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Charting a perfect storm of water quality pressures

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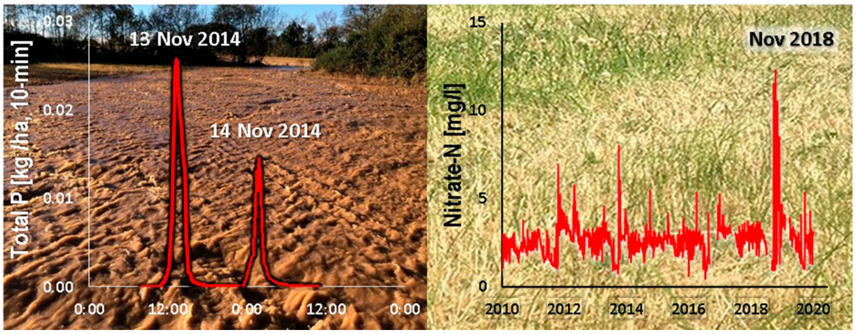
HIGHLIGHTS

- Over 10 yrs. Irish land use pressure increased and water quality state declined.
- A high-resolution water quality and hydrometeorological dataset was also assessed.
- NAO intensity was correlated with shifts in baseline water quality.
- Nutrient fluxes caused by extreme weather events exceeded average annual loads.
- The DPSIR model needs hydrometeorological consideration between pressure and state.

GRAPHICAL ABSTRACT



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ABSTRACT

The agri-food economy can be a significant driver of water quality pressures but the role of hydro-meteorological patterns in a changing climate also requires consideration. For this purpose, an assessment was made of a ten-year synchronous high temporal resolution water quality and hydro-meteorological dataset in Irish agricultural catchments. Changes occurring to rainfall intensity and soil temperature patterns were found to be important drivers of nutrient mobility in soils. There were links between the intensity of the North Atlantic Oscillation over the decade and large shifts in baseline nutrient concentrations in catchments. The data also revealed extreme weather impacts to pollution patterns including short periods of rain induced nutrient flux, that exceeded average annual mass loads in these catchments, and drought influences on point source pollution. These influences need consideration, and may require different mitigation strategies, as links between water quality land use pressure and water quality state in regulatory reviews. In a decade of both increased land use source and hydro-meteorological transport pressures, water quality natural capital in Ireland has faced a perfect storm. Such conditions are difficult to model and only revealed in high temporal resolution datasets.

1. Introduction

The “wicked problem” of balancing agricultural intensification for food security with the protection of natural capital is recognized as a global issue and is particularly relevant for water quality due to nitrogen (N) and phosphorus (P) diffuse pollution (Moal et al., 2019). Expansion of the industry often has to sit with an uncomfortable reality of governments trying to achieve environmental targets at the same time (Godray, 2015; Emmerson et al., 2016).

For example, Ireland operates a modern agricultural economy within the Common Agricultural Policy of the European Union (EU) and a clean environment is important to Irish society and an important part of tourism trade income (Perkumienė et al., 2020). Total agricultural goods output over the 2009–2019 period increased on average by €313 million per year to €8.1 billion in 2019 (CSO, 2020) and linked

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to changes to the EU milk quota and sector calls for growth after the 2008 financial crash (CSO, 2020; DAFM, 2011, 2015; Läpple and Hennessy, 2012). During the period, for example, total cattle and dairy cattle as the most intensive of the land uses increased its herd sizes by 9.8% and 28.0%, to over 6.5 million and 1.4 million, respectively (CSO, 2020). Concurrently, Ireland reported a deterioration of water quality in the period 2012–2018 with 26% of rivers and 29% of lakes indicating increasing nutrient concentrations with significant contributions from agricultural sources (EPA, 2015, 2019). This period, therefore, appears to be one of economic and environmental change (Chen and Holden, 2018) with the former successes occurring at the same time as impacts to an important part of Ireland's natural capital.

