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Long-term water quality monitoring in agricultural catchments in Sweden: Impact of climatic drivers on diffuse nutrient loads

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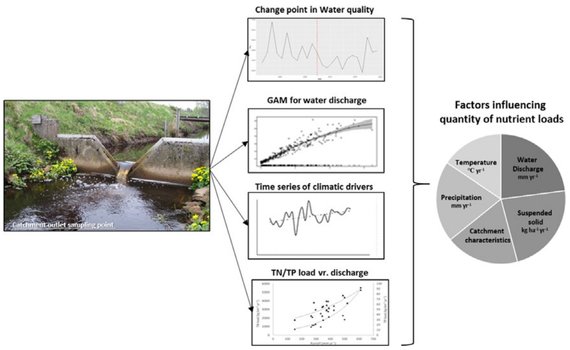
HIGHLIGHTS

- Interaction of climatic drivers with nutrient loads in Swedish catchments was analysed.
- Range of factors including catchment characteristics and climate defines loads.
- Water discharge is a significant indicator of nutrient loads.
- Temperature is a significant driver of total nitrogen loads.
- Climate projections should be incorporated into developing future management decisions.

GRAPHICAL ABSTRACT



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ABSTRACT

Water quality related to non-point source pollution continues to pose challenges in agricultural landscapes, despite two completed cycles of Water Framework Directive actions by farmers and landowners. Future climate projections will cause new challenges in landscape hydrology and subsequently, the potential responses in water quality. Investigating the nutrient trends in surface waters and studying the efficiency of mitigation measures revealed that loads and measures are highly variable both spatially and temporally in catchments with different agro-climatic and environmental conditions. In Sweden, nitrogen and phosphorus loads in eight agricultural catchments (470–3300 ha) have been intensively monitored for >20 years. This study investigated the relationship between precipitation, air temperature, and discharge patterns in relation to nitrogen (N) and phosphorus (P) loads at catchment outlets. The time series data analysis was carried out by integrating Mann-Kendall test, Pettitt break-points, and Generalized Additive Model. The results showed that the nutrient loads highly depend on water discharge, which had large variation in annual average (158–441 mm yr^{-1}). The annual average loads were also considerably different among the catchments with total N (TN) loads ranging from 6.76 to 35.73 kg ha^{-1}, and total P (TP) loads ranging from 0.11 to 1.04 kg ha^{-1}. The climatic drivers were highly significant indicators of nutrient loads but with varying degree of significance. Precipitation (28–962 mm yr^{-1}) was a significant indicator of TN loads in five catchments (loamy sand/sandy loam) while annual average temperature (6.5–8.7 °C yr^{-1}) was a significant driver of TN loads in six out of eight catchments. TP loads were associated with precipitation in two catchments and significantly correlated to water discharge in six catchments. Considering the more frequent occurrence of extreme weather events, it is necessary to tailor N and P mitigation measures to future climate-change features of precipitation, temperature, and discharge.

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1. Introduction

Decades of research have shown that agricultural intensification and loads of nitrogen (N) and phosphorus (P) as major forms of non-point pollution have significantly deteriorated water quality (Carstensen et al., 2020). The excessive loading of nutrients (EU, 2014; Billen et al., 2013; Addy et al., 2016) and sediment inputs to waters (Sherriff et al., 2016) had both direct and indirect impacts on soil function (De Graff et al., 2019) in regulating receiving-water quality. The projected population growth and therefore the necessity of ensuring food security will put soils and water bodies under further pressure (FAO, 2017, 2021). In addition, climate change is affecting food production and the more extreme weather frequency changes rainfall and water discharge responses (Arneth et al., 2019). Understanding the extent of the impact of climate-related stressors such as droughts, floods, and heat waves on agriculture, and the way agriculture in turn impacts the local and global natural resources, is increasingly important both to attain food security and to address undesired impacts on soil, crop and land management (IPCC, 2022). Many studies have investigated the functionality of various cropping systems (Ray et al., 2015; Daryanto et al., 2017) and nutrient leaching under different soils and climate (Costa, 2021). Despite the studies that have investigated the climate-water quality interactions, the links between water quality and climatic drivers are not fully understood (Gascuel-Odoux et al., 2023) and less considered in the policy reviews (Mellander et al., 2018). This is due to their inherent complexity of location specific and temporal and spatial scale dependencies of processes (Michalak, 2016). The difference in the vulnerabilities of different regions to climate changes (Mellander and Jordan, 2021) is also a key limitation in extrapolating the research results (Coffey et al., 2018). Studies to date also leave a gap in the distinction of the influence of climatic drivers on water discharge or loads of a specific nutrient (Li et al., 2021). Understanding the extent of the impact of climatic drivers on nutrient loads is of great importance as they may impair the efficiency of mitigation measures (Mbow et al., 2019) and hence cause great financial burdens.

Extensive research has investigated and developed strategies to prevent nutrient and sediment loads (USDA, 2022) by implementing a wide range of management actions (EC, 2018) to reduce nutrients, i.e., N and P and suspended solid (SS) loads whilst improving nutrient use and water use efficiency in agriculture. For example, European Union Common Agricultural Policy (CAP) was launched in 2008 with a focus on agricultural interests (IEEP, 2008). The EU Strategy for 2030 has set ambitious goal to reduce nutrient loads by at least 50 % while maintaining soil fertility through measures such as Integrated Nutrient Management Action Plan (INMAP) (EC, 2020). Under the Water Framework Directive (WFD), Member States undersign to reach good ecological status in all water bodies (EEA, 2021). The first Swedish plan was established toward the end of 1980s and was later updated based on new research findings and legislations (Ministry of the Environment and energy: Sweden, 2019). These actions were enabled through the EU CAP initiatives, national implementation of EU Water Framework Directive, as well as practices related to nutrient management. However, further improvement of water quality is needed (EEA, 2021). N loads have decreased by 25 % between 1985 and 1995 and another 10 % between 1995 and 2011. The reduction of P loads between 1995 and 2011 was 7 %, (Jordbruksverket, 2020a). In Sweden, farmers have managed to increase yield per hectare production in rainfed-dominated cereal and ley systems during 20th century through a range of intensification efforts. The use of mineral fertilizer has also increased over the previous two decades (Jordbruksverket, 2020b). Today SCB (2020) reports 110 kg N ha^{-1} and 20 kg P ha^{-1} for crop areas in Sweden in 2018/2019 while 106 kg N ha^{-1} and 17 kg P ha^{-1} are recorded for 2000/2001 (SCB, 2014). The yield per hectare increase was also significant, e.g., cereal yield increased by 0.8–1 t ha^{-1} since 2000 (except 2018) (Jordbruksverket, 2020a). Hence, the improved nutrient balance today decreases the amount of nutrients available for leaching. However, the in-country variations are substantial, affected by agro-ecological potentials and actual production systems, and whether manure is added (e.g. in animal dense areas) or if mineral fertilisers dominate (in crop production only).

On the other hand, studies to date suggest that climate change will likely increase the loadings of non-point source pollution such as N and P to water bodies in the Nordic countries (Jeppesen et al., 2011; Hashemi et al., 2018; Pengerud et al., 2015) while the increasing average temperature may increase the stress on freshwater ecosystems and biodiversity (ECA, 2021). The climate change scenarios in Sweden project an increasing trend in annual precipitation, including extreme rainfall events, which may add to increase in water discharge (Eckersten et al., 2008; Grusson et al., 2021). Understanding the extent to which the climatic drivers affect the water quality is therefore important for better development of future nutrient management decisions (Beck et al., 2022).

