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Hydrology under change: long-term annual and seasonal changes in small agricultural catchments in Norway

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ABSTRACT

In agricultural catchments, hydrological processes are highly linked to particle and nutrient loss and can lead to a degradation of the ecological status of the water. Global warming and land use changes influence the hydrological regime. This effect is especially strong in cold regions. In this study, we used long-term hydrological monitoring data (22–26 years) from small agricultural catchments in Norway. We applied a Mann–Kendall trend and wavelet coherence analysis to detect annual and seasonal changes and to evaluate the coupling between runoff, climate, and water sources. The trend analysis showed a significant increase in the annual and seasonal mean air temperature. In all sites, hydrological changes were more difficult to detect. Discharge increased in autumn and winter, but this trend did not hold for all catchments. We found a strong coherence between discharge and precipitation, between discharge and snow water equivalent and discharge and soil water storage capacity. We detected different hydrological regimes of rain and snow-dominated catchments. The catchments responded differently to changes due to their location and inherent characteristics. Our results highlight the importance of studying local annual and seasonal changes in hydrological regimes to understand the effect of climate and the importance for site-specific management plans.

Key words: climate change, coherence, cold climate, trends, water management

HIGHLIGHTS

- Analysis of long-term hydrological monitoring data.
- Novel combination of Mann–Kendall trend and wavelet coherence analysis.
- Clear trends in air temperature but not in hydrological regimes.
- Discharge showed a stronger link to precipitation than to temperature.
- Snowmelt and rainfall-dominated catchments had different responses to climate change.

INTRODUCTION

Preserving water availability and quality is one of the main challenges facing societies globally. In catchments with high agricultural activity, hydrological processes are tightly linked to particle and nutrient loss, and if uncontrolled these losses can result in ecological degradation of water bodies (Bechmann 2014; Wenng *et al.* 2021). In addition to natural processes, hydrology in agricultural catchments is impacted by anthropogenic activities such as deforestation, vegetation shifts, annual soil cultivation practices, channel modification, and artificial drainage (Wagena *et al.* 2018). Furthermore, climate change may influence the hydrological behaviour of a catchment by altering runoff generation (Arheimer & Lindström 2015; Vormoor *et al.* 2015) and subsequently affects nutrient leaching. This is especially important in cold climate regions (defined as average air temperature above 10 °C in their warmest month and under 0 °C in their coldest months (Peel *et al.* 2007)) which are strongly affected by climate change (Aygün *et al.* 2020). According to future climate scenarios, the conditions in the Northern Hemisphere will be warmer and wetter and changes will be disproportionately greater than the global average (Hanssen-Bauer *et al.* 2015; Laudon *et al.* 2017; He *et al.* 2018; Aygün *et al.* 2020). One possible place to study changes in climate and hydrology in the Northern Hemisphere is Norway. In Norway, the annual median temperature is predicted to increase by 2.7 °C, and the median annual precipitation is expected to increase by 8% (intermediate emissions (RCP 4.5), 1991–2000 to 2071–2100) with the biggest temperature change in northern parts of Norway (+4.0 °C for RCP 4.5) (Hanssen-Bauer *et al.* 2015).

Furthermore, in Norway, the median annual discharge is predicted to be relatively small with an increase of 3% (RCP 4.5, 1991–2000 to 2071–2100), whereas seasonal changes are bigger, due to severe seasonal changes in precipitation and temperature (Hanssen-Bauer *et al.* 2015; Donnelly *et al.* 2017). There is also an interaction between climate change and seasonal effects. In winter, the discharge is predicted to increase due to increased precipitation and higher temperatures. Whereas, in summer, discharge will decrease because of earlier snowmelt episodes in the year and an increased evapotranspiration (Hanssen-Bauer *et al.* 2015). In the future, hydrological processes in winters will be more dynamic due to changes in land–water connectivity and will transform the traditional runoff patterns into a more unpredictable temporal distribution of runoff (Tattari *et al.* 2017). Research in Norway has found evidence of an increase in winter discharge and a tendency for more severe summer droughts between the 1940s and the early 2000s (Wilson *et al.* 2010). Additionally, as temperatures increase a transition in precipitation from snow to rain will affect the hydrological regime (Meriö *et al.* 2019). This may have strong effects because under most conditions snow does not immediately create runoff, but instead the precipitation is stored in the snow until temperatures raise above freezing (Meriö *et al.* 2019). Frozen soil may also restrict complete infiltration of water during snowmelt and rain periods and thereby modify surface and subsurface water fluxes (Ala-aho *et al.* 2021). Therefore, a changing climate may impact flood dynamics in Northern Europe both positively and negatively, and this has been supported by observations of increasing and decreasing river floods (Blöschl *et al.* 2019). In agricultural catchments where nutrient loss and hydrology are strongly linked (Bechmann 2014; Deelstra *et al.* 2014), these changes have a strong effect on nutrient loss and the control and mitigation measures that are required (Tattari *et al.* 2017; Liu *et al.* 2019).

Long-term monitoring of catchments plays a key role in observing baselines and detecting long-term changes in hydrological processes (Laudon *et al.* 2017; Brendel *et al.* 2019). Monitoring at the catchment scale of a multitude of hydrological variables, combined with analysis of long-term and seasonal changes provide us an insight into different parameters and variables. Land use, temperature, runoff, precipitation, and the links between the variables are important for land, water, and nutrient management (Brendel *et al.* 2019). In cold climates in particular, there remains a lack of understanding of how water runoff interacts with soils and vegetation and how this might influence nutrient loss (Liu *et al.* 2019). Furthermore, there is a difference in hydrology and nutrient transport between warmer and cold regions. Precipitation can occur as rain, snow, and rain on snow in cold regions and this is highly affected by climate warming (Laudon *et al.* 2017; Liu *et al.* 2019). Therefore, it is not only crucial to study changes of single variables over time but also critical to study interactions between discharge and climate variables and water sources. It is important to understand these interactions and how they influence nutrient loss, so agricultural management practices and mitigation measures can be adapted and developed (Wagena *et al.* 2018; Liu *et al.* 2019).

In this study, we analysed long-term hydrological and climate data (22–26 years) from seven small Norwegian agricultural catchments. Our main goals were:

(1) to identify long-term annual and seasonal trends in hydrology (discharge, high and low flows, soil water) and climate (precipitation, temperature, evapotranspiration, snow) and
(2) to identify causes for variations in discharge and discuss its impact on agricultural practices and water protection.

Study area and data

In this study, we used seven small agricultural catchments (87–680 ha, Table 1), covering different regions of Norway (Figure 1). The catchments are in the long-term Norwegian Agriculture Environmental Monitoring Programme (JOVA), which has been maintained by the Norwegian Institute of Bioeconomy Research since 1992 (Bechmann 2014). We chose to use these catchments because there were long and continuous measurements of their hydrology and land use. Furthermore, the widespread network made it possible to represent different soil textures, elevations, climate conditions, and therefore also different agricultural production systems such as cereal, grass, and vegetable production. Monitoring stations were located at the outlet of each catchment, and all catchments are tile drained (Table 1). The hydrological–climatological areas represented by the catchments are given as follows (Table 1): two types of continental climate, one with no dry seasons (Kolstad and Mørdre), and one with relatively warm and dry summers and cold winters (Volbu); coastal climate in the south (Vasshaglona, Time) and north (Naurstad) with relatively high precipitation compared with the other catchments; and one catchment (Skuterud) characterised between coastal and continental climate with relatively unstable and wet winters and warm summers