However, the Drivers, Pressures, State, Impact and Response (DPSIR) model, where food security is the 'driver', direct land use the 'pressure', resulting in a water quality 'state', is open to question. For example, recent research has identified the need for a more complete systems-science assessment of water body state trends that includes the influences of a changing climate on environmental pressures and specifically where those pressures are linked to hydro-meteorological patterns (Liu et al., 2015; Michalak, 2016; Ockenden et al., 2017). It has been proposed that the 'link' between pressure and state needs to be explored to fully understand 'impact' and hence enable 'response' to be based on realistic expectations (Kim et al., 2020), and is therefore an augmentation of the DPSIR model for policy development.

The weather related influences of a changing climate can be revealed as events and trends superimposed on major systems such as the North Atlantic Oscillation (NAO) (Dong et al., 2011). Expressed as an index from the intensity of north and mid latitude pressure systems, high indices are generally associated with changing rainfall and temperature patterns, and also extreme weather events. Ireland, on the eastern edge of the north Atlantic, is particularly exposed. For example, in 2018 the annual average NAO intensity was the strongest (NAO index = 1.08) on record since 1950. That year, Ireland experienced a series of extreme weather events well documented in the media and scientific reports: i) "Hurricane Ophelia" (Guisado-Pintado and Jackson, 2018), ii) the wettest decade in 300 years (Murphy et al., 2018) in particular 2018 winter, iii) atypically cold weather with snow in March ("Beast from the East" concurrent with "Tropical storm Emma") (Greening and Hodgson, 2019; Vero et al., 2020) and iv) a severe summer drought (Falzoi et al., 2019).

To place this into a nutrient pollution transport context in Irish agricultural catchments (Fig. 1, Table 1), a high temporal resolution water quality and hydro-meteorological dataset was interrogated during the same 10-year period (2010–2019). The focus was on two catchments that represent examples where P mobility risk dominated one catchment and N transport risk the other (Fealy et al., 2010), but in close proximity and exposed to similar weather. In a third catchment defined in terms of high dairy cattle density the seasonal magnification of farm point sources during droughts was assessed.

Assessments allow for a glimpse into future water quality pressure and state scenarios and for policy reviews to be adapted appropriately (Weng et al., 2020).

The objectives of this study were, therefore, to: i) assess the role of recent hydro-meteorological changes on river water quality in the agricultural landscape, and ii) to provide real examples of water quality pressures expected to occur more frequently with a changing climate.

2. Materials and methods

2.1. Experimental design

2.1.1. Study catchments

Ballycanew catchment is 12 km^2 and located in Co. Wexford in South East of Ireland. It is dominated by grasslands on poorly drained soils and

Fig. 1. Map of Ireland and the locations of three catchments monitored within the *Agricultural catchments programme*. The catchments represent intensively managed agricultural land on different physical settings typical for Ireland. Sub-hourly hydro-chemometric parameters have been monitored in these catchments since 2009 or 2010.

Table 1
Catchments characteristics for the *Ballycanew*, *Castledockerell* and *Timoleague catchments*. Hydrochemometric parameters are annual averages for the period 2010–2019 and agronomic parameters for the period 2010–2018.

Catchment	Ballycanew	Castledockerell	Timoleague
Size [km^2]	12	11	8
Altitude range [m a.s.l]	25–230	20–210	5–120
Dominating soil drainage and percentage of soil type	Poor Gley soils (74%) Cambisols (26%)	Well Cambisols (80%) Gley soils (20%)	Well Cambisols (87%) Gley soils, alluvials and peat soils (13%)
Geology	Rhyolite and slate stone	Slate and siltstone	Sand stone and mud stone
Dominating land use	Mixed grassland	Arable	Mixed Grass
Rainfall [mm]	1037	1020	1096
River discharge [mm]	513	530	678
Stocking rate [kg N ha^{-1}]	101	41	166
Stocking rate [kg P ha^{-1}][a]	11	4	23
NO_3-N in the river [mg l^{-1}]	2.62	7.07	6.17
TRP in the river [mg l^{-1}]	0.079	0.028	0.067
TP in the river [mg l^{-1}]	0.118	0.046	0.103
NO_3-N in the river [kg ha^{-1}]	14.04	37.31	45.79
TRP in the river [kg ha^{-1}]	0.62	0.12	0.52
TP in the river [kg ha^{-1}]	1.18	0.37	0.90

