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Key Points:
- Regulation has the most impact on river flow, followed by climate and urbanization, while land-cover changes only have minor and local effects.
- For sustainable river management we recommend attention to direct effects from climate change rather than indirect land-cover changes.
- Detecting change in processes of river-flow generation is facilitated by analyzing model residuals, to avoid weather impact.

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Detecting Changes in River Flow Caused by Wildfires, Storms, Urbanization, Regulation, and Climate Across Sweden

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Abstract Changes in river flow may appear from shifts in land cover, constructions in the river channel, and climatic change, but currently there is a lack of understanding of the relative importance of these drivers. Therefore, we collected gauged river flow time series from 1961 to 2018 from across Sweden for 34 disturbed catchments to quantify how the various types of disturbances have affected river flow. We used trend analysis and the differences in observations versus hydrological modeling to explore the effects on river flow from (1) land cover changes from wildfires, storms, and urbanization; (2) dam constructions with regulations for hydropower production; and (3) climate-change impact in otherwise undisturbed catchments. A mini model ensemble, consisting of three versions of the S-HYPE model, was used, and the three models gave similar results. We searched for changes in annual and daily stream flow, seasonal flow regime, and flow duration curves. The results show that regulation of river flow has the largest impact, reducing spring floods with up to 100% and increasing winter flow by several orders of magnitude, with substantial effects transmitted far downstream. Climate changed the total river flow up to 20%. Tree removal by wildfires and storms has minor impacts at medium and large scales. Urbanization, on the contrary, showed a 20% increase in high flows also at medium scales. This study emphasizes the benefits of combining observed time series with numerical modeling to exclude the effect of varying weather conditions, when quantifying the effects of various drivers on long-term streamflow shifts.

1. Introduction

The ongoing and future change in water systems is currently a frequently targeted area for hydrological research (e.g., Montanari et al., 2013). Last year, we saw enormous wildfires during extended drought periods across large areas of California, Greece, and Australia, but also in regions normally not so prone to wildfires. The wildfires in Sweden were numerous during the summer 2018, and in 2014 a 140-km^2 area of Boreal forest was severely burnt in the county of Västmanland in southern Sweden. This raises the question of what effects these wildfires and other ongoing environmental changes will have on water resources. To understand changes in river flow and flood regimes it is important to know their physical causes, which could also be the basis for predictions and societal preparedness. Merz et al. (2012) defined three main groups of potential drivers of changes in river flow: changes in land cover, constructions in the river channel, and climatic changes. In this study, we hypothesize that these three types of changes would result in a notable shift in river flow from catchments.

First, *land cover* is a core component of the water balance as vegetation controls several state variables and fluxes, such as interception storage available for evaporation (e.g., Gerrits et al., 2010), root water uptake for transpiration from available soil moisture (e.g., Gentine et al., 2010; Liancourt et al., 2012), groundwater recharge (e.g. Allison et al., 1990; Jobbágy & Jackson, 2004): land-atmosphere feedback (e.g. Cassiani et al., 2015; Seneviratne et al., 2013), and ultimately river flow generation (e.g. Donohue et al., 2012). It is well understood that, for instance, deforestation can considerably alter hydrological regimes (e.g. Alila et al., 2009; Andréassian, 2004; Brandt et al., 1988; Brown et al., 2005), often resulting in higher seasonal flows and/or an increased frequency of high flows in streams, due to changes in root-zone storage (e.g., Nijzink et al., 2016). Sudden changes in land cover can be caused by, for instance, clear-cutting of forests, wildfires, or storms with tree felling. However, as these changes often have limited spatial extent and the effect interacts with other processes at the landscape level, their impact on overall river flow is often difficult to detect and understand at the larger scale more distant from the site of disturbance (e.g. Brandt et al., 1988).

Second, *river regulations* from engineering directly in the river channel can have a very immediate effect, such as fragmentation of flow and changes in evaporation and in seasonal flow regime (e.g. Arheimer et al., 2017; Nilsson et al., 2005; Wang et al., 2017). Rivers have been manipulated ever since humans settled (Savenije et al., 2014), first to ensure water availability for consumption and agriculture, and later also for hydropower production, industrial use, flood protection, or esthetical reasons. Consequences such as temporally dry river channels, changed flow patterns, and short-term fluctuations of water level often have severe ecological side effects (e.g. Andersson et al., 2000; Bunn & Arthington, 2002; Leira & Cantonati, 2008). Therefore, there are also many initiatives for more ecologically adapted regulation schemes to maintain critical flow levels (Foran, 2010; Fujikura & Nakayama, 2009; Horne et al., 2017; Opperman et al., 2009; Pittock, 2010). The effects of flow regulation vary with the purpose of regulation and the environmental concerns taken but may have a major impact also at the large scale and far downstream in the river network (e.g. Arheimer et al., 2017; Arheimer & Lindström, 2014).

Third, *climate change* due to global warming will shift temperature and precipitation patterns, which then impact key drivers for flow generation, such as precipitation amount (Trenberth, 2010) and precipitation intensity (Berg et al., 2013; Huntington, 2006), snow fraction and storage (Barnett et al., 2005; Krasting et al., 2013), and snow melt (Bergström et al., 2001; Gelfan et al., 2017; Molini et al., 2011). Accordingly, a shift in flood peaks has been observed at the continental scale over the last 50 years, both for timing (Blöschl et al., 2017) and volume (Blöschl, Hall, et al., 2019), and further time series analyses suggest a potential ongoing shift in evaporation (Berghuijs et al., 2014) or alteration in transpiration and biomass (Jaramillo et al., 2018). However, the climate change signal can be difficult to extract from natural variability (Kjellström et al., 2013), especially at the local catchment scale, which is already exposed to large variation in weather patterns. If the trend is small and the variability is large (as is often the case for precipitation and river flow), it may be very difficult to detect changes beyond natural variability. Consideration of large scale patterns and long time series (at least 30 years) are normally recommended when estimating climate variability and change (e.g. Intergovernmental Panel on Climate Change, 2018). In this paper, we use the terminology so that "climate" reflects weather statistics over decades; "climate change" reflects that there is a trend in the climate, and "climate variability" means that there are oscillations in the climate.

Hall et al. (2014) concluded that there is currently a lack of understanding of the relative effects from changes in these three drivers (i.e., land cover, constructions and climate) on floods. The effect of drivers may be difficult to identify because the dominant flow generation processes vary regionally (Kuentz et al., 2017), which may result in different impacts of a certain change depending on the physiography of the catchment. Moreover, the location of changes within a catchment also influences the resulting effect (e.g., Blöschl et al., 2007). Without sufficient knowledge of driving processes at a specific location, direct predictions from using numerical models to explore effects of changes are uncertain. It has been recognized that catchment models are often poor in reconstructing observed values of hydrological change (e.g., Thirel et al., 2015), and scenarios are often made without empirical data support (e.g., Huisman et al., 2009). One reason could be that it has been difficult to validate internal parameters in complex models because of the lack of supporting empirical data of specific processes controlling the river flow generation. However, hydrological models can still be useful as baselines without explicitly simulating the changes.