In Sweden in general, on-farm actions to reduce non-point source pollution from agricultural land begun in the 1980s (Landsbygdsdepartementet, 2014). A 20-year trend analysis covering 65 small agricultural-dominated water courses in southern and central Sweden (Fölster et al., 2012) concluded that N loads decreased in 65 streams with P to show a tendency toward a downward trend in some rivers despite upward trends in some e.g. central east. A review conducted by Liu et al. (2017) indicated the insufficiency of short-term data (<4 years) on showing the effectiveness of mitigation actions against loads. Such actions can even become sources of pollutants under specific environmental conditions (Ezzati et al., 2019). However, analysing long-term water quality data can inform about slow changes in response to climatic drivers. So far, few studies have investigated the impact of water discharge and long-term nutrient loads in landscape/catchment scale in relation to climatic variables (Pettersen et al., 2021; De Wit et al., 2020). Consequently, few long-term monitored studies exist that distinguish the significance of water discharge and climatic drivers in relation to nutrient loads.

The objective of this study was to investigate the long-term trends (>20 years) in total N (TN) and total P (TP) loads in eight Swedish headwater catchments with contrasting characteristics in view of the impact of climatic drivers. We related time series data of precipitation, temperature, water discharge, and suspended solid (SS) loads using various statistical models to explore potential change points in water quality and understand the relations and the impact of these drivers on TN and TP loads. Using statistical modelling approach, our research aimed to 1) understand specific climatic drivers of water quality (N, P) in relation to water discharge and SS loads, 2) detect breakpoints in drivers and response variables of TN and TP loads, and 3) discuss findings in view of the outlook of the changing climate.

2. Materials and methods

2.1. Sites' description

The data form the “Agricultural Catchment Monitoring Programme” funded by Swedish Environmental Protection Agency related to stream measurements of water quality in agricultural catchments were used. This monitoring has been in place since 1988 and is coordinated by Swedish University of Agricultural Science (Kyllmar et al., 2014b), which also carries out data collection and analyses of surface water quality. The eight agriculturally dominated monitoring catchments (Fig. 1) range from 470 to 3300 ha. The catchments are located in southern and central Sweden, representing different agro-climatic, crop-soil management and soil texture conditions (Table 1). These catchments are all situated within waterbodies with an overall ecological status to be classified as moderate by the Water Information System Sweden (VISS, 2022).

The production systems in these head catchments range from cereal production with almost no manure application (catchment M42) to milk production based on grass fodder and manure as dominating source for fertilisation (catchment F26). Three catchments (M42, M36, N34) are located in coastal areas, mostly sandy loam and intensive crop production (e.g. oilseed, sugar beet, potato, and winter wheat), with mild winters

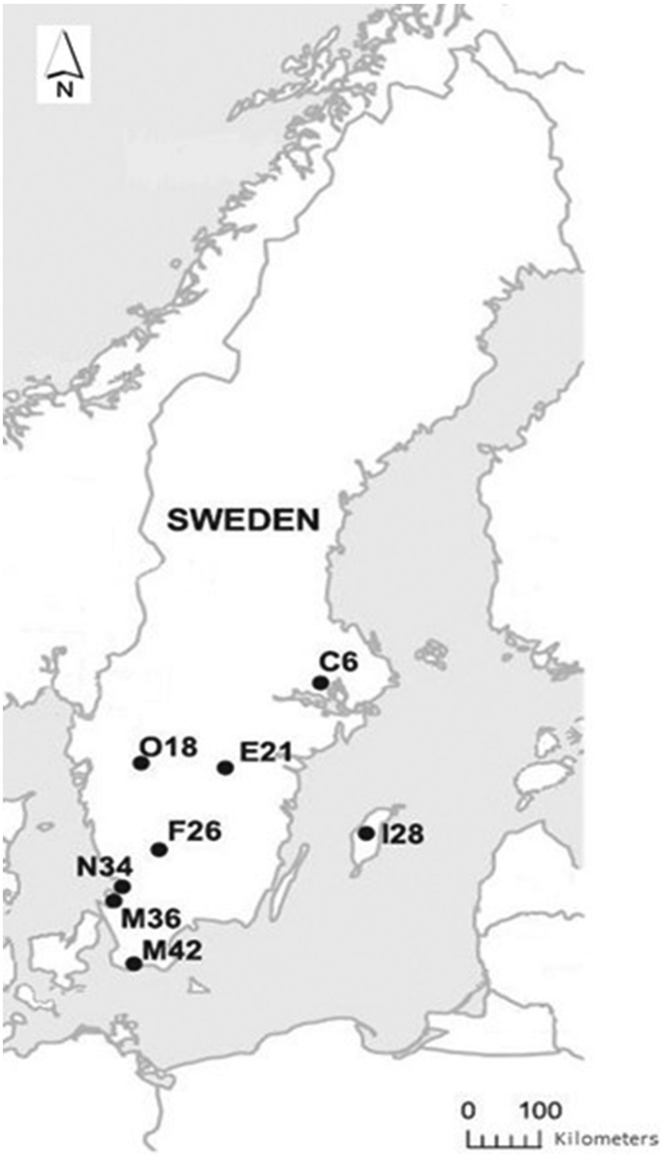

Fig. 1. Location of the eight national agricultural monitoring catchments in Sweden.

and high precipitation. Catchment F26 is located in a more forested inland area with high livestock density and ley production and the highest annual precipitation among the eight catchments. Catchment I28 is located on the island of Gotland with low precipitation. The remaining catchments (O18, C6, E21) are mainly under cereal and oilseed production and are situated in the central arable areas of Sweden.

2.2. Water analyses, water discharge measurements and nutrient load calculations

In order to study the chemical quality elements of surface water we considered the concentrations of TN and TP in water, following to EU WFD (Arle et al., 2016) as robust measures that reflect stream trophic status (Poikane et al., 2019). At catchment stream outlet, water discharge was monitored continuously at defined stream cross sections and stored as hourly or more frequent discharge values (Kyllmar et al., 2014a). Water samples were taken bi-weekly, first as discrete manual samples (1988–2010) and then as flow-weighted composite samples (FWCS) using automatic water sampler consisting of a peristaltic pump, suction tube, a flow detector and a 10 L glass bottle (Kyllmar et al., 2014b). In FWCS sampling method, a sub-sample was taken when a defined volume of water has passed the discharge measuring point, triggered by a data logger (Campbell or ISCO). This means that more sub-samples were taken during high flow events. During flows below a certain level, time-proportional sampling was applied. Water samples were analysed following the standards methods at laboratories accredited by Swedish Board for Accreditation and Conformity Assessment (SWEDAC) (Kyllmar et al., 2006, 2014b) (using persulphate and photometry method). TN and TP loads based on discrete water sampling were achieved by interpolation of concentration values to daily values, which then were multiplied with daily water discharge to daily loads. These daily loads were summarised to monthly values. For composite samples the analysed water concentration values represent the whole sampling period which means that loads are calculated first as two-week values then summed up to monthly values. To obtain area-specific loads, total loads per catchment were divided by total catchment area. Similarly, area-specific water discharge (mm) was calculated by dividing total water volume by total catchment area. For the purpose of this study, a complete long-term dataset for each catchment was constructed by adding the flow proportional composite data series to the discrete manual data series.

2.3. Climatic data

The monthly and annual precipitation and temperature data were retrieved from the Swedish Meteorological and Hydrological Institute (SMHI) from the stations closest to the catchment of study (SMHI, 2022). The stations are inspected, managed and maintained on an ongoing basis by SMHI. The precipitation was measured automatically on daily basis and the temperature was calculated two to three times a day. The data is saved in SMHI's database after quality-checking.

2.4. Statistical analysis to link nutrient loads to climate variables and water discharge

This study integrated different modelling approaches to analyse the impact of drivers on nutrient loads. The models were 1- Mann-Kendall trend analysis to investigate occurrence of trends in time series of annual climatic drivers, SS loads and water discharge; 2- Pettitt test to detect change-points when the probability distribution of time-series data shifts; 3- Generalized

Table 1
The characteristics of the agricultural monitoring catchments.

