter climate long-term trends are found to be positive in general, while short-term trends shift from strongly positive in the first period to predominantly negative in the last period. Variation in SD is here mainly linked to variation in precipitation. In regions of warmer winter climate variation in SD is dominated by temperature, and long-term trends are mainly negative. Short-term trends start out weak overall in the first period but become strongly negative most places in the last period. It is likely that, although more and more regions in Norway will experience declining maximum annual SD in a projected wetter and warmer future climate, some inland and higher mountain regions may still accumulate more snow in the coming decades.” (Dyrrdal et al., 2013)

Norway is also different in that some areas have very high precipitation rates, which makes rainfall an equally important source of runoff (western slopes of the Scandinavian mountain range) The principal expected future changes to streamflow (in Norway) are earlier snowmelt and increased autumn discharge (Beldring et al., 2008).

Purpose

For Norway, there is increasing evidence for gradually increasing temperatures and recent changes in the intensity and frequency of precipitation as well as in the number of days with snow cover. In this paper, we examine the hydro-meteorological trends in 112 near-natural to prestine catchments divided between two distinct regions in Norway, Vestlandet (West-Norway) and Østlandet (East-Norway), which have pronounced differences in their hydro-meteorological regimes. Most catchments in these regions are characterized by mixed snowmelt/rainfall regimes with streamflow peaks during spring (dominant in Østlandet) and autumn (dominant in Vestlandet).

Our study aims at a better understanding the dominant processes driving streamflow trends by analysing daily streamflow records together with daily hydro-meteorological data using a high-resolution trend analysis approach. As precipitation, snow accumulation and timing of snowmelt are the main factor that determine the hydrological regime in Norway (Hanssen-Bauer et al., 2015), we hypothesise that examining daily trends in snowmelt and rainfall should to a large extent explain streamflow trends. Furthermore, we hypothesise that the inclusion of temperature trends could further improve streamflow trend attribution, as a proxy for glacial melt and/or evapotranspiration. Additionally, we analyse the trends in the relative contribution of rainfall and snowmelt to streamflow. We perform a data-based attribution to assess to what extent trends in the hydro-meteorological drivers can explain streamflow trends.

The main research questions we want to address in this paper are:

- ...

2 Study area and data

2.1 Hydro-climatological and runoff conditions

Due to early development of hydropower, Norway has a long tradtition of measuring and monitoring streamflow. Therefore, has some very long streamflow records, also many records. The NVE manages an extensive hydrometric observation network, with some ... gauging stations. Many of these are from catchments which are heavily impacted by athropogenic influences. 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. The area has been divided into two regions, Vestlandet and Østlandet, which lie west and east of the central Norwegian mountains respectively, and correspond to two of the six Norwegian runoff regions defined by NVE, which are based on watershed and administrative boundaries.

The typical flow regime in Norway consists of a winter low flow period, a clearly defined snowmelt flood in spring, a summer low flow period, and the occasional autumn flood due to precipitation as rain (Gottschalk et al., 1979). However, the hydrological condisiton in Norway varies greatly. Vestlandet has generally high precipitation rates, with some areas having a mean annual precipitation as high as 3500-4000 mm, while in some valleys in Østlandet, in the rain shadow of the Scandinavian Mountains, mean annual precipitation is around 300-400 mm (Hanssen-Bauer et al., 2015). Østlandet has a more continental climate with cold and dry winters, the highest summer temperatures and the bulk of the annual precipitation falls in summer. In Vestlandet the bulk of the precipitation falls in autumn and winter, and the winters are mild and humid. Lower-altitude catchments in Vestlandet (coastal) are generally dominated by precipitation, and snowmelt plays a smaller role in the hydrological regime. Vestlandet generally has smaller catchments than Østlandet, in addition to a steeper topography.