Table 1 | Catchment and climate characteristics

Catchment	Total area (km^2)	Agr. land use (%)	Dominant soil texture	Elevation (m.a.s.l.)	Monitoring period mean annual T (°C)	Monitoring period mean annual P (mm)	Monitoring period mean annual Q (mm)	Climate	Monitoring period
Kolstad (Kol)	0.68	68	Loam, loamy sand	200–318	4.5	705	379	Continental climate, without dry seasons	1994–2020
Mørdre (Mor)	6.80	65	Silt, silty clay, loam	130–230	5.3	732	318	Continental climate, without dry seasons	1994–2020
Naurstad (Nau)	1.46	42	Peat soil	4–91	5.5	1,264	1,083	Coastal climate	1994–2020
Skuterud (Sku)	4.50	62	Silty clay, loam, silty loam	91–146	6.2	767	568	Unstable winters, warm summer	1994–2020
Time (Tim)	0.97	88	Loamy sand, organic	35–100	8.4	1,322	804	Coastal climate, mild winters, high precipitation	1996–2020
Vasshaglona (Vas)	0.87	48	Sand, loam	5–40	8.4	1,497	1,095	Coastal climate, mild winters, high precipitation	1998–2020
Volbu (Vol)	1.66	43	Silty sand, silty loam	440–863	3.3	644	294	Continental climate, relative warm and dry summers, cold winters	1994–2020

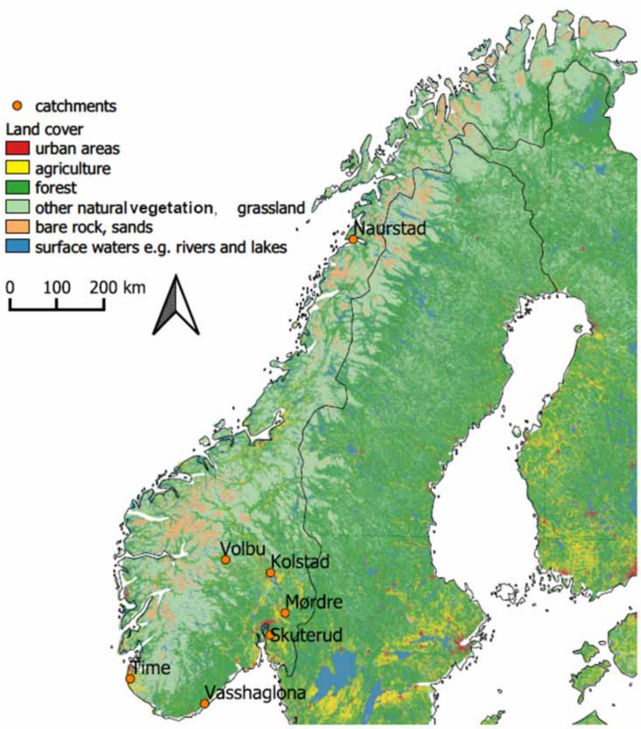

Figure 1 | Locations of the studied catchments in Norway. Land use data: CORINE land cover (https://land.copernicus.eu). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2021.066.

(Table 1). Furthermore, the presented selected catchments can be grouped into snow-dominated (Kolstad, Mørdre, and Volbu), where runoff is determined by snowmelt and rain-dominated catchments (Skuterud, Naurstad, Time, and Vasshaglona), where the runoff is determined by rain.

Monitoring data

The analysis was based on 22–26 years of hydrological observations for each catchment (Table 1). Data collection started between 1994 and 1998. Water levels were measured continuously at the catchment outlet, using a pressure transducer combined with a Campbell data logger, and converted to discharge (flow) at standard weirs (Deelstra *et al.* 2014). Water discharge (Q) was aggregated to daily values. Daily temperature (T) and precipitation (P) were taken from weather stations, located in or near the catchments. Effective precipitation (EP) was calculated as total precipitation minus total evapotranspiration. The daily discharge data was used to calculate flow indices such as baseflow index (BFI), high flows, and low flows using the River Analysis Package (RAP, version 3.0.8; Marsh *et al.* 2003). The BFI describes the proportion of baseflow of the total runoff measured at the catchment outlet (Deelstra *et al.* 2014). The RAP used the method described by Nathan & McMahon (1990) to calculate the BFI. They applied a method based upon a recursive digital filter. It was calculated with a recession coefficient of 0.975. To calculate the high flows, we defined the 10th and 25th (Q10, Q25) percentiles from the flow duration curve, whereas low flows were defined as the 90th and 75th percentiles of the flow duration curve (Q90, Q75). According to Wilson *et al.* (2010), thresholds range between the 10th and 30th percentile are reasonable for perennial streams. We also calculated normalised water runoff seasonality by dividing the total seasonal runoff (Qs) with total annual runoff (Qa).

$$\text{Seasonality in } Q = \frac{Qs}{Qa} \tag{1}$$

This gives an idea of how much the different seasons contribute to the total annual runoff. Seasons were defined as winter: December–February; spring: March–May; summer: June–August; and autumn: September–November.

Model data

We added to our analysis information on daily evapotranspiration (ET), daily soil water storage capacity (SWC) (the subsurface storage capacity in mm compared with a simulated maximum, using the HBV model) and daily snow water equivalent (SWE). The meteorological input to the gridded hydrological model is determined by an interpolation procedure, but the hydrological variables were calculated by the Gridded Water Balance model (GWB; Beldring *et al.* 2003), a spatially distributed version of the HBV hydrological model (Lindström *et al.* 1997). Grids were generated by interpolating between measurement stations, using triangular irregular networks (Vormoor & Skaugen 2013). Evapotranspiration was estimated with a temperature index method by the HBV model (Lindström *et al.* 1997) and snow data was calculated based on precipitation and temperature by the snow map model (Saloranta 2012). All the datasets are available from the Norwegian data platform (http://www.senorge.no/), an open portal run by the Norwegian Water Resources and Energy Directorate (NVE), the Norwegian Meteorological Institute (MET), and the Norwegian Mapping Authority.

Filling of data gaps in the monitoring datasets (discharge, temperature, precipitation) was required for further processing such as indices calculation and wavelet coherence analysis. Single time step gaps were filled with linear interpolation by the RAP. Gaps of several times steps in a row were filled with data available from the SeNorge platform.

METHODS

Trend analysis

Statistical tests and trend analyses were run in R (version 3.5.2). For the trend analysis, we applied the rank-based non-parametric Mann–Kendall trend test to assess the significance of a trend (Bouza-Deaño *et al.* 2008). Here, we used the R package '*TTAinterfaceTrendAnalysis*' (Devreker & Lefebvre 2014). We applied the trend test to mean monthly values to calculate the annual and seasonal trends of Q, precipitation, temperature, ET, SWC, SWE, BFI, low flow, and high flow. We used the Theil–Sen slope to estimate the slope of the changes in the hydrological and climate data (Theil 1950; Sen 1968). It determines for each sample point the median of the slope of the crossing lines (median between ranks). The Theil–Sen estimator can be applied when the data contain outliers or when the data are missing (Bouza-Deaño *et al.* 2008). It is a robust non-parametric estimate of the slope.

Wavelet coherence analysis

We used wavelet coherences to identify correlations and couplings between the flow time series (discharge) and predictor variables such as precipitation, temperature, ET, SWE, and SWC. The wavelet analysis was conducted in R version 4.0. with the R package '*biwavelet*'.

Wavelets decompose time series into time-dependent spectral series which is calculated by applying the wavelet to the time series as a bandpass filter (Grinsted *et al.* 2004). The decomposition of the time series into power spectra enables the features of a time series to be localised into time and frequency. This decomposition shows the dominant periodicities of variability and how these dominant periods vary in time (Torrence & Compo 1998). The wavelet transforms, therefore, allow examination of time series features at different time scales. This allows broad-scale features from time series to be identified at long time scales, and fine-scale features from time series to be identified at short time scales (Carey *et al.* 2013). In this study, we used the Morlet wavelet function. The Morlet wavelet is commonly used within hydrological studies as it is able to provide a good balance between the localisation of frequency and time, thus allowing time-dependent phase and amplitude changes to be observed (Torrence & Compo 1998; Carey *et al.* 2013). The Morlet wavelet can be described as follows:

$$\varphi_0(\eta) = \pi^{-\frac{1}{4}} e^{\omega_0 \eta} e^{-\frac{1}{4}n^2} \tag{2}$$

where $\varphi_0(\eta)$ is the wavelet function, ω_0 is the dimensionless frequency, i is the imaginary unit, and η is dimensionless time (Grinsted *et al.* 2004).