Catchment	Monitoring start	Area ha	% of total area			Dominant soil texture (USDA) % arable land	Dominant crop rotation (>10 % average value between 2002 and 2020 from the highest to lowest)
			Arable land	Forested	Pasture		
C6	1993-	3298	59	32	2	Clay loam	Spring cereals, winter cereals, ley
O18	1988-	766	92	2		Clay	Winter cereals, spring cereals, legumes, Winter oilseed
E21	1988-	1632	89	4	< 0.1	Sandy load	Winter cereals, spring cereals, Winter oilseed
F26	1993-	182	70	19	3	Loamy sand	Ley, spring cereals
I28	1989-	472	79	12	2	Loam	Winter cereals, spring cereals, ley
N34	1996-	1393	85	6	2	Sandy loam	Spring cereals, winter cereals, ley, maize
M36	1988-	789	86	4	1	Loam	Winter cereals, ley, spring cereals
M42	1992-	824	93	1	<1	Sandy loam	Winter cereals (lower in certain years), spring cereals, winter oilseed, sugar beet, ley

additive model (GAM) to investigate the impact of environmental and anthropogenic variables on nutrient concentrations leaving the catchments .

2.4.1. Mann-Kendall trend analysis

The non-parametric rank-based Mann-Kendall test (Kendall, 1975) was used for temporal trend analysis of drivers as it has the capacity to account for non-normality of hydrological (Yue et al., 2002) and climatological data (Partal and Kahya, 2006).The null hypothesis states that the data (x1, …, xn) consists of n independent and identically distributed random variables.

Sen's slope (Sen, 1968) was used to calculate linear slope (s) of time series with significant trends ($p < 0.05$). The intercept (b) was calculated using the following formula:

$$b = x_{0.5} - s^{*}y_{0.5} \tag{1}$$

where $x_{0.5}$ and $y_{0.5}$ are medians of variables.

2.4.2. Pettitt test for change-point detection

Mann-Whitney two sample test (MW) described by Pettitt (1979) was used as one of the robust method for detecting significant change in the mean value by identification of potential breakpoint in the slope (Bouraoui and Malago, 2020) of time series data. The Pettittt method, which is a non-parametric model based on ranks i.e. not based on any assumptions of the underlying distribution of the residuals, detects significant changes in the mean of a time series data and is insensitive and more robust against outliers compared to other parametric method (Anderson, 2014). Another strength of this method is that random spikes do not influence change-point detection and therefore only permanent or long-term changes are detected correctly for different distributions (Mallakpour and Villarini, 2016).

In order to detect change point of nutrient loads, and to show how or if the nutrient trend corresponds to change points in climatic drivers, the Pettitt method was applied on yearly nutrient load data.

$$Y_{t,n} = Y_{t-1,n} + \sum_{i=1}^{2} sgn\,(X_t - X_i), 2 \le t \le n \tag{2}$$

$$\mathrm{Sgn}(X_t - X_i) = \begin{matrix} +1 & X_t > X_i \\ 0 & X_t > X_i \\ -1 & X_t < X_i \end{matrix} \tag{3}$$

where Y is the statistics sequence calculated by time series of $X_1, \ldots, X_n$.

The test statistics K, which counts the number of times that a member of the first sample exceeds a member of the second sample, is

$$K_T = \max_{1 \le t \le T} |y_{t,T}| \tag{4}$$

$$P \cong 2\ exp\left[-6\,K_{Tn}^{2}(T^{3} + T^{2}\right] \tag{5}$$

The null hypothesis is absence of a change point and therefore p value ≤ 0.5 indicates a significant T in which time the data can be divided into before and after the change point (Mallakpour and Villarini, 2016).

2.4.3. Generalized Additive Model (GAM)

The Generalized Additive Models (GAMs) (Hastie and Tibshirani, 1986) was used to estimate the smooth trend (Wood, 2017; von Brömssen et al., 2021) and to understand the complex relationships among response (i.e. TN and TP loads), and explanatory variables (i.e. water discharge, precipitation, temperature, suspended solids), and their significance in regulating the loads. GAMs are an extension of generalized linear models with a smoothing function and are sensitive to the nonlinear driver-response relationship that is commonly observed in environmental systems and their associated nonlinear trends (Yang and Moyer, 2020). This approach also provides estimates on significance of each variables to the nutrient loads for any forms of N and P as the outlier-robust GAMs have the capacity to detect the shape of a fitted trend as a smooth function of time over a long-term time period from the data itself (Murphy et al., 2019).

$$y = s_0 + s_1(x_1) + s_2(x_2) + \ldots + s_n(x_n) \tag{6}$$

where s is the smooth function represented as

$$s(x) = \Sigma_{k=1}^{k} \beta_k b_k(x) \tag{7}$$

where β shows the weight, b is the basis expansion, and k is chosen so that it would be large enough to have enough degree of freedom, and small enough to maintain reasonable computational efficiency.

Finally, the accuracy of results to capture the relationship in the data was checked based on the adequate amount of basis functions or the flexibility of curve fitting. If the p-value of a test result is too small, it shows the residuals are not randomly distributed. The trend is significantly downward if the entire confidence band of the derivative lies below zero, but the trend is significantly upward if the entire confidence band lies above zero (Murphy et al., 2019).

The relationship between annual average water discharge and annual average stream loads of TN and TP was calculated using linear regression between the two variables.

3. Results

3.1. Catchment biogeophysical properties and climate characteristics

The average annual catchment-specific discharge varied considerably among the eight catchments ranging from 158 to 441 L m^{-2} (mm yr^{-1}) in catchments E21 and F26 respectively. The catchments with highest water discharge after F26 were O18, N34, 42, and M36, in a descending order. The average annual precipitation was highest in catchments F26 (962 mm yr^{-1}) and N34 (774 mm yr^{-1}). A large variation between average annual nutrient loads during the monitoring period was found between the catchments in terms of both TN and TP loads. Catchment N34, with sandy loam soil texture, had the highest TN loads (35.73 kg ha^{-1}) compared to catchment C6 (6.76 kg ha^{-1}) which is clay-loam dominated with lowest and had the lowest TN loads across all catchments. Catchment O18 (clay soil texture) had the highest TP load (1.04 kg ha^{-1}) whereas catchment E21 (sandy loam) had the lowest (0.11 kg ha^{-1}) although both of these catchments had similar percentage of lands dedicated to farming. In terms of SS loads, the variation between catchments was huge with maximum of 584.91 kg ha^{-1} in catchment O18 and minimum of 21.44 kg ha^{-1} in catchment I28.

Table 2 shows the annual average values of climatic drivers, and nutrient loads in agro-hydrological years (July–June) from 2002 to 2020 for all eight catchments, both from the start of the monitoring programme, and from 2010 when flow proportional sampling was applied in all catchments. Hence, catchments in which there was an increase of loads during recent years, e.g. O18, have higher average values as well.

3.2. Time series analysis

The Mann-Kendall test on temperature, precipitation, water discharge, and SS (Fig. 2) suggested the shifting trends in climate-change. This time series analysis revealed significant upward trends in temperature in catchments E21, F26, I28, and M36, with varying spatial characteristics across the country. The precipitation trend was significantly positive (upward) in catchment E21 while significant downward trends were observed in catchment F26 and N34. A relatively stable precipitation trend was observed in the rest of the catchments. However, the trends in temperature and precipitation correlated with each other.

The trend in SS loads was fluctuating in all catchments and showed a significant upward trend in catchment O18, I28, and M36. However, the fluctuations were minimum in catchments E21, F26, and M42, which also demonstrated lower SS load values compared to other catchments.