There is an advantage in analysing East- and West-Norway separately. Catchments of both regions are influenced by snow. Østlandet is representative of more continental regions where spring snowmelt dominates the hydrological regime. Such regions have been studied quite intensely. Catchments in Vestlandet, with the exception of those along the coastline, also have a marked spring snowmelt, but is additionally heavily influenced by precipitation(rainfall). "However, the hydrologic impacts of climatic change in areas which receive both winter snow and rain are poorly understood." (Jefferson, 2011) "Mountain ranges along coasts have strong elevational temperature gradients that control phase of precipitation, and many such areas receive abundant winter precipitation. [...] In these areas, lower altitude portions of watersheds may receive winter rain, while at high altitude seasonal snow accumulates. Intermediate elevations are occupied by a transient snow zone, where snow falls and melts more than once per winter [Harr, 1981]." (Jefferson, 2011)

"Mountain climates are determined by four major factors, namely continentality, latitude, altitude, and features related to topography itself (BARRY, 1994)."(Beniston, 2005) Differing *continentality* , Vestlandet is a maritime mountain climate, while Østlandet is more continental. They span the same *altitude* and *latitude* ranges. Similar *topography*, although Vestlandet generally has a steeper topography than Østlandet. "mountains in continental regions experience more sunshine, less precipitation, and a larger range of temperatures than maritime mountains"(Beniston, 2005).

2.2 Streamflow records

Daily streamflow records from 112 gauging stations belonging to the hydrometric observation network of the Norwegian Water Resources and Energy Directorate (NVE) formed the basis of the trend analysis. The majority of these stations are part of the Norwegian Hydrological Reference Network (HRN) compiled by NVE, and have been assessed as suitable for study of the effects of climate variability and change on the hydrology in Norway (Fleig et al., 2013). The catchments were selected according to the criteria set out by Whitfield et al. (2012), meaning they are pristine or near-natural, with less than 10% affected by basin development and absent of significant hydrological alterations. The streamflow data from some 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 streamflow records were added to those of the HRN, whose catchments are more affected by land use, but still unaffected by major hydrological alterations.

The study period from 1983-2012 was chosen to ensure the best spatial and altitudinal coverage. (The most recent records availiable to us were from 2014.) The data quality of the catchments belonging to the Norwegian HRN have already been assessed. We further enured that only streamflow records from catchments with less than 10% days missing in the chosen period were included in the analysis.

Some of the catchments are sub-catchments of each other or the same larger catchment, which can be identified by the first part of the station/catchment number (Tab. 1).

2.3 Hydro-meteorological data

Daily data for the hydro-meteorological drivers, rainfall, snowmelt and temperature, were extracted for each catchment from a daily 1 x 1 km2 gridded dataset covering the entirity of Norway, which contains data for a range of hydro-meteorological variables from 01.09.1957 to the present and is available to the public at www.seNorge.no. The dataset has been updated several times since its launch in 2006 (Engeset, 2016).

Precipitation and temperature data in the seNorge dataset (version 1.1.1) is interpolated from meteorological stations measurements, using triangulation and de-trended kriging respectively (see Mohr and Tveito, 2008). Precipitation is exposure and altitude corrected.

During large parts of the year precipitation accumulates as snow instead of contributing runoff, which complicates the analysis of daily trends. Therefore, we only consider rainfall in this study, which was defined as precipitation on days with temperatures above 0.5 °C. To complement the rainfall data we use daily snowmelt grids, which is 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 simple degree-day method with an additional term related to the seasonal and zonal variation in incoming short-wave radiation (see Saloranta, 2014).

Daily temperature, rainfall and snowmelt time series were extracted from the seNorge grids for each of the 112 catchments by taking the mean.

The fraction of streamflow contributed by snowmelt or rainfall were estimated from the extracted rainfall and snowmelt time series (see Methods).