[a] 2008–2014 average.

has therefore a "flashy hydrology" with most of the hydrological pathways on the surface (Mellander et al., 2015). The bedrock formation consist of rhyolitic volcanic and slates. Most of the land (77%) is mixed grassland for dairy, beef and sheep. In the higher grounds there are freely drained soil and arable land for spring barley. During the period 2010–2018 there was a slight agronomical intensification with initially 13% of the land under derogation increasing to 30% (the E.U. Nitrates Directive allowance to farm at livestock densities above 170 kg N ha^{-1}).

Castledockerell catchment is 11 km^2 and also located in Co. Wexford. In contrast to Ballycanew it is dominated by arable land on freely drained soils and sub-soils. The bedrock formations consist of siltstones and slates. The slate has a highly weathered and permeable layer on top of the competent bedrock. The hydrological pathways are mostly below-ground (Mellander et al., 2016). Most of the agricultural land is arable (72%), mainly spring barley, winter barley, winter wheat and some oilseed rape.

Timoleague catchment is 8 km^2 and located in Co. Cork in the South west of Ireland. This catchment has freely drained soils and sub-soils. The bedrock is Devonian fine to medium grained sandstones with minor siltstone and mudstone and the hydrological pathways are mostly below-ground (Mellander et al., 2016). A majority of the land (83%) is permanent grassland for dairy production. During the period 2010–2018 there was an agronomical intensification with 50% the land under derogation increasing to 66% (the E.U. Nitrates Directive allowance to farm at livestock densities above 170 kg N ha^{-1}).

At each catchment outlet a stage-discharge curve was developed (in WISKI-SKED software) on a Corbett flat-v non-standard weir using the velocity-area method with an OTT Acoustic Doppler Current meter. River discharge was then calculated by converting the stream water level recorded every 10 min with an OTT Orpheus Mini vented-pressure instruments installed in a stilling well adjacent to the weir.

2.1.2. Hydrochemistry and weather data

Each outlet is equipped with a bankside P analyzer (Jordan et al., 2013; Melland et al., 2012) that monitors unfiltered TRP and TP concentrations concurrently with river discharge. The bankside analyzer uses Hach-Lange Sigmatax-Phosphax instruments that continuously analysis unfiltered river water samples for total digested P (TP) and total molybdate-reactive P (TRP) concentrations. The method alternates the digestion step to give up to three TP and up to three TRP data-points in each hour. The measuring range is 0.010 mg l^{-1} to 5.000 mg l^{-1} and the detection limit is 0.010 mg l^{-1}. Total oxidized N (TON) was monitored in the outlets on a 10-min basis using Hach-Lange Nitratax SC-Plus UV instruments with a measuring range of 0.1–50 mg l^{-1}. Based on low NO_2-N concentrations (Melland et al., 2012) it was assumed that the TON concentration were equivalent to NO_3-N concentration.

Weather data were collected from a weather station (BWS200, Campbell Scientific, www.acpmet.ie) located in the central lowlands within each catchment. These measured rainfall, air temperature, soil temperature, relative air humidity, solar radiation, wind speed and wind direction on a 10-min basis. Additional weather data were provided by Met Éireann, the Irish Meteorological Service (www.met.ie/). The North Atlantic Oscillation index was provided by the NOAA Climate Prediction Centre (www.noaa.gov).

Effective rainfall was calculated by subtracting Potential Evapotranspiration, derived from the Penman-Monteith equation (Monteith, 1965), from the measured rainfall.

Antecedent soil moisture conditions were estimated using a Soil Moisture Deficit (SMD) model. The SMD is the amount of rain needed to bring a soil back to field capacity (Schulte et al., 2005) and responds to changes to air temperature and rain patterns.