Table 2

Annual average values of climatic drivers, nutrients loads and sediment losses.

Catchment	n	Climatic variable during the monitoring period						Nutrient load (kg ha^{-1}) from start of the monitoring programme till 2020						Nutrient load (kg ha^{-1}) from 2010 to 2020					
		Water discharge (mm yr^{-1})	std	Precp. (mm yr^{-1})	std	Temp (°C yr^{-1})	std	TN	std	TP	std	SS	std	TN	std	TP	std	SS	std
C6	26	218	96	575	97	6.8	0.9	6.7	2.7	0.41	0.24	276.7	186.7	6.2	2.1	0.47	0.26	288.3	170.2
O18	32	332	105	633	93	7.5	0.8	18.1	6.7	1.04	0.62	584.9	605.4	13.8	3.7	1.38	0.67	1016.6	605.3
E21	32	158	87	528	97	6.5	0.9	16.1	8.8	0.11	0.09	22.5	21.6	14.8	7.8	0.06	0.04	21.4	14.1
F26	26	441	154	962	189	6.9	1.3	17	5.6	0.42	0.24	62.8	49.7	15.7	4.6	0.49	0.33	73.6	69.9
I28	31	163	55	564	100	7.7	0.7	15.7	4.9	0.24	0.16	21.4	20.8	17	4.8	0.37	0.18	36.3	29.4
N34	24	374	119	774	137	8.3	1.2	35.7	11.4	0.37	0.26	120.4	88.7	33	9.8	0.42	0.24	137.8	78.2
M36	31	259	91	695	106	8.7	0.8	19.6	592	0.51	0.25	195.2	132.8	17.3	3.11	0.60	0.21	269.1	135.3
M42	32	247	103	700	139	8.5	0.8	25	25.9	0.37	0.17	47	46.2	28.7	8.37	0.44	0.16	50.3	19.1

n = number of years; std. = standard deviation.

Looking at the water discharge time series data, there were no significant trends over full period of analysis. However, a pattern is observed for all catchments regardless of soil texture or geographical location, with substantial fluctuations. There was an increase in water discharge in 2017 followed by a decline in 2018 across all catchments as well. Still, the response of nutrient loads is not the same across the catchments.

3.3. Change point detection of nutrient loads in relation to water discharge and precipitation

Figs. 3 and 4 present the annual loads of TN and TP, respectively, and the change point detections in nutrient load trends, precipitation, and water discharge, from the start of the monitoring program. The change points of annual average water discharge and annual precipitation are presented on the same graph as they have comparable magnitude. Meanwhile, understanding sudden increases in trends is straightforward in certain years (e.g. 2018–2019) as it can be associated with the drought in the year before and sudden flushing of nutrients into the streams with the first heavy rain afterward.

In general, few linkages between precipitation, water discharge, and loads were found that would create a predictable pattern across all catchments.

It is observed that changes in precipitation in M36, C6, and M42 fell close to abrupt changes in TN loads leaving the catchments with a time lag of 1–2 years (Fig. 3). This indicates the importance of considering climate variables in managing nutrients being flushed into water bodies, as well as the time lag in flushing of the accumulated nutrients (Vero et al., 2018). However, looking at the abrupt change points in water discharge data, the change points in water discharge have fallen in different timings than the precipitation data. This is due to the fact that the management of each catchment is different and the nutrient loads collected at catchment outlets showed the cumulative impacts of implemented measures in many small farming areas. Similar pattern in increase/decrease in TN loads is seen in all catchments except M42 where it declined from 2002 to 2004 and remained constant until 2010 after an increase in 2005 (Fig. 3). The fluctuations continued until it increased in 2018. N34 and E21 also showed to follow opposite trends in their increase/decrease annual TN loads.

As in Fig. 4, the decrease/increase patterns in annual nutrient load were almost similar among the catchments except for C6, I28, and E21 in which the TP loads decreased during 2008–2010 while other catchments (N34, M42, F26, O18, M36) experienced an increase. The TP load increased again from 2010 to 2012 while the loads in other 5 catchments decreased.

There was two instances of TP load change points in catchment M42 and in one instance, it appears to respond and coincide to a change in water discharge. However, no apparent overlap with change points in TN or TP load in any other catchment was observed. Catchment I28 was also the only catchment having two abrupt changes in water discharge.

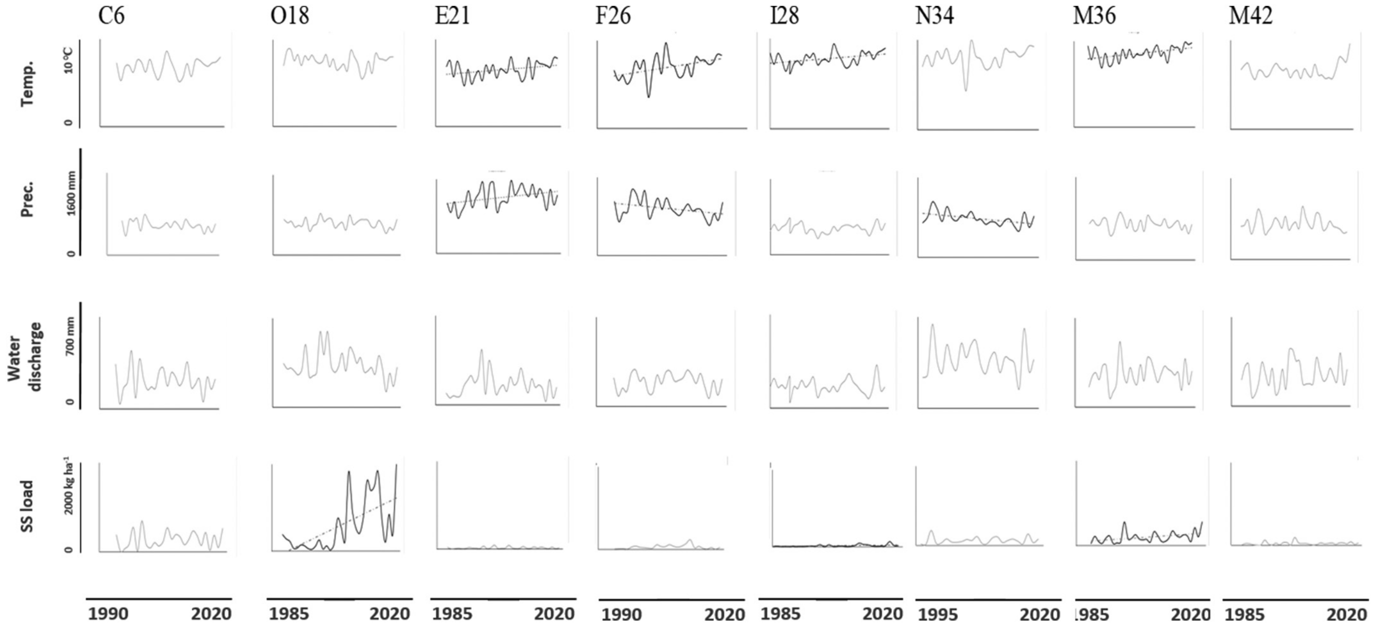

Fig. 2. Time series of annual average values for climatic drivers of temperature and precipitation, water discharge, and suspended solid loads (annual sum). Graphs are bold for significant Mann-Kendall trend ($p < 0.05$) and the dotted lines represents the Sen's slope.