The wavelet coherence then shows the correlation and coupling between two wavelet power spectra. The wavelet coherence thus functions as a correlation coefficient between two wavelet transformed time series. The coherence relates spectra to the two original time series by identifying at what areas in both time and frequency two time series show synchronicity. High coherence between time series can be used to infer details about the hydro-meteorological processes controlling the relationship at different periodicities (Carey *et al.* 2013). The wavelet coherence can be described for two time series that have been wavelet transformed into $W_i^X(s)$ and $W_i^Y(s)$ as (Torrence & Compo 1998):

$$R_n^2 = \frac{|S(s^{-1}W_i^{XY}(s))|^2}{S(s^{-1}|W_i^X(s)|^2) \cdot S(s^{-1}|W_i^Y(s)|^2)} \tag{3}$$

where R_n^2 represents the coherence, W_i^X and W_i^Y represent the wavelet transforms for time series X and Y, and S is a smoothing parameter that is dependent on the type of wavelet used and defined by:

$$S(W) = S_{\text{scale}}(S_{\text{time}} \cdot W_n(s)) \tag{4}$$

where for the smoothing of a wavelet $S(W)$, S_{scale} smooths the scale axis, and S_{time} smooths the time axis (Carey *et al.* 2013).

Coherence values are returned ranging between 0 and 1. Values of 0 indicate no correlation, while 1 would indicate perfect correlation. The wavelet coherences in this study are presented as a heat map showing the wavelet coherences across the time series, and as a table to show the short-term coherence (<30 days). Each coherence plot features arrows. The arrows and their direction indicate the phase of the relationship (directionality of relationship) between discharge and other variables. Right pointing arrows indicate that the two variables are in phase (moving in the same direction, positively correlated), left ones indicate that the variables are out of phase (moving in opposite directions, negatively correlated). Down pointing arrows indicate that the first variable is leading, whereas up pointing indicates that the second variable leads which means the variables are not directly or immediately responding to each other.

To accurately perform wavelet transformations, continuous time series are required. Resultantly, the catchment time was excluded from the analysis because there is a gap in the discharge data from 1999 to 2003, due to problems with the monitoring station.

RESULTS

Long-term annual and seasonal trends

During the monitoring period, air temperature increased significantly in all catchments (sen-slope 0.05–0.1 °C $year^{-1}$), except for the most southern site (Vasshaglona) (Table 2). The seasonal analysis showed that temperature increased in all seasons, with the largest increase in spring (sen-slope 0.05–0.14) for six catchments, and in the winter period (sen-slope 0.05–0.17) for five catchments. Naurstad showed only a tendency in winter and Vasshaglona did not show any seasonal trend. Volbu was

Table 2 | Sen-slopes of annual and seasonal trends of discharge (Q), baseflow index (BFI), low flow (LF), high flow peaks (HF), precipitation (P), temperature (T), soil water storage capacity (SWC), evapotranspiration (ET), and snow water equivalent (SWE), green: significant trend ($p<0.05$), yellow: tendency ($0.05<p<0.1$); minus indicates a negative trend, plus indicates a positive trend

	Qmean [mm]	BFI [-]	LF90 [mm]	HF10 [mm]	P [mm]	T [°C]	SWC [mm]	SWE [mm]	ET [mm]
KOL									
annual	0.01	<0.01	<0.01	0.01	<-0.01	0.07	-0.17	0	<0.01
spring	0.01	0	<0.01	-0.03	-0.01	0.09	0.12	0	0.01
summer	<0.01	0.01	<0.01	-0.03	-0.01	0.05	-0.22		0.01
autumn	0.02	<-0.01	<0.01	0.05	0	0.04	-0.46	0	0.01
winter	0.01	<0.01	<0.01	-0.01	<0.01	0.09	-0.18	-0.49	0
MOR									
annual	<-0.01	<-0.01	0	0.04	<0.01	0.07	-0.22	0	0.01
spring	-0.02	-0.01	0	0.08	-0.02	0.09	0.22	0	0.01
summer	<-0.01	<-0.01		0.07	0.01	0.04	-0.07		0.01
autumn	0.01	-0.01	0	0.04	<0.01	0.06	-0.28	0	0.01
winter	<0.01	<0.01		-0.04	0.01	0.13	-0.75	-0.58	<0.01
NAU									
annual	-0.01	<0.01	0	-0.1	0.02	0.06	0.61	0	<0.01
spring	-0.02	<-0.01	<-0.01	-0.08	0.031	0.07	0.4	0	0.01
summer	<-0.01	0	0	-0.02	0.03	0.05	0.63		-0.01
autumn	-0.03	<0.01	<-0.01	-0.23	0.02	0.06	1.16	0	0.01
winter	0.01	<-0.01	<-0.01	0.05	0.01	0.06	0.39	-0.98	<0.01
SKU									
annual	0.01	<-0.01	<0.01	0.1	-0.01	0.05	-0.29	0	0.01
spring	-0.01	<-0.01	0	<0.01	-0.02	0.07	0.01	0	0.01
summer	0.01	<-0.01	<0.01	0.09	-0.01	0.03	-0.36		0.02
autumn	0.05	<-0.001	<-0.01	0.19	<0.01	0.05	-0.58	0	0.01
winter	0.02	0.01	<0.01	0.01	<0.01	0.08	-0.44	-0.51	<0.01
TIM									
annual	<-0.01	-0.01	<-0.01	-0.15	0	0.05	-0.02	0	0.01
spring	<-0.01	-0.02	0	-0.05	<-0.01	0.05	0.07	0	0.01
summer	0.01	-0.01	<-0.01	-0.23	<0.01	0.04	-0.04		0.01
autumn	-0.09	-0.00	<-0.01	-0.08	-0.01	0.03	-0.03	0	0.01
winter	0.03	<-0.01	<-0.01	-0.17	-0.02	0.08	-0.23	-0.09	0.01
VAS									
annual	0.02	<-0.01	<0.01	0.01	0.01	0.01	-0.02	0	0.01
spring	0.03	<-0.01	<-0.01	0.24	-0.04	0.02	0.03	0	0.01
summer	-0.01	-0.01	<-0.01	-0.26	-0.03	0.01	0.5		<0.01
autumn	0.04	-0.01	<0.01	0.17	0.03	0.01	-0.33	0	0.01
winter	0.09	-0.00	<-0.01	0.11	0.09	0.04	-0.45	0.04	<0.01
VOL									
annual	0.01	<0.01	-0	0.02	0.02	0.11	-0.73	0	<0.01
spring	<0.01	<0.01	-0	-0.03	0.01	0.14	-0.58	0	<0.01
summer	<-0.01	<0.01	<-0.01	<-0.01	0.03	0.06	-0.38		0.01
autumn	0.02	<0.01	<0.01	<0.01	0.03	0.10	-0.88	0	0.01
winter	0.01	0.01	0	-0.19	0.03	0.17	-1.33	2.01	<0.01

Please refer to the online version of this paper to see this figure in colour: https://doi.org/10.2166/nh.2021.066.

the catchment with the highest increase in air temperature in spring and winter (sen-slope 0.14 and 0.17) (Table 2). Annual ET, as expected, followed the long-term pattern of air temperature. Vasshaglona and Naurstad showed no significant annual trends for ET (Table 2).

Annual precipitation only showed a significant long-term increasing trend in Volbu (sen-slope 0.02 mm $year^{-1}$), while Naurstad showed a tendency to increased annual precipitation (Table 2). The seasonal analysis showed a significant increase in summer (sen-slope 0.03) and winter precipitation (sen-slope 0.03) in Volbu (Table 2).