In this study, we thus used hydrological modeling as a reference to discern real changes in the system from natural weather variability without simulating the changes as such. We tried to isolate the drivers by collecting gauged river flow data from across Sweden, using several distinctly disturbed catchments for each type of change affecting river flow. The study was triggered by the 2014 Västmanland fire, but instead of focusing all attention to this site and event, a large-scale approach was taken. High-resolution hydrological modeling, with weather data from 1961, is available for the whole country of Sweden. The national hydrological monitoring network was examined in order to find the catchments that were the most influenced by recent fires, storms, and other changes that may affect river flow. Altogether, 34 river gauges with time series from 1961 to 2018 were selected for analyses of trends in annual observed data and bias of empirical data versus numerical modeling. We studied the effects on river flow from (1) land cover changes from wildfires, storms, and urbanization; (2) dam constructions with regulations for hydropower production; and (3) climate change impact in otherwise undisturbed catchments. We investigated the impact on continuous flow, seasonal regime, and flow duration curves at each gauge, and, in some cases, the gauges were nested so that we could explore impacts further downstream in the river system.

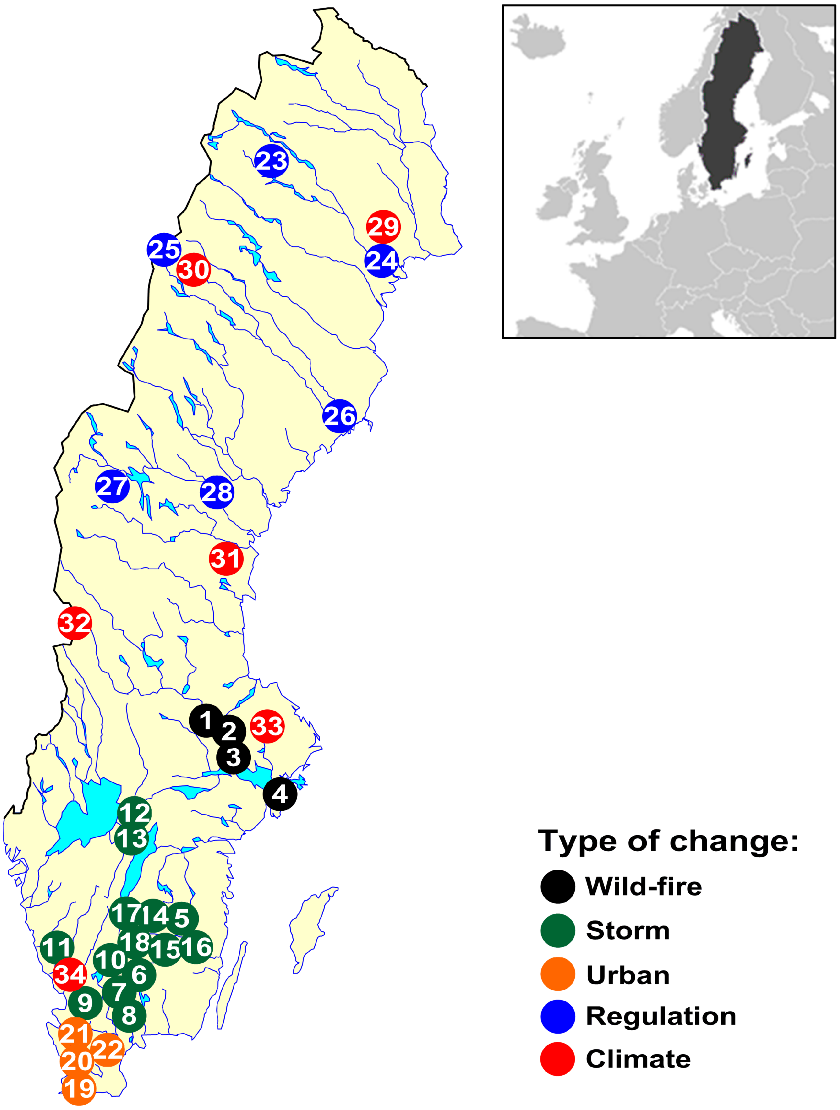

Figure 1. Location of the 34 studied catchments across Sweden, situated in Northern Europe (small map). The colors represent the type of change the catchment has gone through, such as land cover changes, hydropower regulation, or only climate change.

2. Study Sites, Data, and Methods

Sweden is a country in northern Europe covering 450,000 km^2, which is rich in surface water that is used for industry, drinking and sanitation, recreation, and hydropower production. The country is part of the Boreal forest belt with a mountain range (the Scandes) at the North-Western border toward Norway, from which most of the large rivers in the country originate, and then flow east and south to the long coastline of the Baltic Sea and the North Sea. Sweden has about 10 million inhabitants who are mainly settled in the southern part of the country and along the coastline. This is also where most agricultural regions are found. The current land cover is mainly productive forestland (57% of the Swedish land surface) after constantly expanding throughout the 20th century (Jaramillo et al., 2018; Nilsson et al., 2016).

River flow has been monitored since the 19th century, and the present national monitoring network includes some 400 river gauges across the country. Severe storms and wildfires in Sweden occur rarely and are therefore well recognized at the Swedish Meteorological and Hydrological Institute. The institute also has records of catchments with major landscape changes and hydropower dam reservoirs.

For this study, 34 of the gauges were selected as they represent catchments that have been exposed to changes in land cover or regulations, or can be considered as otherwise undisturbed, thus only affected by climate change (Figure 1). The catchments were specifically selected based on local knowledge to represent isolated changes, except for climate change, which occurs everywhere and to which all studied catchments are exposed. Besides climate, the investigated change is the most prominent change recognized in each catchment during the time period studied. The area affected in each catchment was estimated from local reports, maps or satellites, and by local experts. The catchments studied for climate change, on the other hand, were otherwise undisturbed and not exposed to any major changes than climate. Nevertheless, the 34 catchments may be exposed to other unconsidered changes, which have been foreseen, and therefore we have used several catchments for each of the studied changes, to explore if they react in a similar way and if the results are robust.

First, annual flow from all observed time series were validated for normal distribution (using a Kolmogorov-Smirnov measure), and a linear trend test explored if there were obvious trends between years. Then, the S-HYPE model (Strömqvist et al., 2012) was used as a baseline to filter out daily weather impact from the other factors, which were hypothesized to change river flow from catchments. S-HYPE is a national modeling system used for operational forecasting of floods and droughts (e.g. Pechlivanidis et al., 2014), assessments of water quality (e.g., Arheimer et al., 2015), as well as impacts from hydromorphological alterations (e.g., Arheimer & Lindström, 2014) and climate change (e.g., Arheimer & Lindström, 2015) in Sweden. The model system is based on the HYPE model, (Lindström et al., 2010) which is a catchment-based, process-oriented model, describing river flow generation from rainfall distribution and temperature. The model calculates evapotranspiration, snow storage and melt, soil moisture, groundwater fluctuations, and routing in lakes and streams along the river network from source to sea.

The S-HYPE model is continuously developed and improved. The model has a large number of parameters and is largely calibrated manually, making maximum use of hydrological judgment and experience. The S-HYPE model uses a daily time step. It is calibrated regionally, that is, not tuned for individual stations but calibrated stepwise for specific hydrological processes using representative gauges from the full data set to be robust enough for predictions also in ungauged basins (Arheimer & Lindström, 2013). In addition to this, there are deviations in a handful of key parameters (such as precipitation and temperature corrections) for parameter regions (Lindström, 2016).