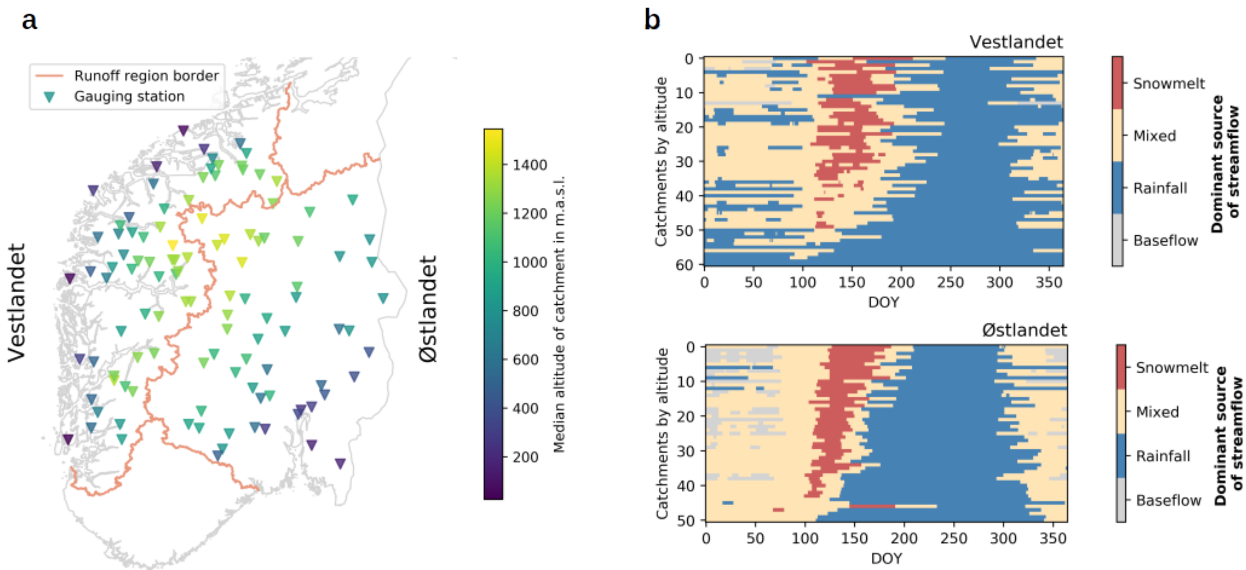

Figure 1: Gauging station locations and altitudes (a) and dominant contributor to runoff (b).

3 Methods

3.1 Relative contribution to streamflow

The relative contribution of rainfall and snowmelt to streamflow was estimated with a simple procedure, using the catchment specific parameter "normal flood duration" (NFD) and daily rainfall and snowmelt data. NFD is comprised of the concentration and recession times of a maximum flood event for a specific catchment, and, depending on the catchment, was either modelled or estimated empirically (see Vormoor et al., 2016). The runoff R contributed by X, i.e. either snowmelt or rainfall, at time t describes the amount of runoff that theoretically can be contributed by X to streamflow at any given day.

$$R_{X,t} = \sum_{i=t-NFD}^{t} X_i \tag{1}$$

The relative contribution C of either snowmelt (SM) or rainfall (RF) at time t can therefore be defined as

$$C_{RF,t} = \frac{R_{RF,t}}{R_{SM,t} + R_{RF,t}} \; ; \; C_{SM,t} = \frac{R_{SM,t}}{R_{SM,t} + R_{RF,t}} \tag{2}$$

On days where neither snowmelt nor rainfall contributed to streamflow, which is common during the colder months, C was set to 0. It is assumed that baseflow is the dominant source of streamflow in these periods.

3.2 High-resolution trend analysis

Rather than examining the trends in aggregated monthly, seasonal or annual values, a high-resolution trend analysis approach which determines the trend for each day of year (DOY) was used to determine daily trends in streamflow (Q), rainfall (RF), relative rainfall contribution (RFC), snowmelt (SM), relative snowmelt contribution (SMC), and temperature (T) for each of the 112 catchments. The approach (Fig.2) was developed by Kormann et al. (2014, 2015). The high-resolution trend analysis approach was developed for analysing streamflow, snow … changes (Kormann et al., 2014, 2015, 2016), and has also been used to assess elevation-dependent temperature trends and their underlying mechanisms (Rottler et al., 2019), but has yet to be applied to a region other than the Alps.

First, the original time series is smoothed with a 10-day moving average (10dMA) filter (Fig.2) to minimise the effect of transient storms on precipitation fluctuations (Whitfield et al., 2012) and to obtain similar hydrological responses from catchments of varying sizes (Déry et al., 2009). Furthermore, the inter-annual variability of daily values, i.e. the variability in each DOY time series (Fig.2), is high, which impacts the ability of the MK test to detect trends (Kormann et al., 2014). Kormann et al. (2014, 2015) used a 30dMA filter, but similar approaches have also applied a 3dMA filter (Kim and Jain, 2010) and 5-day averages (Déry et al., 2009). We opted for a 10dMA filter because previous work shows that the use of 30dMA gives the appearance of trends being more coherent and occurring over longer time periods (Skålevåg, 2019).

Second, the trend in each DOY time series is estimated separately, i.e. values from all years for 1st of January, 2nd of January, and so on (Fig.2). The trend magnitude is estimated with the Theil-Sen (TS) estimator (Sen, 1968; Theil, 1950) (also Sen's slope estimator and Kendall-Theil robust line), which is the median of the slopes of all data point pairs. As 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 (Skaugen et al., 2012).