Four of the sites had a significant increase in mean discharge (sen-slope 0.01–0.02 mm $year^{-1}$), as a result of increases in autumn or/and in winter (Table 2). The seasonality of the discharge showed that summer contributes the least (9–16%) to the total annual discharge in all catchments (Figure 2). In Vasshaglona, the difference between seasons, especially summer to the other seasons, was smaller (average difference of 0.13). Seasonality of the discharge was strongly influenced by whether the sites were rain-or snow-dominated. In rain-dominated catchments, most of the runoff occurred in autumn (~30%) and winter (30–40%), whereas, in snow-dominated catchments, runoff occurred primarily during snowmelt episodes in spring (40–50%, Figure 2). Mørdre had more hydrologically active winters lately because more precipitation fell as rain instead. This could be shown by a significantly decreasing SWE in winter for Mørdre (Table 2). The discharge might increase or decrease in the seasons as we could show that discharge increased significantly in autumn in Skuterud (sen-slope 0.05 mm $year^{-1}$) and

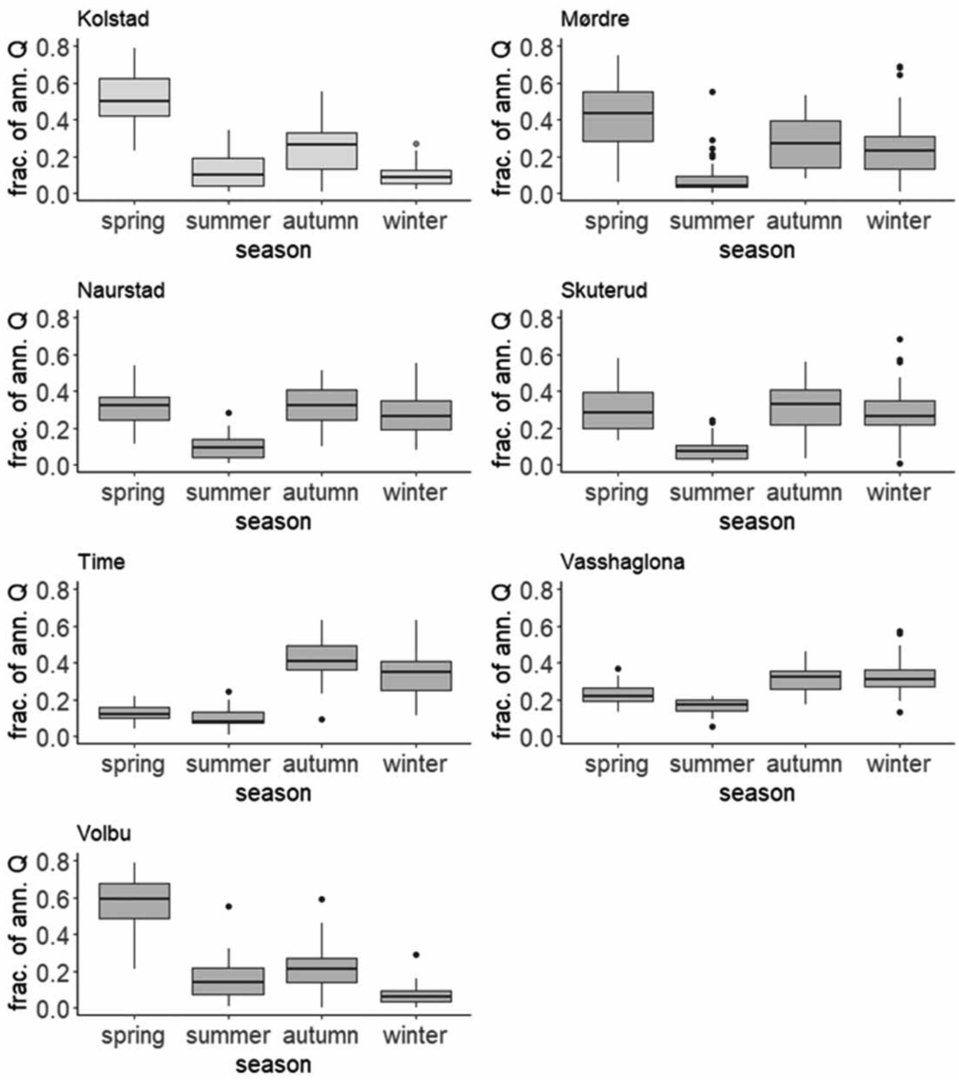

Figure 2 | Seasonality of the discharge in study sites: contribution of seasonal discharge to the total annual discharge for the monitoring periods.

Volbu (sen-slope 0.02). In contrast, discharge decreased significantly in autumn in Time (sen-slope 0.09, Table 2). In Kolstad, Vasshaglona and Volbu discharge increased significantly in winter (sen-slope 0.01–0.09).

The annual BFI increased significantly in Volbu (sen-slope <0.01 year^{-1}, Table 2), where winter was responsible for this change (Table 2). In Mørdre, Time, and Vasshaglona, the annual BFI significantly decreased (sen-slope <-0.01 to -0.01). Mørdre showed a significant decrease in spring, summer, and autumn (sen-slope -0.01 to <-0.01), Time showed a significant decrease in spring (sen-slope -0.02), summer (-0.01), and winter (<-0.01), and Vasshaglona showed a significant decrease in summer (sen-slope -0.01), which generally refers to drier conditions. The low flows of 90th percentile showed a significant positive annual trend for Skuterud and Kolstad and a negative trend for Time (Table 2). For the high flows of the 10th and 25th percentile, Time showed a significant decrease (sen-slopes -0.15, -0.09 mm year^{-1}), whereas Skuterud (sen-slope 0.1, 0.06) and Vasshaglona (0.12, 0.8) showed a significant increase (Table 2 and Supplementary Table SI-1). The seasonal analysis of Skuterud and Vasshaglona showed a significant increase for the high flows in autumn and winter respectively, which is also supported by a significant increase in maximum discharge in autumn in these catchments (Supplementary Table SI-1). This refers to even higher discharge during high flow periods (extremes) (Table 2 and Supplementary Table SI-1). In contrast, in Time and Volbu, low flow during summer significantly decreased and in Naurstad and Time, winter low flows became more extreme, according to the 90th percentile (Table 2). Vasshaglona was the only catchment that did not show any significant trends in low flows (Table 2 and Supplementary Table SI-1). The trend analysis on the annual frequency of high flows (10th percentile) only resulted in one significant trend: Skuterud (rain-dominated), which also showed a significant increasing trend in the annual numbers of high flow events.

The annual mean SWC increased significantly in Naurstad (sen-slope 0.61 mm year^{-1}, Table 2), hence more water could be stored. Volbu showed a significant decrease in annual, mainly autumn and winter, SWC (sen-slope -0.73), hence less water could be stored.

Annual changes in SWE were difficult to detect. However, four catchments (Mørdre, Naurstad, Skuterud, and Time) showed a significant decrease in SWE in winter (Table 2). In Volbu, a significant and large increase in SWE (sen-slope 2.01 mm year^{-1}) during the winter seasons was found.

Long-term annual and seasonal coherence

Figure 3 shows the coherence over time between discharge and precipitation. The coherences shown within the black lines are significant. There is a clear difference between the rain-dominated catchments Naurstad, Vasshaglona (coastal catchments) and to some degree, Skuterud with a strong coherency (red colour) and the snow-dominated catchments (inland catchments) with less coherence (blue colour) such as Kolstad, Volbu, and Mørdre. They showed a weak coherency in the short term (~30 days) and at the annual time scale (>256 days). These catchments were also the ones with the lowest total precipitation compared with the other catchments (Supplementary Figure SI-1). The rain-dominated catchments showed a coupling of runoff and precipitation in the short-term period (<30 days) and the coupling got even stronger closer to the annual period (<256 days). When considering the average wavelet power for each period (dominant periodicity), it turned out that the dominant cycle for precipitation was at smaller periodicity (days, weeks, 4–64 days). This result reflects the seasonal precipitation patterns (Figure 2 and Supplementary Figure SI-22). All rain-dominated catchments showed that discharge and precipitation are in phase (right pointed arrow) which suggests a rapid runoff generation. Furthermore, the inland sites (Kolstad and Volbu) showed a smaller coherence during spring (0.37, 0.32) and winter (0.29, 0. 23) than more costal catchments (Table 3, Figure 3, and Supplementary Figure SI-3). This decoupling of discharge and precipitation in the inland sites was likely a result of spring and winter snow.