To account for model uncertainty we here created a mini ensemble of models, by using three recent S-HYPE versions, instead of only one. The S-HYPE model versions are managed and documented at SMHI, and the three versions applied are sh12e (official name S-HYPE2012_4_0_0), sh16b (S-HYPE_2016_2_0_1), and the latest available version: sh16c (S-HYPE_2016_2_0_2). The models' structures are similar, but the versions differ in source code (archived and openly available at hypeweb.smhi.se), and for some process descriptions, catchment delineation, soil and land cover information, water abstractions, and parameter values, due to the continuous corrections and modifications to better simulate knowledge of Swedish hydrology. All three versions were calibrated individually, reflecting differences in input data and calibration strategies. Some parameter settings are similar in all three models, particularly for lakes routing and reservoir regulation, which are very site specific and are estimated locally. For all gauging sites in the national monitoring network, with both regulated and unregulated rivers, the mean Nash-Sutcliffe efficiency (NSE; Nash & Sutcliffe, 1970) for the latest S-HYPE version is 0.81. The two preceding versions used here had corresponding NSE values of 0.78 and 0.79. These numbers refer to a total of 284 stations, over the calibration period 1999–2008. The average NSE values for the 165 stations in unregulated basins, for the three model versions, are in the range 0.83–0.87. Corresponding NSE values for the 119 regulated basins are 0.70–0.73. These NSE numbers refer to catchments ranging from a few to several tens of thousands of square kilometer and various land covers across the country. The performance of the S-HYPE model in the 34 selected catchments of this study is described using both NSE and relative volume errors (RE).

Like most hydrological models, S-HYPE is a stationary description of the hydrological system, with land cover and other characteristics that do not change over the years. Only the forcing data in the form of daily precipitation and temperature vary with time. This means that a shift in land cover or water management would cause a change in the observed discharge that the model cannot describe. In this study we took advantage of this and used the model as a reference to filter out changes in discharge from weather fluctuations.

The differences between observed discharge (*qobs*) and the reference (*qmod*) are thus the basis for our study. In this study, the daily accumulated difference (*Accdiff*) is defined as

$$Accdiff(t) = \sum_{i=1}^{t} (qobs(t) - qmod(t)). \tag{1}$$

This definition means that a flow increase beyond variability resulting from weather fluctuations will result in an increase in the *Accdiff*. Changes in *Accdiff* can thus be used to infer changes in the system. Since the S-HYPE model is not calibrated individually for each gauging station there may be volume errors in the simulation for some stations. The method can still be used even if there is a volume error prior to an event, since it is only the changes in the differences that are being interpreted. Similar approaches have been used by, for instance, Brandt et al. (1988) who quantified an increased runoff from intensely clear-felled experimental basins in Sweden and Grimvall et al. (2014) who detected changes in nitrogen concentrations in runoff from agricultural basins in Sweden.

The slope of the accumulated difference curve expresses the volume error in the simulation. If an event occurs, causing a sudden change in runoff volume, the slope of the accumulated difference will change at this point in time. Changes in slope, that is, break points, were estimated using the second derivative as

$$Accdiff''(t) = Accdiff(t+1) - 2Accdiff(t) + Accdiff(t-1). \tag{2}$$

This was here calculated with a yearly time step, using the last value of *Accdiff* for each year. The set of annual break points was normalized by subtraction of the mean and division by the standard deviation. If the normalized break point during the event years is statistically different from the rest of the years, this is interpreted as a real change in the system. The significance and strength of the change was estimated by a *t*-test. The underlying assumption is thus that in a stationary system there would be normally distributed random disturbances. The visual inspection of the graphs is, however, the most important tool for identifying break points, and the statistical analysis is used here as a complement to the graphical presentation. The calculation of break points only makes sense for events that are specific in time, as for instance storms or fires, and not the gradual changes due to urbanization or climate change. Neither are they relevant for the regulated catchments since the break points only measure changes in volume.

In addition, the S-HYPE model was used to estimate natural flow (conditions before river regulations) and integrated precipitation and temperature for undisturbed catchments (see below). In all cases, we analyzed continuous time series (annual observation of flow and daily *Accdiff*), flow duration curves, and shifts in seasonal regime before and after the disturbance in each catchment to detect changes in river flow. For robustness, we used at least four catchments with similar disturbance for each type of change studied.

2.1. Land Cover Changes From Wildfires, Storms, and Urbanization

In total, 22 catchments were used to investigate the effects of removal of vegetation (Table 1) with on average 20% of the upstream area affected by either wildfires, tree felling from large storms, or gradually growing urban areas. The catchment areas upstream of each of the gauges range from a few square kilometer to a few thousands of square kilometer, and the affected areas range from a few percent to 75%. Two recent forest fires were included, as were the tree felling by the recent storms called Per and Gudrun and a series of hurricanes in 1969. The effect of the sudden shift in vegetation cover and the following recovery process was estimated by comparing observed river flow with the model residuals from S-HYPE modeling of undisturbed conditions. Urbanization, on the other hand, is a continuous process, which has increased recently. In this case we compare the historical period 1961–1990 with the more recent period 1991–2018.

2.2. Dam Constructions With Regulations for Hydropower Production

Most rivers in Sweden are regulated with dams for hydropower production to store the snow melt during spring and release water throughout the year when electricity is needed (e.g., Arheimer et al., 2017). During the early 20th century the development of hydropower production was a major contribution to the industrialization of Sweden, and today hydropower amounts to half of the electricity supply for the country. As a consequence, the rivers are fragmented by in total some 1,800 hydropower plants across the country, of which some 200 produce >10 MW, providing 94% of the total hydropower energy production. In this study

Table 1
Catchments Studied With Respect to Land Cover Changes and the S-HYPE Model Performance Versus Daily Observations Over the Full Time Period 1961–2018 at the River Gauge of Each Catchment Outlet.

No.	Cause of change	Time of event	Gauging station	Catchment area (km^2)	Affected part of catchment (approx.)	S-HYPE performance	
						NSE	RE (%)
1	Fire of Västmanland	31 July 2014	Skräddartorp	18	75%	0.79	−17
2	Fire of Västmanland	31 July 2014	Hällsjön	539	20%	0.70	+19
3	Fire of Västmanland	31 July 2014	Åkesta kvarn	727	15%	0.88	+3
4	Fire of Tyresta	1 August 1999	Stormyra	4	10%	0.73	−8
5	Storm of Gudrun	8 January 2005	Brusafors	240	15%	0.88	+1
6	Storm of Gudrun	8 January 2005	Lissbro	97	25%	0.88	+8
7	Storm of Gudrun	8 January 2005	Möckeln	1,026	25%	0.90	+11
8	Storm of Gudrun	8 January 2005	Skeingesjön	1,984	25%	0.94	+3
9	Storm of Gudrun	8 January 2005	Ängabäck	5,480	20%	0.82	+4
10	Storm of Gudrun	8 January 2005	Fryele	594	15%	0.89	+3
11	Storm of Gudrun	8 January 2005	Pepparforsen	384	20%	0.94	0
12	Storm of Per	14 January 2007	Nolsjön	18	15%	0.85	+1
13	Storm of Per	14 January 2007	Velen	45	15%	0.87	−3
14	Storm of Per	14 January 2007	Nömmen	157	15%	0.88	+7
15	Storm of Per	14 January 2007	Steninge	9	15%	0.79	−3
16	Storm of Per	14 January 2007	Stensåkra	656	15%	0.92	+6
17	Storm of Per	14 January 2007	Rörvik	159	15%	0.92	+9
17	Hurricanes of 1969	22 September 1969	Rörvik	159	20%	0.92	+9
18	Hurricanes of 1969	22 September 1969	Värmeshult	1,193	20%	0.81	+7
19	Urbanization	1991–2018	Svedala	52	8%	0.83	+4
20	Urbanization	1991–2018	Trolleberg	237	16%	0.85	−5
21	Urbanization	1991–2018	Ellinge	151	7%	0.84	−3
22	Urbanization	1991–2018	Heåkra	147	3%	0.83	0