2.2. Data analysis

The change in rainfall intensity was analysed by comparing the probability of exceedance (PE) for five 10-year periods of daily total rainfall 1970–2019 (data provided by Met Éireann). Change in temperature was analysed by plotting the number of events when the three-day mean soil temperature exceeded 17 °C (the 95th percentile) over 10 years (2010–2019). A linear regression illustrated the gradual increase in number of warm days.

The effects of weather impacts on water quality were estimated based on offsets from the linear correlation of river discharge and nutrient mass load and compared to annual average nutrient loss over ten years.

Ten years of hydrological and water chemistry data (reactive P and nitrate-N) were used covering the period 1st Oct 2009 to 31st Dec 2019. The synchronous sub-hourly water quality data were collated to hourly average discharges, concentrations and loads. Further coarser (annual) analyses, including the NAO index data, were made on these foundation hourly datasets. Temporal delays in water quality were accounted for with moving average filters (two antecedent years with the current year), where appropriate for freer draining conditions. Linear regressions and probability estimations on all datasets of concern were undertaken in Sigma Plot 14.0.

Inter-annual and inter-seasonal Mann-Kendall trend analysis of meteorological and water chemistry data for the period 2010–2019 was made using a Macro in MS Excel (GSI Mann-Kendall toolkit, Aziz et al., 2003). In this toolkit trends were categorised into: Increasing (Standard deviation (S) > 0 and Confidence in trend (C) > 95%), Probably increasing (S > 0, 95% ≥ C ≥ 90%), No trend (S > 0, C < 90%), No trend (S ≤ 0, C < 90%, Coefficient of Variance (COV) ≥ 1), Stable (S ≤ 0, C < 90%, COV < 1), Probably decreasing (S < 0, 95% ≥ CF ≥ 90%) and Decreasing (S < 0, C > 95%).

3. Results

There was no inter-annual increase in the monthly effective rainfall over the 10-year period in any of the three catchments (Fig. 2). The long-term rain data (1960–2019) in Dublin airport (Met Éireann), however, had a gradual decadal increase in the probability of large rainfall days (Fig. 3). The number of large rain events exceeding 25 mm/day also increased in December in *Ballycanew* and *Castledockerell catchment*