One inland site (Volbu) showed a long-term decline in the coherence between discharge and precipitation (Supplementary Figure SI-5). However, an increasing long-term trend of the coherence was apparent with the most northern coastal site (Naurstad) (Supplementary Figure SI-5). Nevertheless, this trend had declined in recent years.

The impact of snow in the catchments could also be seen in the coherence between discharge and SWE (Table 3 and Figure 4), where Kolstad (0.36), Mørdre (0.38), and Volbu (0.40) exhibit the strongest coherence in spring. The coupling was strongest after a 6-month periodicity (>128 days). The average wavelet power (dominant periodicity) was highest on 6 months to a yearly cycle for all catchments (Supplementary Figure SI-23). There was a seasonal trend in the data at all sites with low coherence in summer and autumn (Supplementary Figure SI-11). Interestingly, Volbu showed a strong coherency in seasonal periods, but also on an annual scale. This suggests that Volbu's annual runoff primarily depends on meltwater. Considering the long-term trend of the coherence between discharge and SWE (Supplementary Figure SI-11),

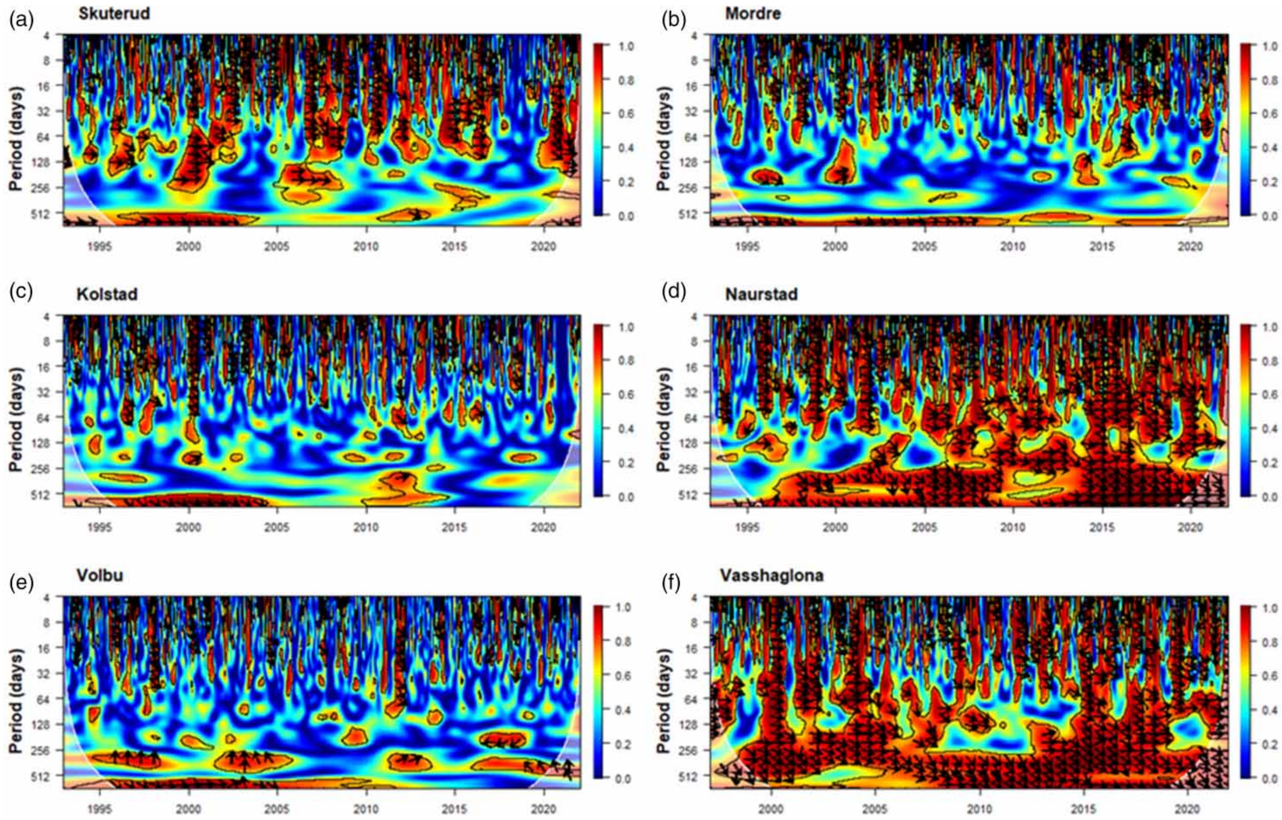

Figure 3 | Wavelet coherence between discharge and precipitation for 24–26 years of data. Colours indicate the strength of the relationship, with red to orange areas within the black lines significant at a 95% level. Please refer to the online version of this paper to see this figure in colour: https://doi.org/10.2166/nh.2021.066.

Kolstad, Naurstad, and Vasshaglona were quite stable (Supplementary Figure SI-13). Whereas Mørdre and Skuterud exhibited a decreasing trend that might be due to changes in the snow regime. Both showed a significant declining trend in SWE in winter (Table 2). Volbu also showed a decreasing trend in coherence with a particular drop in the last years (2017–2019).

Discharge and SWC are strongly connected to each other (Figure 5). The relationship is anti-phase (left pointed arrow, negatively correlated), meaning that small storage capacity results in higher discharge. The wavelet coherence analysis indicated that coupling between discharge and SWC is already apparent at short-term period (<30 days) and got even clearer at a 6-month period (>128 days) (Figure 5). The average wavelet power (dominant periodicity) was highest on 6 months to a yearly cycle for all catchments (Supplementary Figure SI-24). The coherence was strongest in autumn for all catchments (0.61–0.68, Table 3). Volbu and Kolstad showed the lowest coherence in winter (0.43 and 0.44) (Table 3 and Supplementary Figure SI-7). This is likely due to snow and frozen soil. No short-term (<30 days) trends in coherence between discharge and SWC was detected. In the long-term trend, this relationship for Volbu has decreased and particularly rapidly in the recent years. This pattern could to some extent also be seen in Mørdre (Figure 5(b) and 5(e) and Supplementary Figure SI-9). A gap occurred in the coupling between discharge and SWC in 2010 at periodicity of 256 days, which was particularly strong in Skuterud, Mørdre, and Kolstad and partly Naurstad and Volbu, but not in Vasshaglona (Figure 5).

Although temperature increased in six of seven catchments and in most of the seasons (Table 2), the coherence between discharge and temperature was low (Table 3 and Supplementary Figure SI-14). This result contrasts with our findings related to precipitation and SWC. The coherence between discharge and ET was low, too (Table 3 and Supplementary Figure SI-18). Discharge and temperature showed similar seasonal cycles in most of the sites. Furthermore, we did not detect any trends (short-term or long-term) of coherence between discharge and temperature. Only one site (Volbu) had a long-term trend of decoupling between discharge and temperature (Supplementary Figure SI-14). This might be due to the inland location of the catchment. Furthermore, Volbu showed the highest temperature increase and an increase in precipitation which might affect the hydrological regime.