Finally, the trend magnitude for each DOY time series is aggregated into a yearly trend cycle, i.e. daily resolved trends throughout the year (Fig.2). These daily trends of each catchment are in turn compiled to a regional trend array ordered by median catchment altitude.

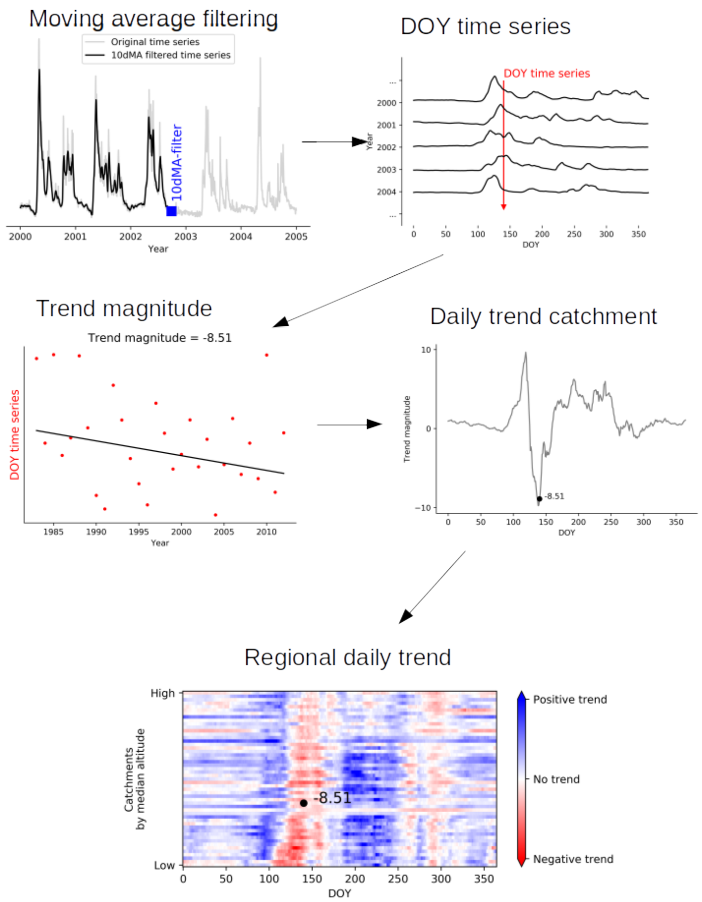

Figure 2: Daily trend analysis approach

3.2.1 Trend significance

The trend significance was determined at the local significance level α_{local}, i.e. for each catchment, and at the field (global) significance level α_{field}, i.e. for regional trends.

The Mann-Kendall (MK) test (Kendall, 1975; Mann, 1945) is is a non-parametric trend test for the detection of monotonic trends (Chandler and Scott, 2011; Helsel and Hirsch, 1992) and widely applied in hydrology for the detection of significant trends in time series (Burn et al., 2012). The presence of significant autocorrelation (serial correlation) in the time series leads to a disproportionate rejection of the null hypothesis of no trend by the MK test (Yue et al., 2002). Therefore, where a significant ($\alpha = 0.05$) lag-1-autocorrelation was detected with the Ljung-Box test (Ljung and Box, 1978), a prewhitening procedure after Wang and Swail (2001) was applied to the DOY time series

$$W_t = \frac{Y_t - cY_{t-1}}{1-c} \tag{3}$$

where Y_t is the original time series, c the auto-correlation coefficient, and W_t the modified time series. The MK test was applied to the (prewhitened) DOY time series to determine the significance of a trend ($\alpha_{local} = 0.1$).

Hydro-climatological data from different sites located in the same geographical area often cross-correlated (Wilks, 2006; Renard et al., 2008). The field significance can be used to determine whether detected trends at multiple sites are significant at the field (global) significance level α_{field}, and not purely detected by chance (Burn and 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 with a resampling approach (see Burn and Hag Elnur, 2002), which is considered a robust tool for determining the field significance (Renard et al., 2008). The resampling removes any temporal structure, but preserves any cross-correlation in the original dataset. The MK test is then applied to the re-sampled time series. This procedure is repeated N times, and the percentage of catchments with a significant trend in each resampling is combined to create a distribution ($N = 600$). The critical value p_{crit} is defined as the $1 - \alpha_{field}$ percentile of this distribution. If the percentage of catchments with significant trends exceeds p_{crit}, then the trend is deemed to be field significant, i.e. likely not caused by randomness and not significantly impacted by cross-correlation.