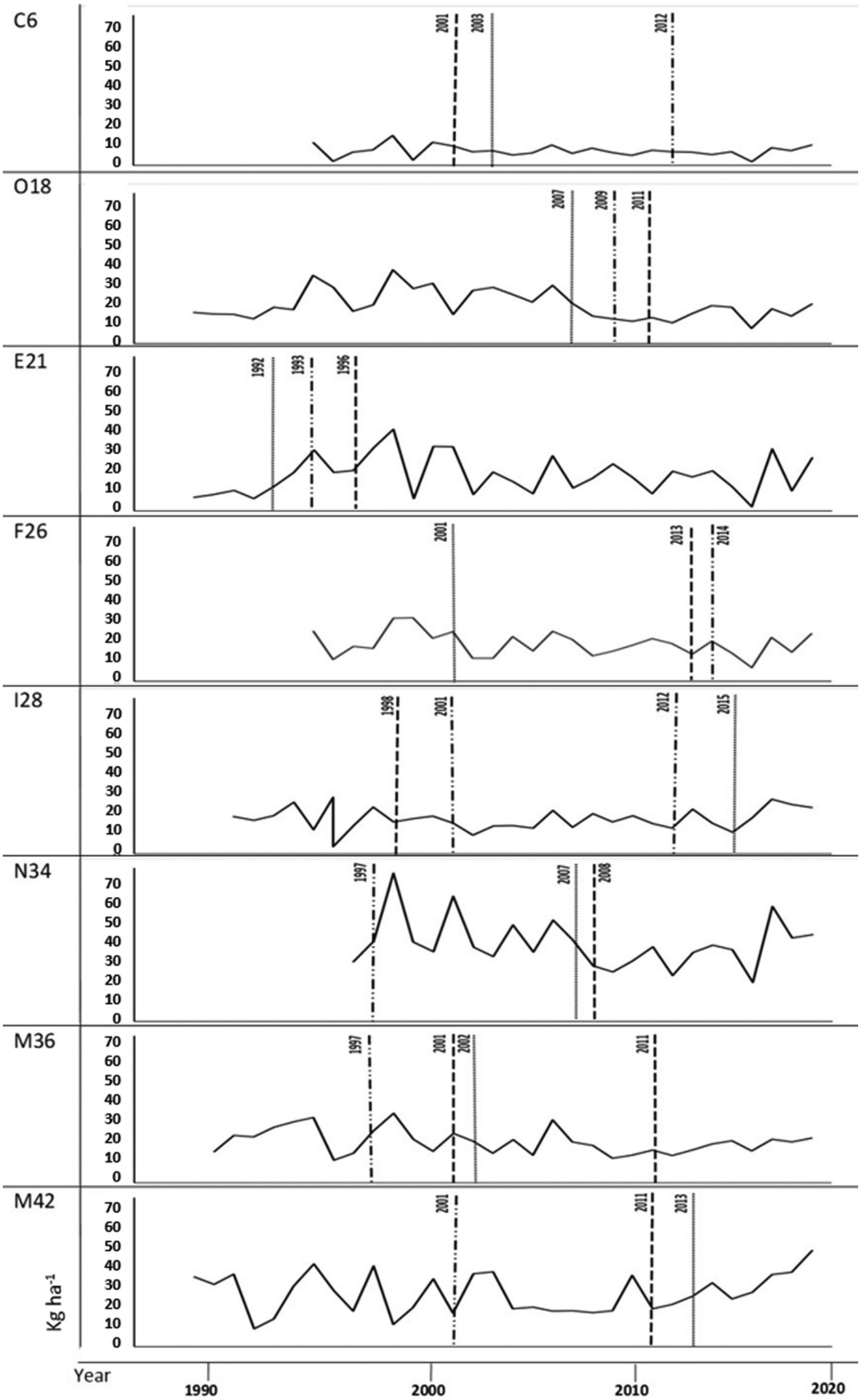

Fig. 3. Annual TN load (kg ha^{-1}), and change-point detection for TN loads (dotted lines), precipitation (dashed lines), and water discharge (dashed lines between two points) from start of monitoring programme until 2020 in eight agricultural catchments.

3.4. Significance of drivers on nutrient loads

The GAM technique was used to study the relations between variables and to test the significance of water discharge, precipitation, temperature, and SS loads against TN and TP loads. Fig. 5 shows the response plots from the best-fitting GAMs on the significance of above-mentioned drives, separately, in regulating the trends of loads in the investigated catchments.

3.4.1. Significance of water discharge

The GAM analysis (Fig. 5) showed that the significance of explanatory variables of water discharge and SS was correlated and consistent across all study sites in regulating both TN and TP loads.

Water discharge was a highly significant regulator of TN loads with a consistent upward trend in all catchments ($p \leq 0.001$). This is aligned with many studies indicating the discharge to be the main driver, or one

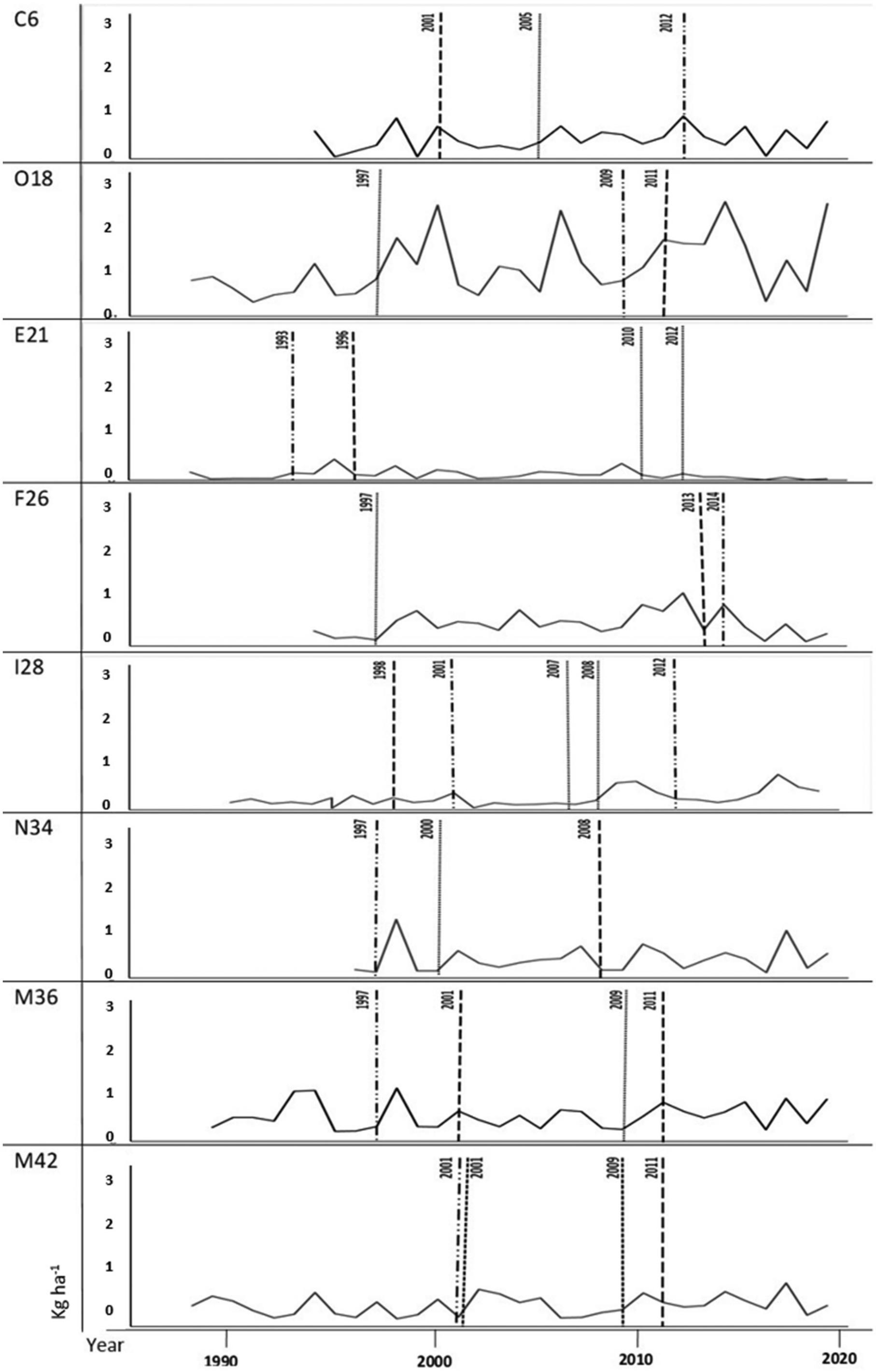

Fig. 4. Annual TP load (kg ha^{-1}), and change-point detection for TP loads (dotted lines), precipitation (dashed lines), and water discharge (dashed lines between two points) from start of monitoring programme until 2020 in eight agricultural catchments.