Table 3 | Mean wavelet coherence by seasons at less than 30-day periodicity for flow against temperature, precipitation, soil water storage capacity, snow water equivalent and evapotranspiration (Mean ± SD)

	T	P	SWC	SWE	ET
KOL					
Spring	0.26 ± 0.11	0.37 ± 0.19	0.48 ± 0.16	0.36 ± 0.15	0.37 ± 0.13
Summer	0.26 ± 0.09	0.57 ± 0.14	0.57 ± 0.13	0.11 ± 0.08	0.31 ± 0.09
Autumn	0.30 ± 0.10	0.61 ± 0.18	0.66 ± 0.14	0.21 ± 0.16	0.34 ± 0.11
Winter	0.26 ± 0.10	0.29 ± 0.16	0.44 ± 0.17	0.28 ± 0.11	0.44 ± 0.15
MOR					
Spring	0.28 ± 0.11	0.46 ± 0.21	0.59 ± 0.15	0.38 ± 0.19	0.35 ± 0.13
Summer	0.25 ± 0.10	0.53 ± 0.16	0.50 ± 0.16	0.12 ± 0.11	0.29 ± 0.10
Autumn	0.31 ± 0.10	0.64 ± 0.16	0.65 ± 0.16	0.18 ± 0.14	0.35 ± 0.13
Winter	0.31 ± 0.11	0.42 ± 0.19	0.59 ± 0.15	0.36 ± 0.14	0.50 ± 0.15
NAU					
Spring	0.34 ± 0.10	0.54 ± 0.20	0.54 ± 0.14	0.33 ± 0.15	0.42 ± 0.15
Summer	0.27 ± 0.11	0.60 ± 0.19	0.57 ± 0.18	0.10 ± 0.08	0.27 ± 0.11
Autumn	0.32 ± 0.10	0.69 ± 0.14	0.67 ± 0.11	0.19 ± 0.16	0.35 ± 0.09
Winter	0.36 ± 0.12	0.58 ± 0.18	0.55 ± 0.16	0.38 ± 0.14	0.48 ± 0.13
SKU					
Spring	0.29 ± 0.11	0.50 ± 0.18	0.60 ± 0.16	0.37 ± 0.19	0.34 ± 0.13
Summer	0.27 ± 0.08	0.51 ± 0.17	0.54 ± 0.15	0.10 ± 0.08	0.32 ± 0.11
Autumn	0.30 ± 0.10	0.63 ± 0.21	0.67 ± 0.15	0.14 ± 0.12	0.35 ± 0.12
Winter	0.32 ± 0.11	0.49 ± 0.22	0.65 ± 0.16	0.33 ± 0.14	0.47 ± 0.15
VAS					
Spring	0.28 ± 0.10	0.53 ± 0.18	0.61 ± 0.16	0.26 ± 0.16	0.28 ± 0.11
Summer	0.29 ± 0.09	0.64 ± 0.14	0.61 ± 0.14	0.07 ± 0.05	0.37 ± 0.10
Autumn	0.30 ± 0.09	0.69 ± 0.21	0.68 ± 0.16	0.10 ± 0.10	0.35 ± 0.10
Winter	0.32 ± 0.11	0.52 ± 0.20	0.68 ± 0.14	0.31 ± 0.16	0.39 ± 0.14
VOL					
Spring	0.32 ± 0.15	0.32 ± 0.16	0.50 ± 0.15	0.40 ± 0.16	0.38 ± 0.12
Summer	0.25 ± 0.10	0.50 ± 0.19	0.52 ± 0.18	0.14 ± 0.11	0.28 ± 0.10
Autumn	0.29 ± 0.10	0.53 ± 0.18	0.61 ± 0.17	0.19 ± 0.13	0.34 ± 0.11
Winter	0.28 ± 0.11	0.23 ± 0.10	0.43 ± 0.17	0.29 ± 0.12	0.37 ± 0.16

DISCUSSION

Long-term annual and seasonal changes

We found significant trends in seasonal and annual air temperature in all catchments, except Vasshaglona. Also, other research showed that Vasshaglona had a mild climate compared with the other catchments and changes were lower in this region (+0.44 °C) during the period 1985–2014 (Hanssen-Bauer *et al.* 2015). The long-term prediction for this area are projected to be smaller (+2.2 °C) there than in other Norwegian regions like Finnmark (+4.5 °C) (Hanssen-Bauer *et al.* 2015). Trends might, therefore, not be significant in Vasshaglona. The largest changes were observed in winter. In the short-term (1985–2014), Hanssen-Bauer *et al.* (2015) found that the biggest increase was in autumn (+0.6 °C) on a national average. Additionally, the temperature in Norway is projected to increase by 3.3 °C by 2100 (Hanssen-Bauer *et al.* 2015). Evapotranspiration is also projected to increase in Fennoscandia (Donnelly *et al.* 2017). These projections fit with our result, as we observed an increase in ET in five of the seven catchments. However, ET used here was calculated based on a temperature

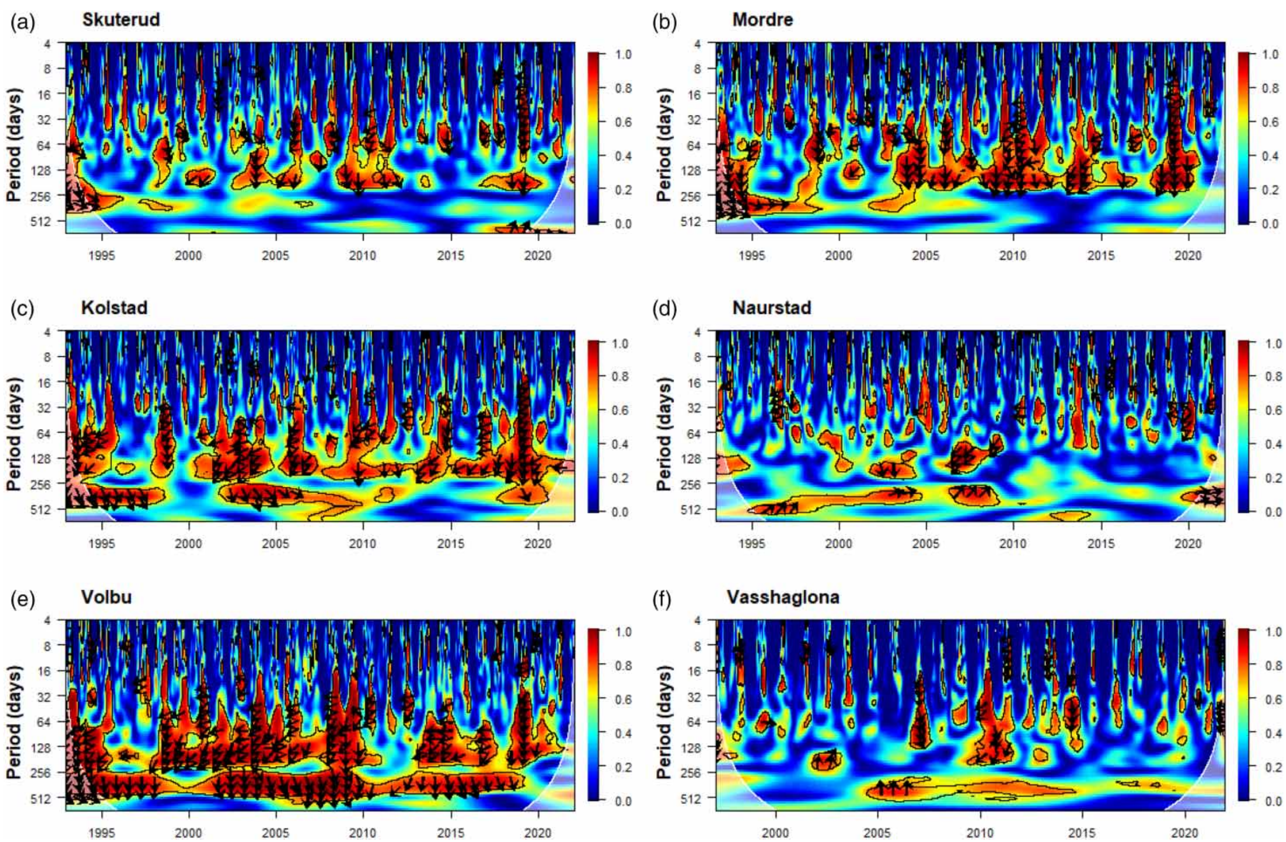

Figure 4 | Wavelet coherence between discharge and snow water equivalent for 24–26 years of data. The coherence within the black lines is significant. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2021.066.

index which might cause a similar pattern to temperature. Moreover, ET does not only depend on temperature. Humidity, wind, and CO_2 air concentrations are additional important variables impacting ET (Snyder *et al.* 2011).