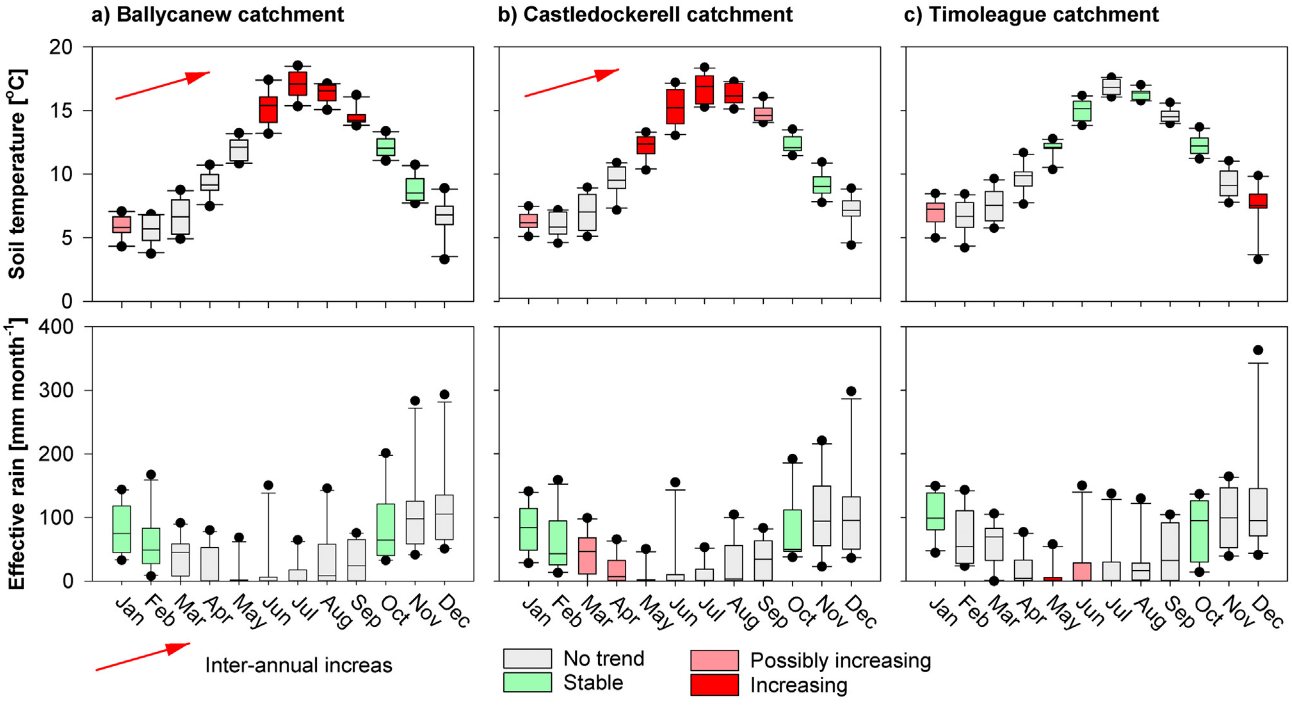

Fig. 2. Monthly total effective rainfall and monthly mean soil temperature (10 cm) in: a) the *Ballycanew catchment*, b) the *Castledockerell catchment* and d) the *Timoleague catchment*, based on sub-hourly monitoring during 2010–2019. The arrows illustrates the inter-annual Mann-Kendall trend and the coloured filling of the boxes illustrates the inter-seasonal Mann-Kendall trend. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

while it decreased in July in *Ballycanew catchment* (data not shown). The interquartile range and outliers of effective rain were higher in October to December in all three catchments, indicating large rain events (Fig. 2). In the *Ballycanew* and *Catledockerell catchments* there was an inter-annual increase in soil temperature (10 cm depth) during the 10-year period. This increase was only apparent in June to September. In the *Timoleague catchment* there was an increase in the soil temperature in December (Fig. 2). The number of occasions with three-day average soil temperature exceeding 17 °C has steadily increased in the *Ballycanew catchment* over the 10-year period (Fig. 3).

In the *Timoleague catchment* there was an inter-annual increase in river flow and in both *Castledockerell* and *Timoleague catchment* but the increase was only seen in March (Fig. 4). In all three catchments, there was a likely increase in river flow in December that concurred with substantially higher outliers (up to 48% of annual average flow).

In the *Ballycanew catchment* the highest TP and TRP concentrations were in June to November and NO_3-N concentrations in April, May and September to November. This concurred with the highest interquartile range and outliers (Fig. 4a). There were inter-annual increases in TRP and NO_3-N concentrations reflected by increases in March and September for TRP. Total P concentrations also increased in September but this was not revealed in the inter-annual trend. Similar to river flow there was a likely decrease in TP concentration in July. In the *Castledockerell catchment,* the highest TP and TRP concentrations occurred during low stream flow in June to September (Fig. 4b). The highest interquartile spread was in August and the highest outlier was in November for TP and in August for TRP. The NO_3-N concentration was high throughout the year with but highest in May, November and December. The highest outlier was in November. There TP and TRP concentrations were inter-annually stable throughout the period. However,