of the main drivers of TN loads, both in Nordic countries (Deelstra et al., 2014; Stålnacke et al., 2014; Øygarden et al., 2014; Chen and Bechmann, 2019) or in other geographically different locations (Bie, 2017; Yao et al., 2021). However, the extent of this overall positive relationship of discharge with loads was different among catchments. The TN load in catchments C6, O18, and E21 increased and then stabilized and got diluted, whereas in rest of the catchments, there seems to be no limit for TN discharges. The TP loads in catchments O18 and E21 reached a peak and stabilized with a downward shift afterwards. This is explained by the fact that very high flows would wash out suspended solids (and consequently the bound P) and exhaust the system (Nagara et al., 2022) until nutrients start building up again. The annual average water discharge (as well as SS loads) in E21 was lowest compared to other catchments (Table 1) and there was a consistent positive (upward) trend in relation to significance of SS on regulating TP loads. On contrary, the annual average water discharge was highest in O18 (Table 1). Since O18 is the only-clay dominated catchment, the GAM analysis showed similar trend in exhaustion of the system with regard to SS as in the water discharge. A high annual TP load (Fig. 4) and fluctuating high time series analysis of water discharge over the long monitoring period (Fig. 2) were already observed in this catchment. The higher water discharge in the intensively-farmed O18 is related to the high precipitation in this area as it is located in west Sweden. The high clay content of the soil

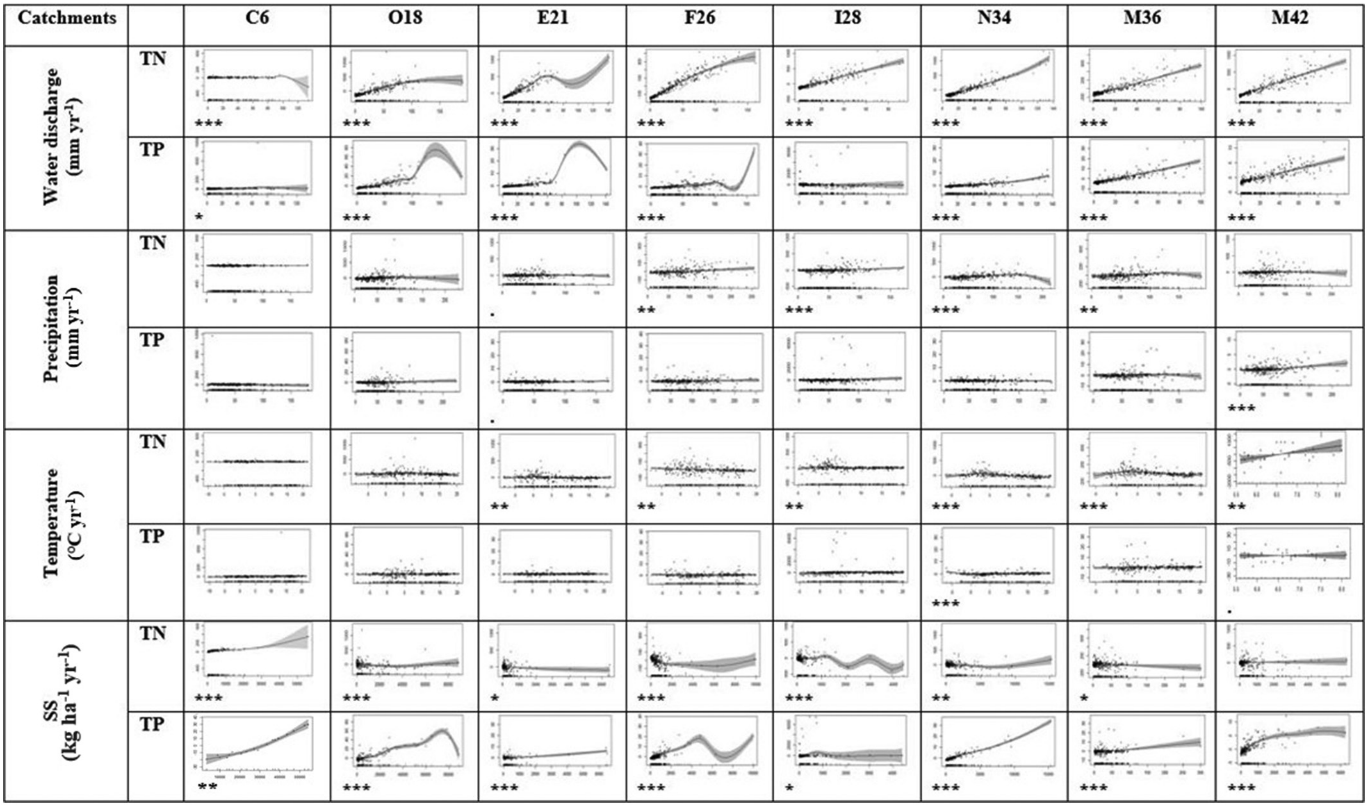

Fig. 5. Generalized Additive Model plots showing the separate partial effects of average annual values of climatic drivers (precipitation, temperature), water discharge, and suspended solids (SS) on trends of TN loads (upper row) and TP loads (lower row) from the start of the monitoring programme. The x-axis is the explanatory variable and the y-axis shows partial effects of each variable on regulating the trends of loads. The dots on the plots are the partial residuals as the difference between the partial effect and the data after partial effects have been accounted for. The grey shadings surrounding the estimated trends are the range of observations with approximate 95 % confidence intervals.

The asterisks show significance of each variables: $p \leq 0.001$ “***”; $p \leq 0.01$ “**”; $p \leq 0.05$ “*”; $p \leq 0{,}1$ “*”.

acts as an additional factor contributing to more water discharge since clay catchments are often situated low in the landscape where more ground water reaches surface waters, contributing to higher loads as well. The proportion of arable lands in this catchment is also one of the highest among other catchments (i.e. 92 % compared to only 59 % in catchment C6). The notably different land use in catchment C6 highlights the importance of the physical settings of the agricultural landscape in regulating the nutrient loads (Bieroza et al., 2020).

The above observation was unlike TP discharge pattern in F26 in which very high water discharge would cause very high TP loads with no limit. The increase in water discharge was very significant driver of increase in TP loads in catchment N34, M42, and M36 but with a smoother inclined upward trend.

Catchment N34, M36, M42 appeared to be more vulnerable against climatic changes (precipitation and temperature), followed by I28, F26, and E21. These two drivers were very significant regulator of loads, although the magnitude of changes was not as high as water discharge or SS. These catchments showed behaviour of a chemodynamic catchment with high concentration variability (Pohle et al., 2021). Recent studies are also highlighting the significance influence of changes in air and soil temperature and rainfall on nutrient concentrations (Mellander and Jordan, 2021; Seyedhashemi et al., 2022). In contrary, the clay-dominated catchments (C6 and O18) had higher water-holding capacity (Mäkinen et al., 2017) and suggested chemostatic behaviour (hydrologically controlled) over long time series (Knapp et al., 2019).