3.3 Data-based attribution with multiple regression

Due to the large number of catchments, we opted for a data-based attribution approach using ordinary least squares multiple regression, rather than a model-based one. Such an approach establishes a quantitative relationship between trends and their possible drivers (Duethmann et al., 2015). We asses to what degree various combinations daily trends in snowmelt, rainfall and temperature explains daily trends in streamflow for each of the 112 catchments. We assessed relationship between the trends for the entire yearly cycle, but also per season, i.e. winter, spring, summer, and autumn.

The streamflow trend in each DOY is assumed to be proportional to the trend in the hydrological drivers (4). RF and SM clearly has a strong influence on streamflow, and trends in these variables should therefore explain a large part of the streamflow trends. T trend is treated as a proxy for evapotranspiration (ET) and/or glacial melt. We performed an attribution with and without T trends (4). RFC and SMC trends were not included in the attribution.

$$Q_{trend}[m^3s^{-1}\ yr^{-1}]\ \sim\ SM_{trend}[mm\ yr^{-1}] + RF_{trend}[mm\ yr^{-1}]\ (+T_{trend}[^{\circ}C\ yr^{-1}]) \tag{4}$$

All analyses were realised with Python 3.7 (Python Software Foundation, 2018). The MK test and TS estimator were obtained from USGS's "trend" module (Hodson, 2018).

4 Results

A significant warming was found in ...

The streamflow trends ...

Two key findings in Østlandet are; (1) Increased streamflow in summer and (2) a positive-negative signal in spring (related to earlier snowmelt). In comparison the streamflow trends in Vestlandet are less coherent, although the same positive-negative signal can be detected, in the latter half of the year there are a sucsession of positive and negative phases that appear not to be altitude dependent (these correspond clearly with rainfall trends).

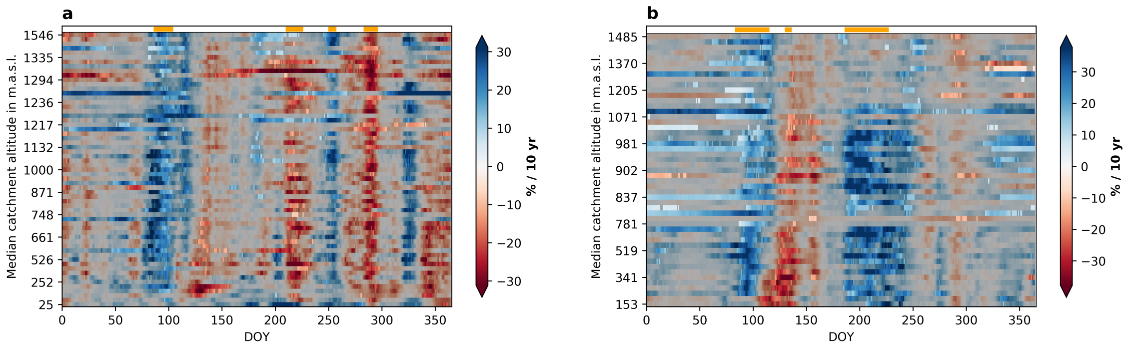

Figure 3: Streamflow trends

The snowmelt trends show a clear and consistent shift to earlier onset of snowmelt across all catchments in both regions, except low-altitude catchments.