In the hydrological data, trends were not easily detectable, and a spatial pattern was difficult to draw. Precipitation increased in recent years (1985–2014) in Norway and is projected to increase further in Norway and Northern Europe in all seasons (Hanssen-Bauer *et al.* 2015; Donnelly *et al.* 2017). We did not find any significant trends in precipitation in most of the catchments. However, we did find an increase in precipitation in summer and winter at one site located in the mountains (Volbu). Hanssen-Bauer *et al.* (2015) projected for the Volbu area (inland Norway) an increase of the total annual precipitation of 13% which is one of the highest regional increases. In general, changes in precipitation are more difficult to detect, because they are not only dependent on temperature, but on atmospheric circulations (Wilson *et al.* 2010; Irannezhad *et al.* 2014; Bailey *et al.* 2021). In addition, measurement errors for precipitation as snow might also play a role due to underestimation of 20–50% due to, for example, wind and wetting losses (Rasmussen *et al.* 2012). Furthermore, the dataset used in this study might be too short to detect trends in precipitation. Some publications suggest that hydrological time series should at least cover 40 years (Whitfield *et al.* 2012).

The catchments have different seasonal patterns in runoff, depending on location and whether they are snow-or rain-dominated. Therefore, changes in temperature and precipitation cause differing responses. Increased precipitation during autumn and more precipitation falling as rain instead of snow in winter, in combination with the increased number of intermediate snowmelt periods in winter and high soil moisture (reduced infiltration capacity) can cause increased high discharge (e.g., Skuterud) (Blöschl *et al.* 2019; Meriö *et al.* 2019). Increases in precipitation have been observed in south and west Norway (Blöschl *et al.* 2019) and in nearby countries such as the United Kingdom as the cause for changes in flood discharge extremes (Blöschl *et al.* 2019).

Snow-dominated inland catchments (Kolstad and Volbu) showed an increase in winter discharge, which might be due to higher temperature. This leads to reductions in snowfall and increase in rainfall, and an increased number of thaw-melt

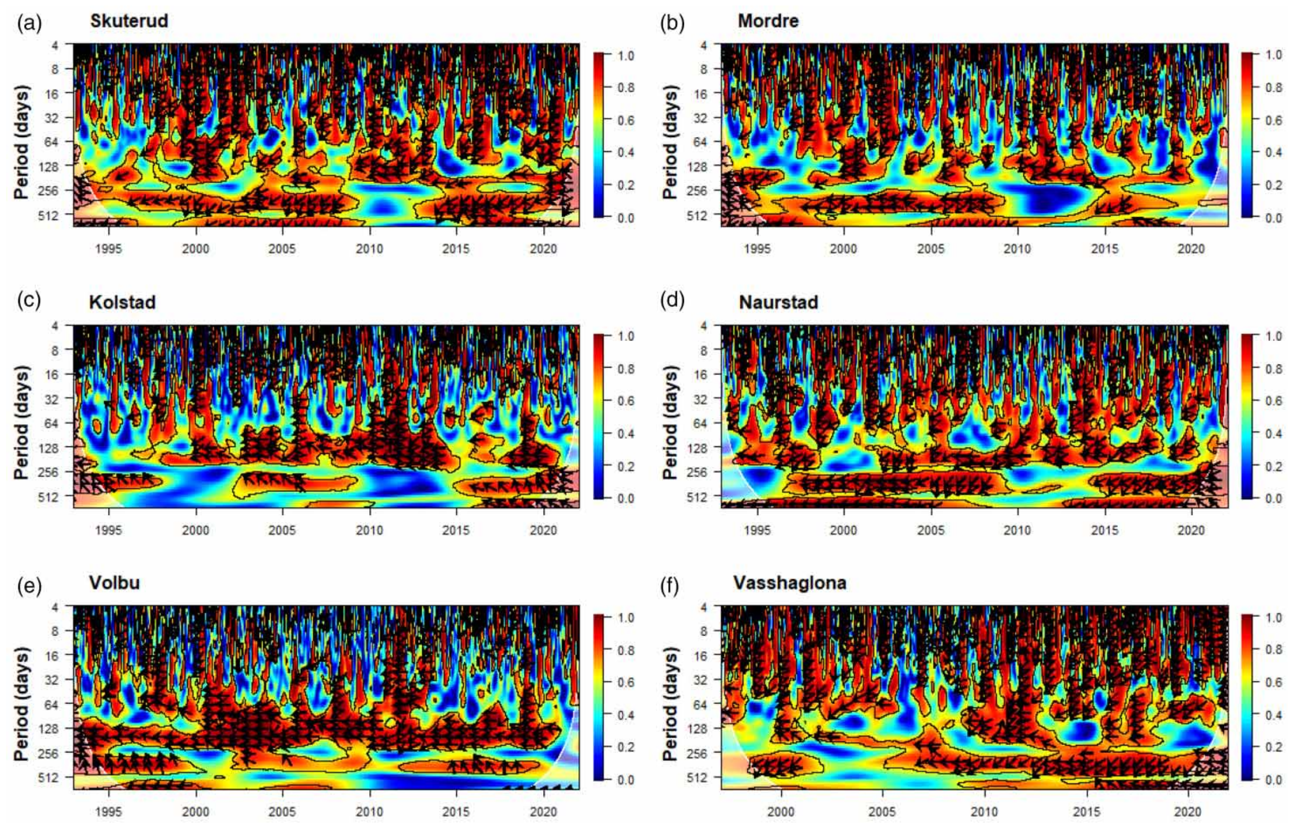

Figure 5 | Wavelet coherence between discharge and soil water storage capacity for 24–26 years of data. The coherence within the black lines is significant.

periods. An increase in winter runoff for Scandinavia was also found by other studies (Wilson *et al.* 2010; Donnelly *et al.* 2017). Hanssen-Bauer *et al.* (2015) projected a relative change in winter runoff of 26% (period 1971–2000 to 2071–2100, RCP 4.5). Seasonal snow cover and snowfall are in some catchments (Kolstad, Mørdre, and Volbu) an important part of the water cycle (in Norway 30% of the annual P falls as snow) and the runoff is dominated by meltwater (e.g., Volbu). Changes in climate will affect snow and soil frost conditions, influencing infiltration capacities and discharge event participation (Ala-aho *et al.* 2021). The mountainous catchment (Volbu) was the only catchment where SWE increased, despite increasing winter temperature. Large-scale regional differences in snow accumulation have been documented, for example, SWE was found to be increasing in the Baltics and decreasing in the North American prairies (Pulliainen *et al.* 2020). Skaugen *et al.* (2012) found that stations in southern Norway above 850 m.a.s.l. still accumulate snow in winter, despite increased temperatures. Volbu covers elevation levels from 440 to 863 m.a.s.l. and also accumulates snow. The increased amount of snow in Volbu may be due to higher temperatures which can transport more air moisture and hence can result in more snow, especially in northern Fennoscandia and mountain areas (Pulliainen *et al.* 2020). This pattern might also explain the long-term decline in coherence between discharge and precipitation in this catchment because precipitation is stored as snow and water is only released during melting periods.

Discharge is typically the highest in spring. In particular, in the snowmelt-dominated catchments (here e.g., Kolstad and Volbu), spring snowmelt is typically the biggest hydrological event of the year (Casson *et al.* 2019). We found some indications that this might be changing as we observed decreasing spring runoff in four of seven catchments (not significant). Hansen-Bauer *et al.* (2015) did not predict a decrease in spring runoff for Norway, but this may vary by region. Nevertheless, decreasing spring runoff might have several causes: snowmelts occurring in winter, lower precipitation, and higher temperature and hence more ET during this period (Donnelly *et al.* 2017) and extreme dry years such as 2018 might have an effect as well (Bakke *et al.* 2020). This also has an effect on the low-flow conditions in the upcoming seasons. The possible causes for decrease in summer low flow in Volbu can be the decrease in spring runoff which affects the summer discharge (Meriö *et al.*

2019). The significant decrease in autumn discharge and in annual low flows in Time might refer to the higher temperature and therefore increased ET. These results fit the projected hotspots of decreased low flow in Norwegian south-west coastal areas (Donnelly *et al.* 2017).