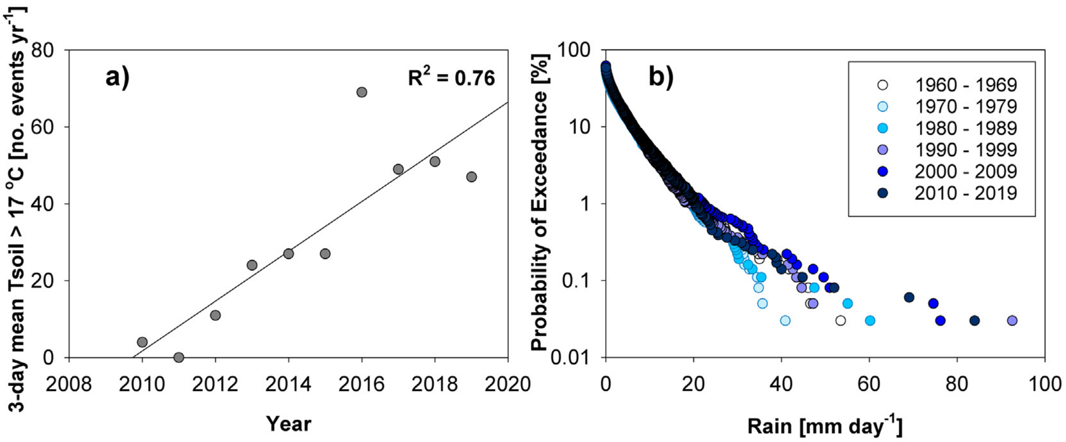

Fig. 3. Changes in weather parameters that affect nutrient loss to water. a) There has been an increase in large rain events occurring in more recent time as described by decadal probability of exceedance of daily total rainfall in Dublin airport 1960–2019 (data provided by Met Éireann). b) The number of events with warm soils, here when the three-day mean soil temperature exceeded 17 °C, has increased in the *Ballycanew catchment* over 10 years (2010–2019).