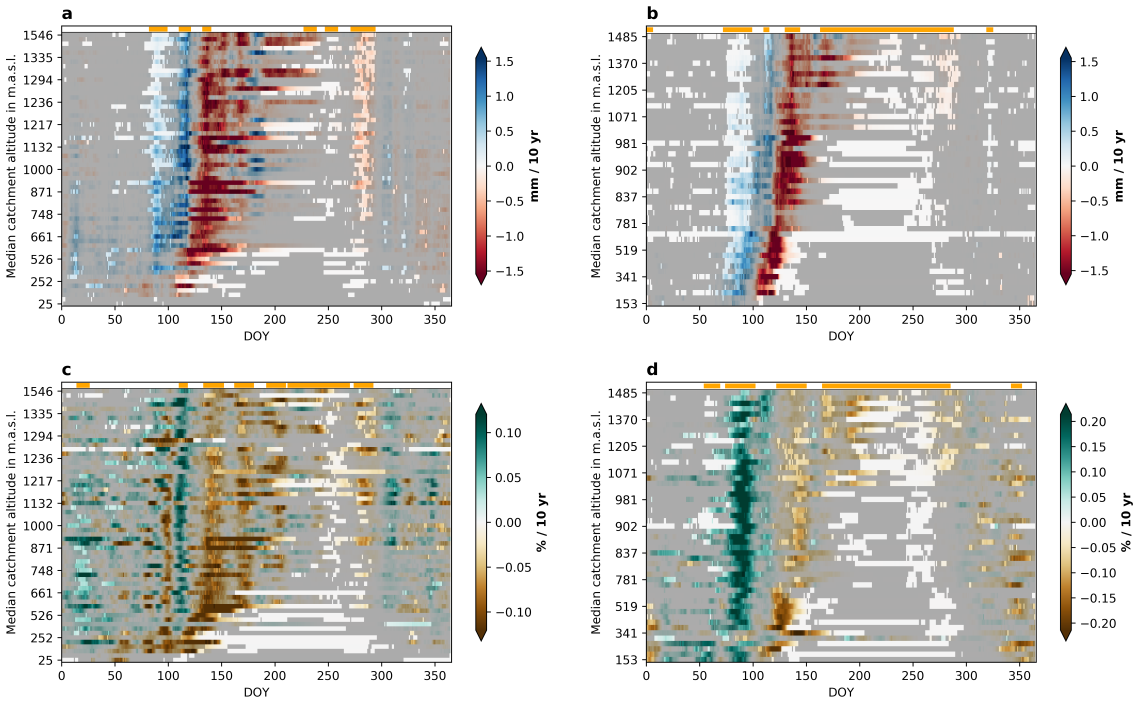

Figure 4: Snowmelt trends

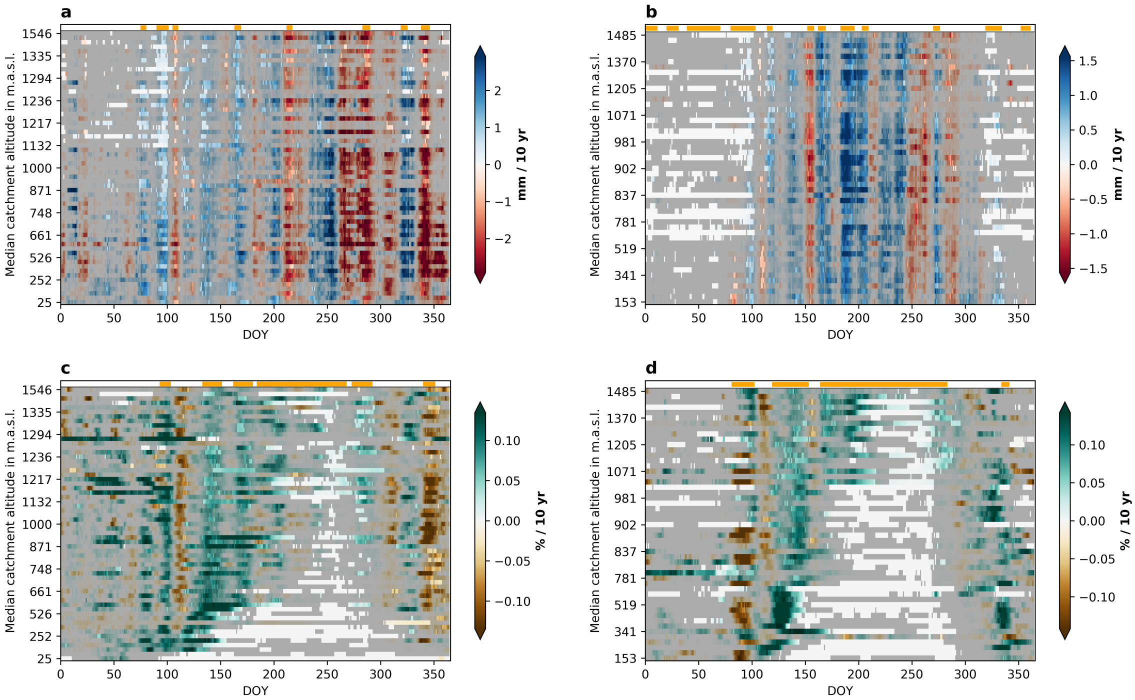

Figure 5: Rainfall trends

Adding the temperature trends improved the regression ... Attempts at creating an empirical model were unsuccessful, even when including independent variables to represent glacial melt, catchment gradient, etc.