Note: Locations of catchments are given by corresponding numbers in Figure 1. S-HYPE performance is given for the latest version.

we included gauges representing upstream and downstream conditions in three large rivers (Table 2). The study sites represent 25–82% degree of regulation (i.e., the fraction of the annual mean flow that can be stored in upstream reservoirs). This indicates the degree with which river flow can be modified by regulation, on an annual scale. The NSE on a daily scale is low for some of the highly regulated systems (Table 2), since it is difficult to model the day-to-day variations in hydroelectrical production. The flow during the year is also evened out by regulation, since the main purpose is to store water from the spring flood to the winter when the natural flow is low. The redistribution reduces the flow variance. It also leads to lower NSE values, since NSE measures the fraction of the variance that is captured by a model.

The effect of regulation was estimated by comparing differences between regulated and unregulated conditions using the S-HYPE model and comparing present regulated conditions with modeled reconstructions of

Table 2
Catchments Studied With Respect to Regulations for Hydropower Production and the S-HYPE Model Performance Versus Daily Observations Over the Time Period 1981–2018 at the River Gauge of Each Catchment Outlet.

No.	Regulated river	Regulated from	Gauging station	Catchment area (km^2)	Degree of regulation	S-HYPE performance	
						NSE	RE (%)
23	Luleälven River	1967	Tjaktjajaure	2,255	82%	0.34	+1
24	Luleälven River	1922	Boden	24,924	66%	0.26	−1
25	Umeälven River	1964	Överuman	652	46%	0.08	−18
26	Umeälven River	1958	Umeå	26,568	25%	0.83	0
27	Indalsälven River	1967	Sällsjön	1,297	49%	0.15	0
28	Indalsälven River	1924	Hammarforsen	23,842	40%	0.66	0

Note: Locations of catchments are given by corresponding numbers in Figure 1. The years 1961–1980 were omitted from the S-HYPE evaluation, since regulations were introduced gradually during these years. S-HYPE performance is given for the newest version.

Table 3

Catchments Studied With Respect to Climate Change Impact in Undisturbed Catchments and the S-HYPE Model Performance Versus Daily Observations Over the Full Time Period 1961–2018 at the River Gauge of Each Catchment Outlet.

No.	Climate zone in Sweden	Time period	Gauging station	Catchment area (km^2)	Affected part of catchment (approx.)	S-HYPE performance	
						NSE	RE (%)
29	Northeast	1961–2018	Ytterholmen	1,012	100%	0.87	−1
30	North west	1961–2018	Solberg	1,084	100%	0.87	−9
31	Central east	1961–2018	Hassela	651	100%	0.88	−11
32	Central west	1961–2018	Ersbo	1,103	100%	0.83	−14
33	Southeast	1961–2018	Vattholma	294	100%	0.8	−4
34	Southwest	1961–2018	Simlången	260	100%	0.87	−6

Note: Locations of catchments are given by corresponding numbers in Fig. 1. S-HYPE performance is given for the newest version.

natural flows (Arheimer et al., 2017; Arheimer & Lindström, 2014). The daily change, that is, redistribution in time of river flow (ΔQ) from hydropower regulation was calculated as

$$\Delta Q\ (t) = QR\ (t) - QN\ (t) \tag{Eq3}$$

where QR is the observed regulated flow from gauges, and QN is the simulated naturalized flow.

The naturalized flow was simulated using the S-HYPE model by removal of all regulation storages and man-made diversions in the model (see Arheimer & Lindström, 2014). The non-regulated conditions of lakes, which are regulated today, were established using a specific rating curve to describe naturalized flow based on measurements of water discharge and lake level fluctuations, either by observations prior to regulations or by using reconstructions made by hydropower companies, which are currently used for legal justifications. For remaining lakes, we used the equations for the spillways from regulated conditions. This method of HYPE modeling of naturalized flow has been evaluated against more detailed independent reconstructions based on observed water levels for reservoirs across Sweden, resulting in a NSE > 0.7 (Arheimer et al., 2017; Arheimer & Lindström, 2014).

2.3. Climate Impact in Otherwise Undisturbed Catchments

The effect of climate variability and ongoing global warming was studied in six otherwise undisturbed catchments representing different climate zones of Sweden (Table 3) and the northern ones are within the Arctic Circle at the latitude >66°N. The catchments were chosen to represent different climatic conditions in the country and to be of about the same size as the catchments with observed land cover changes and located nearby, so that potential changes would be comparable. In addition, they should have no records of wildfires, storm-felled trees, hydropower regulations, or growing urbanization. The S-HYPE model was used to integrate precipitation and temperature for the whole upstream catchment of each gauging station, as well as to estimate shifts in evapotranspiration. This information was then used to understand the climate drivers behind possible changes in the observed river flow. Trends and the significance of the trends were calculated by linear regression for annual mean flows. A Kolmogorov-Smirnov measure was calculated to check that the distribution of annual flow data can be approximately described by a normal distribution.

3. Results

For the 34 catchments, we found significant trends in seven time series of annual observed river flow (Table 4). These trends ranged from 3.1 to 10.5 % increase per decade. The significant trends found were evenly spread among catchments with different causes of change and could not be referred to any of the specific drivers studied. Hence, none of the studied potential drivers to river flow changes had a pronounced effect on long-term trends in the water balance. Neither could we detect significant break points during years with changing conditions from random fluctuations in the rest of the period (t in Table 4, the critical value of t at confidence level of 95% is $\approx \pm 2$). The break points (t values) were very similar between the three different S-HYPE versions.

Table 4
Statistics of Trends of Observed Flow and the Anomaly (t) of Break Points in the Accumulated Differences Between Observations and S-HYPE.