Eventually, in order to investigate the relationship between water discharge and TN and TP loads a step further, regression lines were fitted to the data (Fig. 6).

The shape of the relationship between annual TN loads and annual water discharge differed between the catchments (Fig. 6). The analysis gave exponential or logarithmic results in all catchments with significantly different regression slopes and coefficients. The non-linearity of relationship was expected as we had already observed step point changes in all catchments for at least one occasion (Figs. 3 and 4).

None of the regression slopes in any of the catchments decreased although the shape significantly varied showing that the increase of TN and/or TP loads with increasing water discharge was not equally related in all catchments. Also, the regression coefficients of TP load versus water discharge was significant for all established relationship. The regression coefficient of TN loads was also significant in all catchments except I28, M42, and O18.

3.4.2. Significance of climatic drivers

From Fig. 5, precipitation appeared to be highly significant indicator of TN loads in catchments M36, N34, I28, and F26. The dominant soil texture in these catchments is loamy sand/sandy loam, and loam. Excess moisture in soil profile acts as one of the main reasons for N loads from crops due to denitrification when anaerobic soil conditions cause microbes to convert nitrate to nitrous oxide. Also, water percolation through soil profile that carries nitrate below rooting zone cause leaching (N loads) (White et al., 2021). Precipitation was a significant driver of TP loads in E21 and highly significant in M42 while temperature was on the first level of significance ($p \leq 0.001$) for both TN and TP loads in this catchment. Therefore, drainage system of the catchment is of great importance.

Temperature was also a significant driver of explaining TN loads to water bodies in all these catchments in addition to catchments M42 and

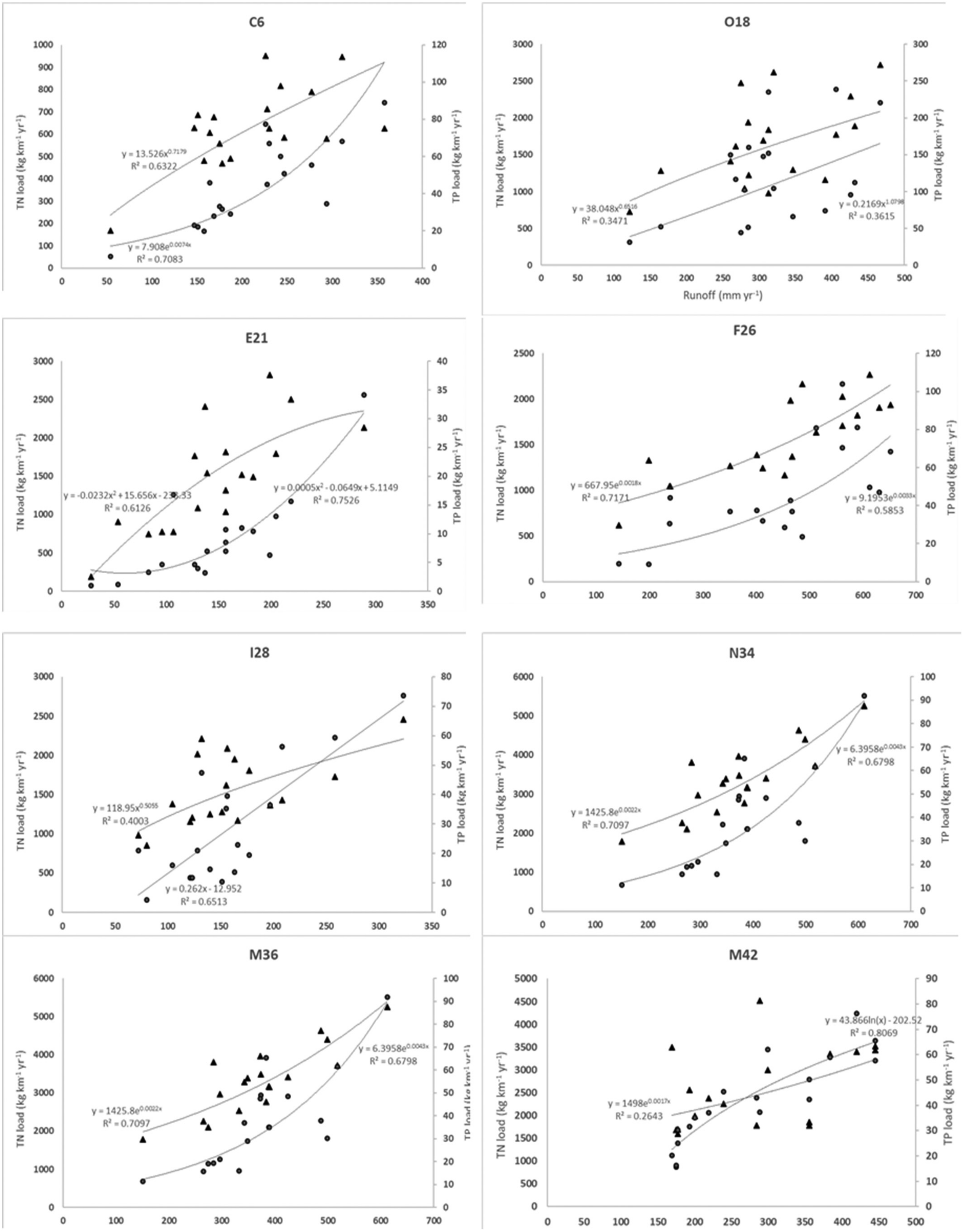

Fig. 6. Stream TN and TP loads versus water discharge (mm yr^{-1}) from the start of monitoring until 2020. The triangular markers represent TN and the circular markers represent TP.

E21. Temperature was only highly significant in TP loads in catchment N34 and precipitation showed to be important in TP loads in E21. Suspended solids appeared to be highly significant variable contributing to TP loads in almost all catchments. The same trend is observe with regard to correlation between suspended solid loads and TN loads in all catchments as they are closely related except M42.

Catchment E21 shows how an extreme weather event such as the drought in 2018 and consequent flushing of nutrients in the year after impacts nutrient loads. This catchment has lighter soil texture (sandy loam) with higher hydraulic conductivity and therefore lower chance of surface water discharge compared to clay-dominated catchments.

4. Discussion

Previous studies have reported transportation of N and P via displacement by water discharge although anthropogenic activities, weathering, and wind-induced displacement contribute to transport of sediments too (Lintern et al., 2018). According to HELCOM (2019), water discharge is responsible for 75 % and 93 % of TN and TP loads, respectively. HELCOM simulated precipitation experiment showed the water discharge rate and/or precipitation had significant relationships with N and P loads and they all had similar temporal patterns with variations during the beginning of the precipitation. In general, soils with high clay content, high water tables, claypan or clay layer at the top or near the surface, or very slow infiltration rates have great nutrient discharge potential (Follet and Hatfield, 2001), such as catchment O18 in the current study.

The key factors influencing water discharge-associated N loads along surface or pathways are the amount and timing of precipitation, soil functions (soil properties and farming practices on the land), and N application rates (Clagnan et al., 2019). In addition, the increase in suspended solid materials in surface water leads to an increase load of N in water discharge due to hydraulic erosion effect of raindrops on the surface of soil (Li and Zuo, 2020). Then nitrogen is mainly transported by surface water discharge (Li and Zuo, 2020) with high percentage of loamy soil texture (Panday et al., 2020). This can also be observed in Fig. 5 with relationship between TN loads and precipitation in sandy loam/loamy catchments in catchments N34 and M42.