5 Discussion

Compared to previous studiesconducted with the daily trend approach, which focused more on the influence of snow and glacial melt on streamflow in the Alps (Kormann et al., 2015, 2014, 2016), we have demonstrated the method on catchments that are influenced by both rainfall and snowmelt to varying degrees.

Findings suggest that streamflow during summer has increased in Østlandet from 1983-2012, caused by increasing precipitation/rainfall. However, in recent years Østlandet has experienced severe summer droughts, indicating that evapotranspiration trends could be playing an increasingly important role in modifying the hydrological regime. Quatifying the effects of evapotranspiration, especially with future warming in mind, should be a focus of future research.

The temperature trend is thought to be a proxy for evapotranspiration, meaning a positive temperature trend indicates a negative streamflow trend. However, in catchments with glaciation, temperature trend could also be a proxy for glacial melt. In such catchments a positive temperature trend could result in a positive streamflow trend due to increased glacial melt. Catchments with high glaciation are located at high altitudes and have a colder climate. It can therefore be assumed that evapotranspiration plays a minor role compared to glacial melt in these catchments, so that the temperature trend is a proxy for glacial melt. Conversely, in catchments with little to no glaciation, the temperature trend is a proxy for evapotranspiration.

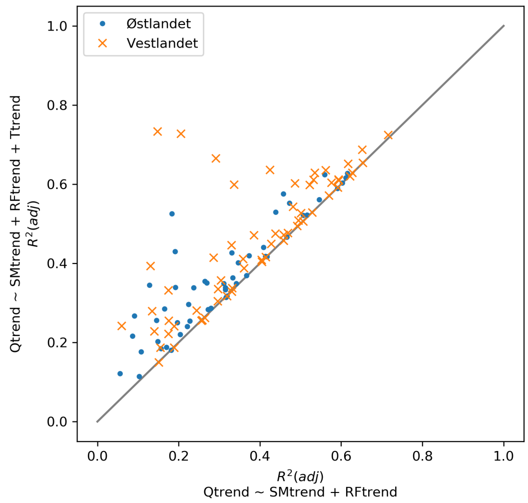

Figure 6: Influence of including temperature trends on R^2

seNorge data based on meteorological station measurements that are interpolated, high altitude areas are underrepresented (see Fig.1, Lussana et al., 2018). We acknowledge that since the MK test and TS estimator is designed to detect monotonic trends, abrupt change behaviour may not be accurately represented my out method. Nevertheless, the method has been proven to provide valuable insights into sub-seasonal trends. Our method for defining rainfall (precipitation falling on days with mean temperature > 0.5) is especially uncertain in winter: some of the precipitation may still fall as snow, and rainfall may freeze on the ground. In both cases, the "rainfall" doesn't contribute to streamflow. This may explain why rainfall and snowmelt trends so poorly explain streamflow trends during winter. Rizzi et al. (2018) suggested a similar issue impacted their results.

These effects could be masking any trends seen due to global warming, but also these effects (and climate variability) are in turn affected by climate change. Rottler et al. (2019) argued that “changing frequencies of weather types have to be taken into account when discussing yearly cycles of trend magnitudes of climatic variables”. In examining recent climatic trends in Canada Vincent et al. (2015) found that ”There is no evidence that the large-scale oscillations have influenced the temperature and precipitation trends over 1900– 2012 and the snow-cover and streamflow indices trends over 1950–2012. These results clearly demonstrate that, while the oscillations explain some of the climate variations during 1948–2012, the observed temperature and precipitation trends cannot be explained by low-frequency variability modes alone.”

This paper discusses observed hydrological trends, but what about the future? Climate change will lead to higher temperatures, higher precipitation(?), and less snow accumulation(?). As snow is (mainly) governed by both precipitation and temperature, it may respond differently to future climate change than what has been observed. E.g. the observed longer snowmelt period in higher lying catchments, may be different if warming reaches a point where snowpack trends are only negative. Additionally, any changes in prevailing weather patterns may have a much stronger influence than a mean warming. (See Hanssen-Bauer)

6 Conclusion

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