No.	Q station	% decade^{-1}	t sh12e	t sh16b	t sh16c
1	Skräddartorp	−3.7	n.a.	n.a.	n.a.
2	Hällsjön	n.a.	n.a.	n.a.	n.a.
3	Åkesta kvarn	−10.5*	0.09	−0.03	−0.16
4	Stormyra	−2.5	−0.87	−0.70	−0.68
5	Brusafors	0.7	−0.70	−0.56	−0.44
6	Lissbro	2.8	−0.13	−0.77	−0.72
7	Möckeln	1.5	−1.08	−1.29	−0.99
8	Skeingesjön	0.5	0.01	−0.18	−0.11
9	Ängabäck	3.0	−0.35	−0.28	−0.13
10	Fryele	−0.4	−0.30	−0.34	−0.33
11	Pepparforsen	0.3	−0.86	−0.41	−0.59
12	Nolsjön	0.9	−0.60	−0.53	−0.31
13	Velen	2.4	−0.52	−0.49	−0.47
14	Nömmen	4.1	−1.24	−1.11	−1.12
15	Steninge	−4.5	−0.49	−0.33	−0.29
16	Stensåkra	−3.2	−0.69	−0.44	−0.64
17	Rörvik	3.7	−1.11	−0.79	−1.20
18	Värmeshult	5.6*	−0.20	−0.19	0.01
19	Svedala	9.1*	n.a.	n.a.	n.a.
20	Trolleberg	−0.7	n.a.	n.a.	n.a.
21	Ellinge	−4.3	n.a.	n.a.	n.a.
22	Heåkra	−3.5	n.a.	n.a.	n.a.
23	Tjaktjajaure	4.6*	0.20	0.77	0.55
24	Boden	3.1*	n.a.	n.a.	n.a.
25	Överuman	1.5	−2.01	−1.95	−1.95
26	Umeå	1.4	n.a.	n.a.	n.a.
27	Sällsjön	3.5*	−0.44	−0.46	−0.52
28	Hammarforsen	1.1	n.a.	n.a.	n.a.
29	Ytterholmen	4.2*	n.a.	n.a.	n.a.
30	Solberg	0.5	n.a.	n.a.	n.a.
31	Hassela	−2.6	n.a.	n.a.	n.a.
32	Ersbo	2.1	n.a.	n.a.	n.a.
33	Vattholma	−4.8	n.a.	n.a.	n.a.
34	Simlången	2.0	n.a.	n.a.	n.a.

Note: *t* values are given for all three S-HYPE versions. Locations of catchments and type of change are given by corresponding numbers in Figure 1.
Abbreviation: n.a. = not applicable.
*denotes significance at 95%.

The trends found in the observed annual flow are probably an effect of the chosen time period, since the 1960s and 1970s were relatively dry in Sweden (Lindström & Bergström, 2004) rather than the catchment changes studied. Trends were more dominant for catchments in northern Sweden where increased precipitation has been observed in previous studies (Lindström & Alexandersson, 2004). Following analysis of daily stream flow (model bias), seasonal flow regime and flow duration curves are presented below in section 3.1 to 3.3. All analyses were made for all catchments, but in the following sections we highlight the detected changes for each driver by visualizing the results that best illustrate the findings in each case.

3.1. Land Cover Changes From Wildfires, Storms, and Urbanization

The minor effects from wildfires and storms were best illustrated by the difference in accumulated bias between observations and the S-HYPE model. In the three catchments affected by the Västmanland fire between 15 and 75% of the area was affected. However, we could not find any evidence for changes in river flow, not even in the most affected catchment, Skräddartorp (Figure 2). The model bias varies over time but without dramatic shifts due to the fire. For the 1999 fire in Stormyra there is a minor shift in bias. Since it starts already before the fire it is unlikely that it is caused by land cover changes (lower panel of Figure 2). Neither the visual inspection of the accumulated difference, nor the statistical analysis of break points, reveal any large changes in discharge volume due to land cover changes. Hence, the loss of vegetation due to fires does not control the dominant flow generation processes of these catchments. The three different S-HYPE versions gave rather similar results, with minor differences in slope in the accumulated difference, due to differences in the volume calibration. The pattern of variation over time and break points were similar between the three model versions (see further Table 4).

The effects of tree felling from storms are illustrated in the same way, and also here we lack clear evidence on change in flow generating processes in the results (Figure 3). The accumulated bias varies over the periods but is normally not corresponding to the induced changes in land cover. Fryele, Pepparforsen, and Stensåkra show a turning point in bias that could be related to the storm and so do the hurricanes of 1969 (No. 17 and 18 in Figure 3). The former indicates increased flow, while the hurricanes would have resulted in decreased flow. Nevertheless, 10 of the storms show no change in bias. Note that Rörvik was affected twice, both by the hurricanes of 1969 and by the Per storm in 2007. The graphs show no systematic break points at the storm events, nor does the statistical treatment of break points show convincing changes at the particular storm events. After the Gudrun storm in 2005 there was public concern of increased flooding due to the loss of forest, since that particular area had experienced floods in the preceding summer. From our results, however, we cannot detect any clear evidence on general impact on dominant flow generation processes from the loss of vegetation due to tree felling by storms. Nevertheless, it should be noted that only around 20% of the catchment areas were affected, and the results might be different at the local scale with a larger part of the catchment disturbed (e.g., Brandt et al., 1988). The three different S-HYPE versions gave slightly different results for some of the catchments, due to differences in the calibration between versions (e.g., Lissbro and Skeingesjön). The pattern of variation and break points were, however, similar (see further Table 4).

Urbanization, with reduced infiltration capacity from impervious areas, is expected to especially influence the infiltration rate at high flows. Figure 4 shows how the observed minus the modeled flow has changed from the period before 1991 to the period thereafter. An increase is interpreted as an increase in discharge

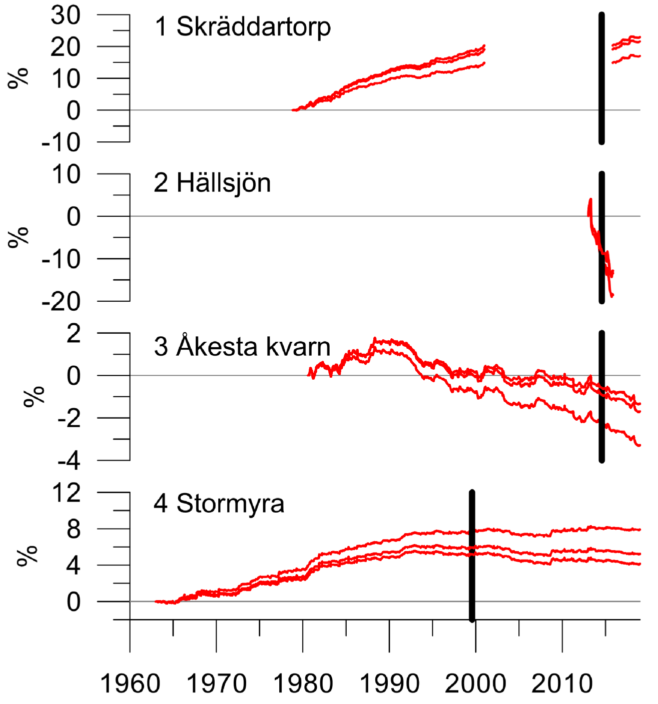

Figure 2. Impact of wildfires on S-HYPE model performance (three model versions). The graphs show the accumulated difference (%) between observed and modeled annual mean flow over the period studied. The timing of the selected wildfires is depicted as vertical lines. Note that the axes have different scales. Locations of catchments are given by corresponding numbers in Figure 1.

that cannot be explained due to weather effects and vice versa. The highest discharges appear to have increased, as expected, in all four catchments, in the order of 20%. In Svedala the discharge increased at all frequencies. This is in agreement with the positive trend in the overall discharge at that station (Table 4). The results were more varied in the other three basins, with overall slightly decreasing volumes in Ellinge and Heåkra, and a stable volume in Trolleberg (Table 4). The lowest flows were removed from this analysis due to the large relative differences obtained for low flows. It should be noted that the fraction of urban areas in the study sites is still rather low, so a more pronounced impact would probably be found at local scales where a higher percentage of the catchment is affected. The effect we found corresponds to impacts also at the mesoscale, that is, further away from the affected local site. The effect of urbanization can thus be considered to be transmitted downstream to a larger degree than the effect of wildfires and storms. Similar results were obtained with the three S-HYPE versions.