Contrary to N, organic and inorganic forms of P are mainly associated to soil texture/chemistry (Ducousso-Detrez et al., 2022). Thus, the mobilisation or retention of P depends on the soil type, drainage status, and the type of water resources (surface or groundwater) (Ezzati et al., 2020). The increase in suspended solid materials in surface water (Fig. 5) leads to an increase loads in P via surface water /subsurface flow (leaching) (Penn et al., 2017). However, the suspended solid trends in catchments O18 and M36 could be due to changes in sampling method. In addition, the mixing times series with different sampling methods (manual versus flow proportional) to generate the models might produce some level of uncertainty. In order to eliminate that, the models were initially generated specific to each sampling methods and then comparing the mixing of the methods proved to be more aligned to the general observed trend. Table 2 also demonstrates the subtle difference.

In Sweden, Johnsson et al. (2016) showed that the high leakage of nutrients in south western Sweden was mainly due to high water discharge and a high proportion of light soils, i.e. soils with a low clay content. The study claimed that precipitation and water discharge conditions are particularly important for P loads (Johnsson et al., 2016). This necessities the importance of considering both water discharge volume control as well as mitigation techniques at high-flow events. Kyllmar et al. (2020) also stated that there is great potential in renovation of drainage systems not only to enhance nutrient utilization, but also prevention of soil entering drainage pipes and being carried further into water courses. This is of great concern as the soil can be accumulated as sediments, which are significant sources of P transport to water bodies (Ezzati et al., 2019; Krasa et al., 2019). Hence, considering the significance of water discharge in nutrient loads, other sophisticated measures for better nutrient-load management practices could be considered such as developing stabilized slope to reduce risk of erosion (Kyllmar et al., 2020), or mechanical design of unterraced field for water flow-direction and then removing sediment-associated pollutants by filtration, deposition, sorption, and volatilization, in field tillage measures.

Looking at the impact of climatic drivers on nutrient loads, the influence of precipitation on water discharge has also been established in other studies (Wenng et al., 2020) which leads to significant increase in nutrient loads (Yao et al., 2021). Catchment-scale studies in Denmark have shown that nation-wide implemented measures to reduce nutrient loads were ignoring the fact that the response of catchments to measures is unique and a combination of multiple drivers such as precipitation, temperature, hydrology, farm practices, etc. (Hashemi et al., 2018; Hoffmann et al., 2020) are important drivers of loads. Another Danish study investigated the future nutrient loads in view of climate change scenarios and concluded that an increase in discharge and N transport is expected on an annual basis (Jeppesen et al., 2011). A higher temperature will create a low-oxygen induced reduction of nitrification leading to higher N concentrations in streams. A prolonged warm period may also lead to increased stratification. This would enhance sediment release due to oxygen depletion (Wilhelm and Adrian, 2008) and nutrients would consequently be flushed into the surface waters by heavy rains. Higher temperature changes planting/harvesting times (Olesen, 2005) and thus the strategies of fertilizer application (Olesen et al., 2007). It also enhances summer mineralisation which increases the risk of nutrient losses at the beginning of the wet period (Mellander et al., 2018). Our data analysis also showed the same trend with the sudden increases in nutrient loads (e.g. E21 and F26 in Fig. 3 and Fig. 4) in year 2018–2019 when a prolonged draught period hit Sweden. Similar observations on flushing of nutrients following the first heavy rain after a dry-spell have been reported by other studies (Lisboa et al., 2020; Mellander and Jordan, 2021) as well. In addition, the crop rotation considers best timing to control weeds and pests, which influences the amount and pattern of N loads to waterbodies in different seasons (Jeppesen et al., 2011). On the other hand, higher evapotranspiration will also lead to higher nutrient concentrations in the water (Jeppesen et al., 2011). It is projected that the more frequent rainfall events with greater intensity and duration (Robertson et al., 2016; Mellander et al., 2018; William and King, 2020) will change the nutrient loadings mainly via subsurface drainage networks in agricultural catchments (Hanrahan et al., 2021).

Hellsten et al. (2017) also found knowledge gap in defining, evaluating, and adapting nutrient load reduction and mitigation measures in Nordic agriculture to predicted climate change scenarios. Øygarden et al. (2014) raised the issue that not only the precipitation and water discharge would probably increase in the Nordic-Baltic region, but extreme water discharge leading to high nutrient loads to water bodies is also expected. Hence, the resilience of an agricultural catchment against changes in climatic drivers and the ability to bounce back from extreme weather events depends on complex interactions of drivers within the catchment (Beevers et al., 2021). For example, if there is high storage potential in groundwater or the soil provide high natural attenuation capacity due to a longer residence time, an extreme event would not lead to high concentration of nutrients in runoff (Mellander et al., 2018).

In general, the nutrient discharges in Nordic catchments have huge variability in loads within catchments and it is believed that the contrasting patterns in nutrient trends and fluxes of TN and TP between Nordic countries could not be explained straightforward by variations in water discharge or weather (De Wit et al., 2020). Therefore, considering more frequent occurrence of extreme weather events, and the consequent sudden changes in nutrient loads (Jeppesen et al., 2021), there is an urgent need to incorporate different underlying processes and factors including catchments' unique characteristics and climate trends into developing realistic management decisions (Mellander et al., 2022).

5. Conclusion and future recommendations

The unique long-term catchment monitoring data (>20 years) collected from eight agriculturally dominated catchments in Sweden allowed to investigate the water quality trends in catchments. The current study integrated various modelling techniques (Mann-Kendall, Pettitt, GAM) to detect change points in trends and to analyse nutrient loads in relation to climatic variables (precipitation, temperature), water discharge, and SS loads. The trend of loads was quite different among catchments with inter-annual fluctuations (Figs. 3 and 4). We observed the lowest annual average TN loads in catchment C6 (minimum 6.76 kg ha^{-1}) compared to high TN loads in N34 (maximum 35.73 kg ha^{-1}), and M42 (maximum 25.07 kg ha^{-1}) (Table 1). On the other hand, the annual average TP values in catchment O18 wash high (maximum 1.04 kg ha`$^{-1}$) compared to low values in catchment E21 (minimum 0.11 kg ha^{-1}) (Table 1).

The trend analysis in relation to climatic and other drivers proved the complexity of detecting a generic trend as the data patterns were context specific and highly related to catchment properties, such as the soil texture, land use, and proportion of arable lands (e.g. C6). Precipitation and temperature appeared to be significant contributors to TN and TP loads mostly in sandy loam/loamy/loamy sand catchments (e.g. M42, N34, I28 (see Fig. 5). Extreme weather events also influenced the loads, e.g., there was a dramatic increase in TN and TP loads from catchment E21 and F26 in 2018 due to drought (extreme weather) the previous year and flushing of nutrients with the heavy rains afterwards. It was also observed that water discharge was a significant indicator ($p \leq 0.001$; $p \leq 0.01$; $p \leq 0.1$) of the nutrient loads in all catchments, along with SS.

Hence, future research needs to advance the understanding of the co variation of land cover, land uses, soil type, and crop management in addition to long-term climate trends in order to explain the response in non-point source pollution. In view of the more frequent extreme weather events, agricultural measures must not only be site-specific considering the unique characteristics of each catchments, but an event based approach may better inform on strategies for mitigation of non-point source N and P loads in agricultural catchments. To support the analyses needed under the progression of climate change, it is important to continue data collection and include catchments in northern latitude of Sweden which present extreme winter and summer in Scandinavia.

CRediT authorship contribution statement

All the authors have equally contributed to conception and design of the work.

Dr. Golnaz Ezzati contributed to data curation and database creation, data analysis and modelling, and writing of the manuscript.

Dr. Katarina Kyllmar contributed to acquisition of long-term monitoring data from Environment Monitoring Catchment Programme in Sweden, project administration, data interpretation and discussion, and review/editing the writing.

Prof. Jennie Barron contributed to project conceptualization, resources, data interpretation and discussion, and review/editing the writing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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