Coupling between discharge, climate, and water sources

Catchments in cold climates are expected to react more sensitively and rapidly to global warming and human activities than catchments in the temperate zone (Laudon *et al.* 2017; Bakke *et al.* 2020). Presenting an understanding of variability and coupling over time is important and provides an insight into how sensitive catchments are to climate change (Carey *et al.* 2013). The missing link between temperature and discharge in the seven Norwegian catchments may be explained by the opposing effects of temperature during the year. Increasing temperature will increase ET and thereby reduce runoff in the warm seasons, whereas increasing temperature might decrease snow accumulation and increase runoff during winter (Blöschl *et al.* 2019). The opposing effects of temperature on runoff might mask the coherence analysis. Temperature affects runoff indirectly through SWE and ET for which clearer connections than to runoff were detected. Furthermore, other factors like land use, soil type, and precipitation patterns might have a stronger effect on runoff.

Generally, discharge and precipitation are closely linked to each other. The reason for a close relationship and a short lag-time between precipitation and discharge in the presented catchments are the small catchment size, relatively low ET, and a limited storage capacity of the soil due to wet conditions. In addition, tile drainage systems in the study areas cause a fast response of runoff to precipitation for short-term and annual periods (Wenng *et al.* 2021). That soil water storage capacity impacts the actual runoff could be shown by a high coherence. The link between runoff and SWC is important and determines how fast precipitation is translated to runoff (Carey *et al.* 2013; Wenng *et al.* 2021). SWE is also closely related to runoff and the coherency is determined by a seasonal anti-phase pattern. That means catchments that are impacted by snow have a disconnection from terrestrial pathways to stream during winter as water is stored in the snow-pack and will first be active in spring (Carey *et al.* 2013). This could clearly be seen in inland and mountainous catchments and these processes are highly impacted by climate change (Vormoor *et al.* 2016; Blöschl *et al.* 2019; Meriö *et al.* 2019).

Volbu, the mountainous inland catchment, exhibits more marked changes compared with all other catchments. Volbu had the biggest temperature increase, increasing precipitation, and had the greatest dependency on snow, hence the highest discharge occurs in spring during snowmelt. This gives us a hint of how mountainous inland catchment might behave in the future. As the hydrology of mountainous catchments is very snow dependent, changes in winter temperature above 0 °C not only impact the storage of water, the shift in the snowmelt peak, and subsequent seasons but also the entire hydrological regime (Meriö *et al.* 2019).

Furthermore, our analysis indicated that single extreme conditions such as colder average temperature and high average temperatures can influence the total hydrological regime and have a tail to the following years. The year 2010 had a colder average temperature compared with others years and the winter was drier than usual (Dyrrdal *et al.* 2013). The decoupling between discharge and temperature, and discharge and SWC in the year 2010 for four catchments (Skuterud, Kolstad, Naurstad, and Volbu) could be due to the cold temperatures observed in the year 2010. Furthermore, the drier winters might lead to larger storage capacity of water in the soil. In the year 2018, Northern Europe was affected by an extreme drought and extreme low-flow conditions were recorded (Bakke *et al.* 2020; Fennell *et al.* 2020). A strong increase in mean temperature from 2017 (mean T 3.1 °C) to the year 2018 (mean T 6.6 °C) in Volbu was observed which might have affected the decoupled coherency between discharge and precipitation, SWC, SWE, and ET in the recent years. In regions affected by seasonal snow, droughts are also determined by accumulated snow volume and timing of snowmelt. High temperatures occurring already in the snowmelt season can lead to extreme high runoff during spring in mountainous catchments (Bakke *et al.* 2020). The catchment in northern Norway (Naurstad) also indicated a change in the precipitation regime during 2018 and 2019, when total precipitation was smaller than in the years before related to high-pressure systems centred over the Norwegian Sea (Bakke *et al.* 2020). This led to a weakening of the coupling between runoff and precipitation. Groundwater is important to mention in this context, because it plays a crucial role in the occurrence, timing, and magnitude of a hydrological drought (Bakke *et al.* 2020). Due to regional shallow groundwater (Deelstra *et al.* 2014), Vasshaglona showed the smallest seasonal difference in discharge of the seven catchments. Furthermore, it did not show any significant trends in low flows, assuming that it has quite stable conditions also during dry periods. Groundwater is important for drought resilience of a catchment (Fennell *et al.* 2020).

Implications for agriculture and hydrology

Climate change affects not only the hydrological regime but also water quality as hydrology and nutrient loss are strongly linked in agricultural catchments (Wagena *et al.* 2018; Liu *et al.* 2019). Farmers and catchment managers in the presented Norwegian agricultural catchments and in the Nordic region will have to deal with increased discharge in autumn and winter and drier conditions in summer, including extreme high runoff and low runoff conditions and changes in snow accumulation and ET. Furthermore, in agricultural catchments, hydrological pathways are impacted by human activities due to cultivation activities and artificial drainage systems. Tile drainage is in favour of subsurface runoff (Kværnø 2013; Bechmann & Bøe 2021). Soil tillage and harrowing affect the soil surface and determine how much water can infiltrate. Moreover, heavy field activities in autumn such as harvesting and ploughing and bare soil in winter expose the land to erosion and runoff, hence to nutrient loss. This requires, on the one hand, increasing and restoring water storage in the landscape (Wilson *et al.* 2019) and, on the other hand, different ploughing and fertilising management plans, taking into account nutrient legacy, vegetation covers such as catch/cover crops or straw stubbles, and buffer stripes (Bechmann 2014; Casson *et al.* 2019; Liu *et al.* 2019). Even in summer, when agricultural fields are fully vegetated, extreme runoff events can have the same impact on, for example, total phosphorus concentration, as a snowmelt event in spring (Wilson *et al.* 2019). In addition, warm and dry conditions can lead to a mineralisation of nitrogen and limit the ability to take up nutrients that are then available for runoff in autumn (Wenng *et al.* 2020). Furthermore, dry conditions in summer can have a severe effect on water availability for plants which might make watering necessary. For all regions in Norway, a decrease in summer runoff is projected (Hanssen-Bauer *et al.* 2015). Spring runoff events in snow-dominated catchments often account for large nutrient export (Casson *et al.* 2019), which might change under future climate due to less pronounced snowmelt events (Pulliainen *et al.* 2020) and an earlier start of the growing season due to warmer spring temperatures (Wenng *et al.* 2020). In our study, we show that there is not an overall pattern, the Norwegian agricultural catchments show individual patterns and high spatial variation. This requires changes to current site-specific water and nutrient management plans to gain and maintain good ecological status of the catchments' water and ecosystem (Liu *et al.* 2019).

CONCLUSION

In this study, we presented long-term and seasonal trends of 22–26 years of hydrological data. We used strong analytical methods in our study, namely a Mann–Kendall trend and a wavelet coherence analysis. Our results indicated that there were changes in hydrology of small agricultural catchments in Norway. We found a significant increase in annual and seasonal air temperature. Annual changes in hydrology were more difficult to detect, while seasonal differences were much more apparent. We found no trends related to precipitation. However, we did find increasing trends in discharge, primarily in winter and autumn. We found that there were numerous differences in the hydrological regime of rain and snow dominant catchments, and this influence the coherency between discharge and precipitation. Specifically, discharge is not directly linked to temperature. Whereas precipitation, soil water storage capacity, and snow water equivalent showed a strong coherence with discharge and affected the variability in the runoff. This is especially apparent in agricultural catchments in a cold climate, where there is a strong seasonality in runoff. We found changes in seasonal discharge patterns, especially in winter which might no longer be a hydrological inactive season. These changes in winter hydrology are also relevant for the subsequent seasons. Understanding these changes in hydrology and their effects on nutrient export is of great importance for cold climate regions as they are severely and disproportionately impacted by increased temperature. Lastly, we found that each catchment showed its site-specific patterns, and this implies that site-specific water and nutrient management solutions are needed. This is important to meet climate change and threats to hydrology and water quality.

AUTHOR CONTRIBUTION

This article resulted from a cooperation within the BIOWATER project. Hannah Wenng: concept, M-K trend analysis, result interpretation, writing – original draft. Danny Croghan: wavelet coherence analysis, result interpretation, writing – review, and editing. Marianne Bechmann: result interpretation, writing – review, and editing. Hannu Marttila: concept, result interpretation, writing – review, and editing.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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