Several authors report that land cover changes mainly change the seasonal pattern in river flow (e.g., Guo et al., 2008; Nijzink et al., 2016; Ogden et al., 2013; Pimentel & Arheimer, 2018). Figure 5 shows smoothed average daily differences (before the change vs after) for each day of the year. The largest variations over the year were found for the Skräddartorp catchment, affected by the forest fire in Västmanland 2014. This is the catchment with the largest fraction being affected by the land cover change (Table 1). Here, there is a slight tendency toward a shift of the snow melt peak and slightly higher flow during the autumn. This is consistent with another study of effects from this wildfire by Pimentel and Arheimer (2018), which linked changes in snowmelt and evapotranspiration to a lack of forest canopy and interception. There was, however, only slightly more than 2 years of discharge data from Skräddartorp, when that analysis was made. A tendency to similar effects could be found also due to storm felling (No. 6 and 11 in Figure 5), but not due to the fire at Stormyra (No.4 in Figure 5). Overall, the signal in seasonal changes is weak and could rather be an effect of noise. The differences between the three S-HYPE versions were negligible.

3.2. Dam Constructions With Regulations for Hydropower Production

The purpose of hydropower regulation is to store water for production of electricity during the winter, when the natural flow in Northern Sweden is low and the demand for energy is high. Regulation for hydropower production does not affect the long-term water balance, but changes the seasonality in river flow considerably resulting in very different flow regimes (Figure 6). Much of the discharge due to snowmelt and summer rains is stored and subsequently released in the winter. The spring flood is reduced by almost 100% (Figure 6, upper panel) in the large reservoirs in the upstream areas (cf. map of Figure 1). The winter flow is increased considerably by up to several orders of magnitude in the most regulated systems (Figure 6, upper panel). In the reservoirs further downstream, hydropower is generated from the water released upstream, and the river flow is more continuous, due to contribution from a large upstream area of both regulated and unregulated river branches. Thus, the effect from river regulations is dependent on the degree of regulation, and in Sweden it is normally lower further downstream in the catchment (Arheimer et al., 2017). Calculations based on different S-HYPE versions gave similar results but slight differences in magnitude.

3.3. Climate Change Impact in Undisturbed Catchments

Climate related drivers of river flow showed increasing trends of observed temperature and precipitation in all climate zones across the country for the 58-years period studied (Figure 7). The overall change in precipitation was about 10–25% over the study period, while the temperature was found to have increased with about 2 °C. No clear regional patterns could be seen from this small set of catchments. It should be pointed out, however, that the period is too short from climatological trend studies and that the study starts immediately after a period with a cooling trend from around 1930 to 1960 in Sweden (see e.g., Lindström &

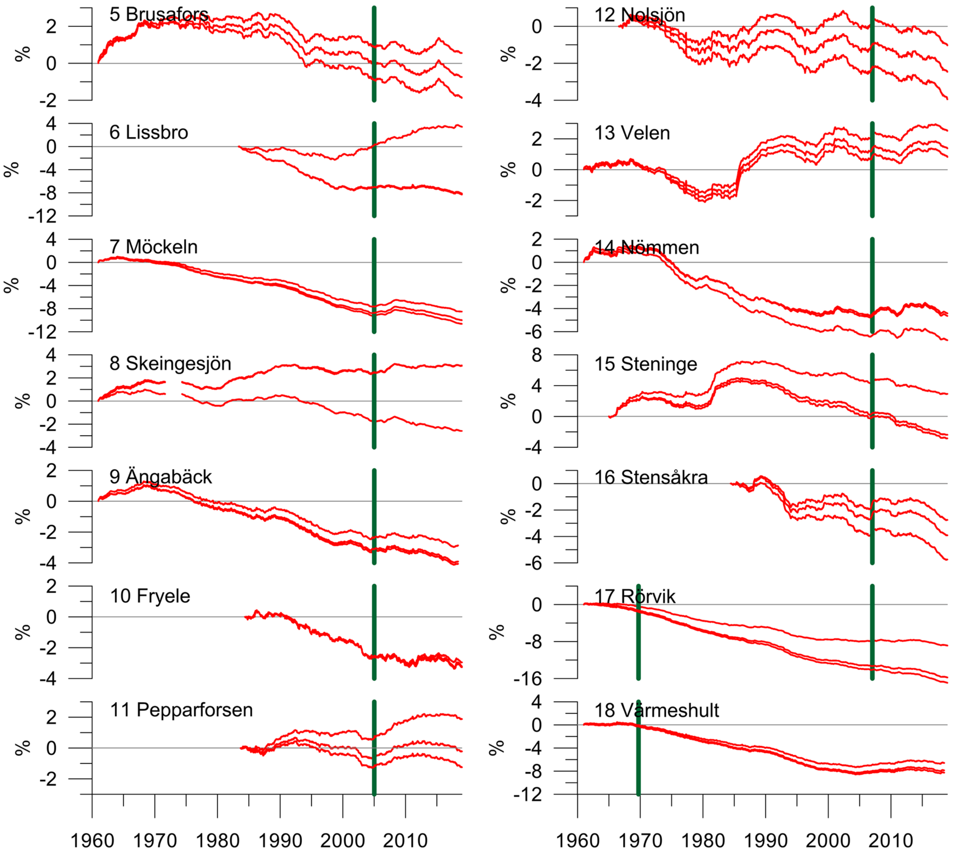

Figure 3. Impact of storms on S-HYPE model performance (three model versions). The graphs show the accumulated difference (%) between observed and modeled annual mean flow over the period studied. The timing of the selected storms is depicted as vertical lines. Left panel: the Gudrun storm. Right panel: the Per storm and the hurricanes of 1969. Note that the axes have different scales. Locations of catchments are given by corresponding numbers in Figure 1.

Alexandersson, 2004). The estimated increase in evapotranspiration was in general about 10–20%. Evaporation was calculated using three model versions of S-HYPE, which all gave very similar results, and the differences between the models in the evapotranspiration graphs are almost impossible to see. There were no systematic trends in the observed river flow from climate change, as there are considerable irregular variations in the time series (see black lines in Figure 7) with fluctuations between wet and dry periods. In general the 1960s and 1970s were dry. A wetter period followed during the 1980s and 1990s. The fluctuations between wet and dry periods can be seen more clearly if longer time periods are studied (Lindström & Bergström, 2004). The only river with a continuous trend in river flow was the Northeastern one (Ytterholmen), where the river flow increased some 20% (cf. Table 4). In general, the impact of variation in climate variables resulted in at most 25% changes in river flow in the undisturbed catchments.

4. Discussion

As in all research, our study includes uncertainties, and it is understood that another data set, other methods, and different analysis tools might give slightly different outcome. It could be that the ensemble of catchments we investigated for each driver is biased or not large enough, that there are unknown disturbances in the catchments that could affect the *Accdiff* when filtering out weather impact, or that another ensemble of hydrological models might respond differently to weather dynamics. This study is one contribution to a very large and interesting science field of the influence of various natural or anthropogenic pressures on hydrological conditions (i.e. Panta Rhei, Montanari et al., 2013). We therefore strongly encourage further studies to validate the robustness of the findings we presented here.

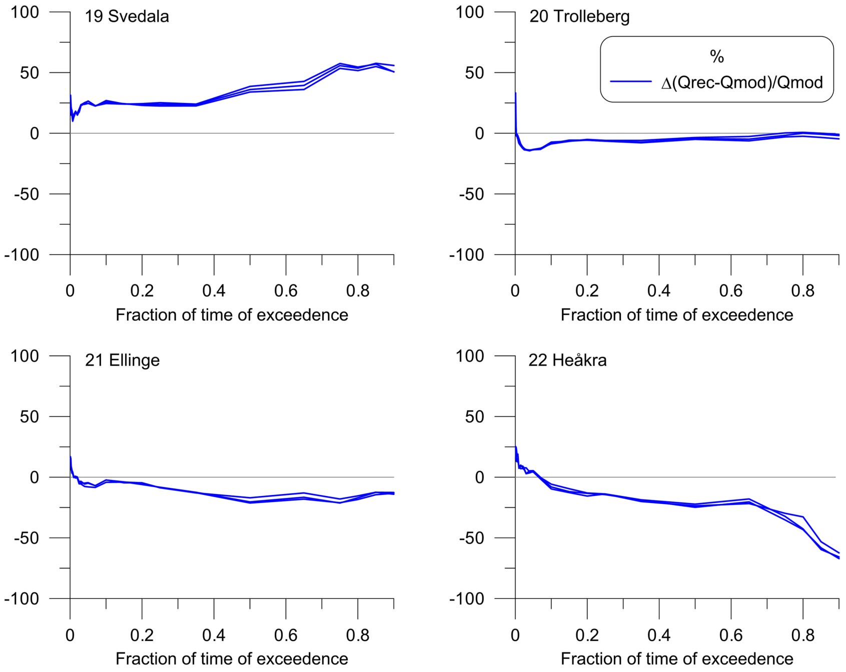

Figure 4. Impact of urbanization on discharge at different frequencies in the duration curve, modeled with S-HYPE (three model versions). The graphs show how the observed-modeled flow has changed from the period before 1991 to the period thereafter. A positive change is interpreted as an increase in discharge, and vice versa. Locations of catchments are given by corresponding numbers in Figure 1.

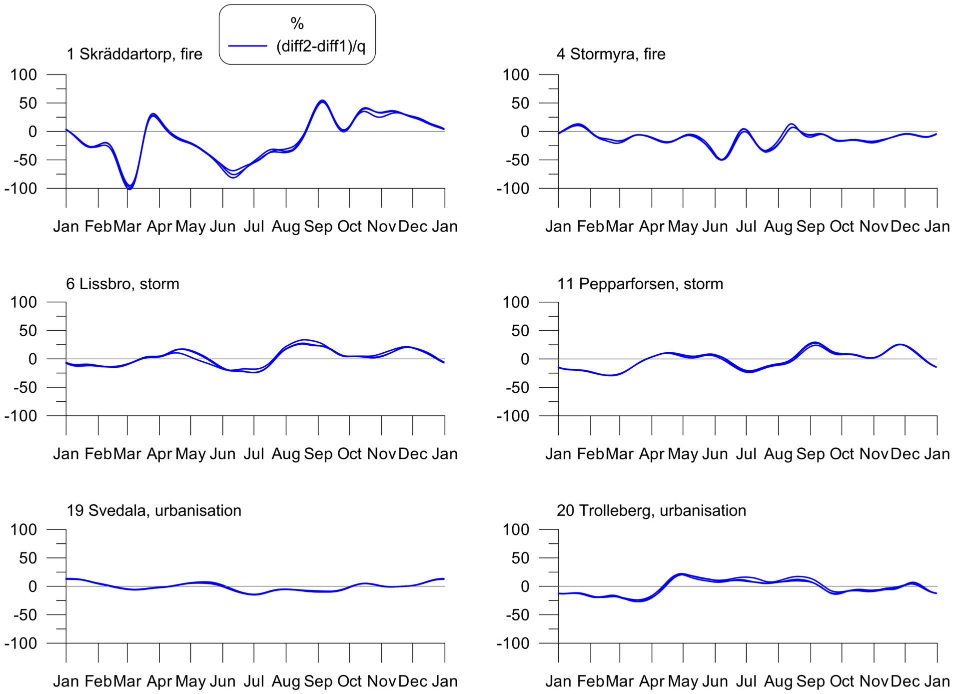

Figure 5. Seasonal differences between observed and modeled water discharge due to land cover changes (three model versions). The graphs show how the differences between observed and modeled flow has changed from the period before the event (for urbanization defined as 1991) and thereafter. A positive change is interpreted as an increase in discharge.

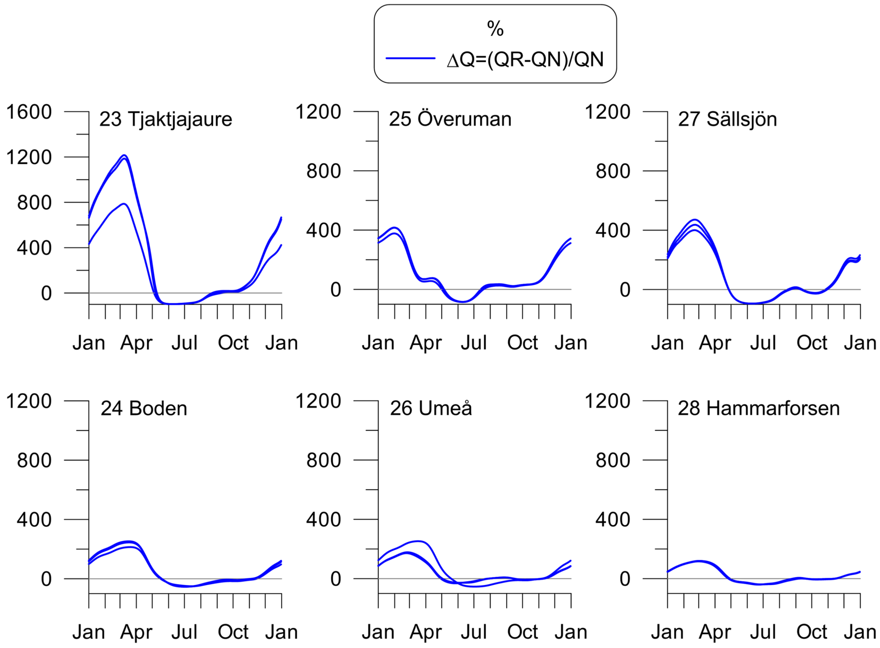

Figure 6. Impact of river regulation according to the S-HYPE model (three model versions). The graphs show the difference between seasonal flow regimes for regulated Swedish Rivers under recorded, regulated conditions (QR), and under reconstructed, naturalized conditions (QN). Smoothed daily mean values are shown for the reference period 1961–1990. The upper row shows an upstream catchment and the lower row shows a downstream catchment in the same river basin. Locations of catchments are given by corresponding numbers in Figure 1.

Nevertheless, in this specific study, the hypothesis that shifts in river regulation and climate would result in a notable shift in river flow from catchments could not be rejected. On the other hand, the hypothesis that land cover has major impact on river flow could be rejected for most analysis and catchments. This is a very interesting result, as land cover is so well recognized for being a key driver in hydrology by the scientific community. For instance, the impacts of land cover change on water fluxes was recently appointed as one of 23 unsolved problems in hydrology (Blöschl, Bierkens, et al., 2019). The methods used in our study can be refined, and more aspects of the hydrograph could be analyzed, but we show that the signal from change is often weak and difficult to separate from noise in many cases. In addition to the methods used in this study, there are several other potential factors that might limit the detection of change, for instance data quality, flow generation processes, and magnitude of the disturbance studied, as discussed below.

The changes in river flow due to land cover changes that could possibly be detected are quite small compared to other uncertainties involved. This is especially true when taking into account the uncertainties in measured precipitation, temperature and discharge, and the hydrological model. For instance, the river gauges only observe water level, and the estimated discharge may change with up to 10%, as an average, when a new rating curve is adopted. Extreme values may even differ much more than that between different rating curves for the same gauging station. It is likely that current methods and data are not accurate enough to detect the relatively small changes that actually occur from environmental changes in Sweden, but are masked by other sources of uncertainty.

In a future of global warming, we might expect changes in vegetation and more frequent natural hazards as storms and fires from extreme weather events (e.g. Intergovernmental Panel on Climate Change, 2018). Nevertheless, our results suggest that these indirect effects of climate change will not have a large impact on the river flow volume. This is to some extent surprising as we could expect reduced water up-take from vegetation, higher groundwater table, changed balance of solar radiation, and damaged soil structure (e.g., Shakesby & Doerr, 2006). However, most studies supporting extensive effects on river flow due to changes in land cover are from warm and dry climate, while in northern countries the lake and snow conditions are the dominant drivers in flow generation (Kuentz et al., 2017). Therefore, we found only small effects

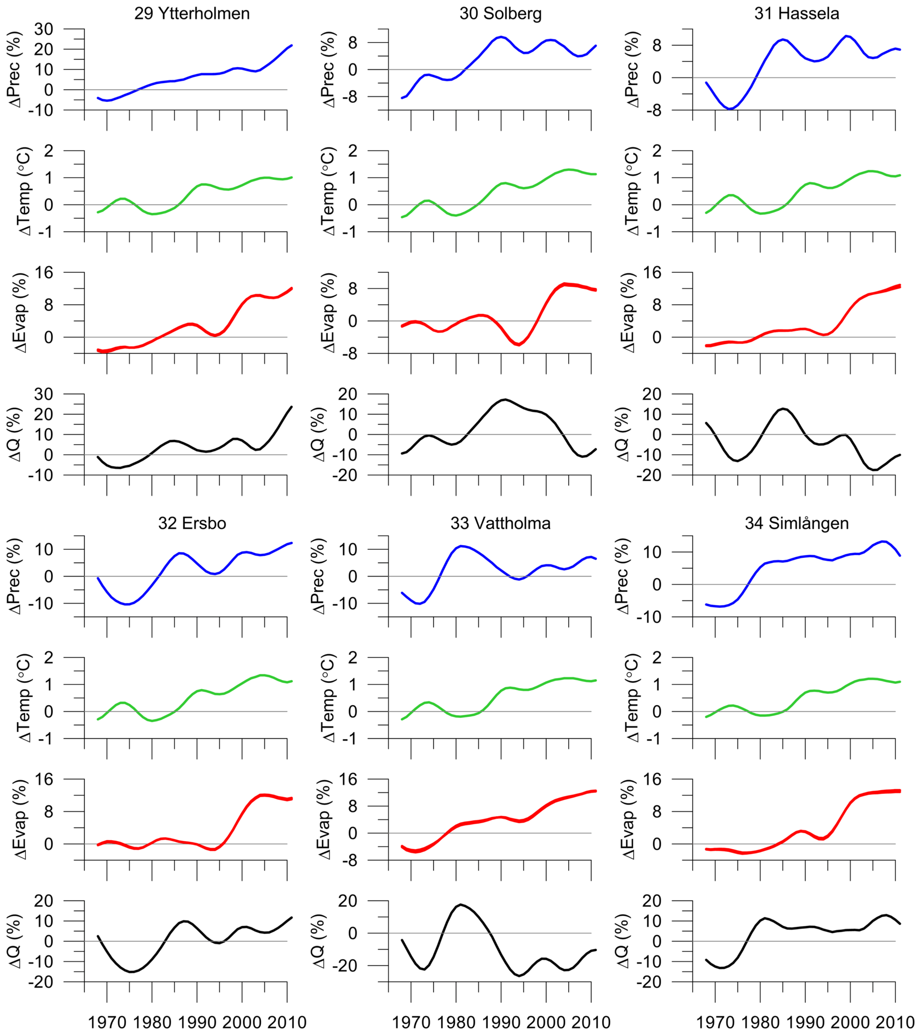

Figure 7. Impact of climate variability by S-HYPE (three model versions). The graphs show the deviation of climate related drivers from the reference period (1961–1990), Gauss-filtered with sigma = 3 years to highlight variations on a decadal scale. Estimates are given for undisturbed catchments across Sweden: interpolations from observed precipitation (blue), temperature (green), and modeled evapotranspiration (red) over the catchments, along with the observed river flow (black) at the outlets. Note that the axes have different scales. Locations of catchments are given by corresponding numbers in Figure 1.

from land cover change on river flow. Our results confirm previous studies from this environment by Brandt et al. (1988) that the effects from tree removal on river flow may be of importance only locally and that regulations of rivers are the most significant factor for hydrological change (Arheimer et al., 2017; Killingtveit et al., 2000).

It could well be that the hydrological processes affected by land cover changes have minor impact on flow generation in this part of the world and are overridden by other more dominant processes. In that case, land cover could affect river flow more in other physiographical environments. It could also be that the land cover changes are too small in spatial extent to impact on river flow from medium-sized catchments. Despite the fact that the river gauges were selected for capturing major changes and being as much affected by changes as possible, land cover changes still affected relatively small fractions of the catchments. For instance, the large Västmanland fire of 2014, which prompted this study, affected an area that corresponds to 0.6% of the total river basin at the outlet to the sea, and is of course not detectable at such large scale. The national monitoring system of Sweden is then too coarse to detect river flow changes, which might occur at local scale close to the area of disturbance.

5. Conclusions

The study shows the benefits from combining observed time series with numerical modeling to filter out the effect of natural variability in flow, when searching for other factors than weather that may cause a shift in flow generating processes. A mini ensemble of models increases the robustness of the results and conclusions. To sum up the result of the relative impact from various drivers of change in river flow from 34 catchments across Sweden, we found that

1. No drastic shift in river flow volume could be related to changes in land cover from wildfires, storms, or gradual urbanization. In the most affected catchment, a slight increase in autumn flow discerned. An increase in peak flows (in the order of 20%) due to urbanization was noted.
2. River regulation has the largest impact on flow regime, with almost 100% reduction during spring flood near the dams and roughly half of that at the river outlets to the sea. Winter flow was increased by orders of magnitude.
3. Climate variability between wet and dry decades affects the river flow to some 25% at maximum. Although clear trends in climate variables (e.g. precipitation and temperature) were found, only one catchment in the far north showed a significant trend in annual river flow; otherwise it was difficult to detect any changes beyond natural variability between years and decades.

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