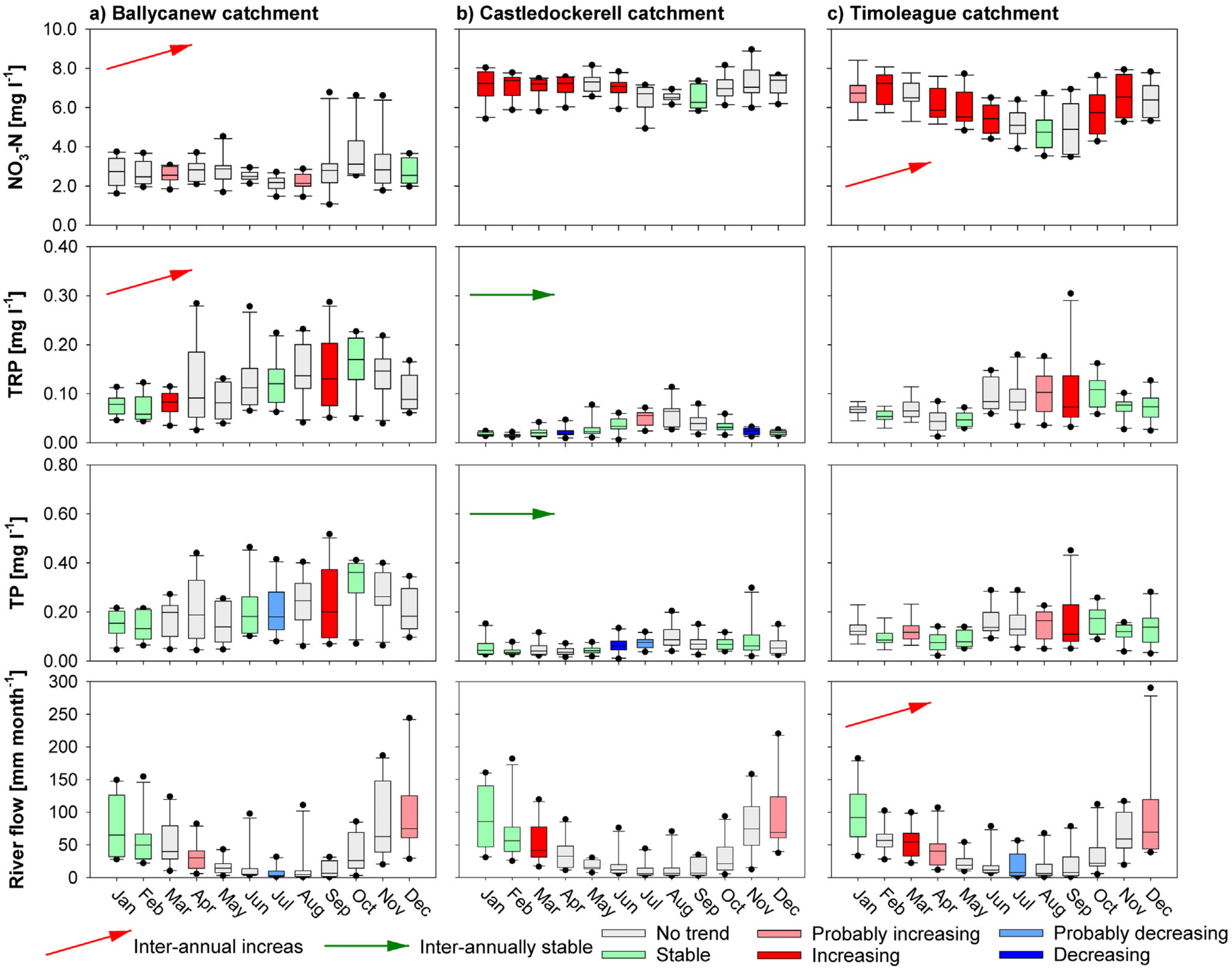

Fig. 4. Monthly total river flow and monthly flow-weighted mean Total Phosphorus (TP), Total Reactive Phosphorus (TRP) and nitrate-N (NO_3-N) concentrations in the catchments river outlets of: a) the *Ballycanew catchment*, b) the *Castledockerell catchment* and d) the *Timoleague catchment*, based on sub-hourly monitoring during 2010–2019. The arrows illustrates the inter-annual Mann-Kendall trend and the coloured filling of the boxes illustrates the inter-seasonal Mann-Kendall trend. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

there was a decreasing trend in TP concentration in June. The TRP concentration decreased in April and November. While there was no inter-annual trend in NO_3-N concentration there was an increasing trend in January to April and in June. In the *Timoleague catchment*, the highest TP and TRP concentrations occurred in June to October with the highest interquartile spread and outlier in September (Fig. 4c). The NO_3-N concentration was highest in November to March with the largest interquartile spread and outlier in September. There was no inter-annual trend in TRP and TP concentrations, but there was an increasing trend in August and September. The NO_3-N concentration increased inter-annually reflected by changes in a large part of the year (February, April to June and October to November).

There was a significant positive linear correlation between the annual N concentrations and the NAO index over the 10-year period in the *Castledockerell catchment* ($R^2 = 0.83$ and $p < 0.001$). In the *Ballycanew catchment* there was a positive and significant correlation ($R^2 = 0.82$, $p < 0.05$) between the P concentrations and the NAO index (Fig. 5a and b). The two catchments were only ca. 15 km apart and were therefore exposed to similar weather but they were hydrologically contrasting.

The more frequently occurring large rain events in winter will connect a larger part of the landscape and more of the P sources to the streams. This typically will lead to a net increase in diffuse P loss in rivers and can be the underlying factor for the long-term increase in P concentrations of rivers such as in the *Ballycanew catchment* (Fig. 5a). However, in winter, when the well-drained soils of the *Castledockerell catchment* became saturated, subsequent large rain events lead to more surface runoff and soil erosion, in particular from riverbanks and bare soils. In that catchment the soils were bare and saturated after seven days of rainfall (Soil Moisture Deficit (SMD) = 0 mm) when in 13th–14th November 2014, two large rain events (39 and 24 mm) caused severe surface runoff. Over the two days the river total P (TP) concentration reached 2.7 mg l^{-1} (below the 1st percentile) and the catchment lost 0.275 kg TP ha^{-1} in the first event and 0.131 kg TP ha^{-1} (Fig. 6a and b) in the second event which together was more than the annual average TP loss from this catchment.

When comparing TP loss for river flow events generated by a daily effective rain of 15 mm or more, on saturated and unsaturated soil conditions, the TP loss in the river was 4.8 times higher for the saturated soil conditions (Fig. 6c).

In the *Ballycanew catchment*, with mostly poorly drained clay soils, the 10-year average river NO_3-N concentration was 2.6 mg l^{-1}. During the rains in September, after the summer drought in 2018, the daily average river NO_3-N concentrations reached 13.6 mg l^{-1}, which is well above an estuary Environmental Quality Standard (EQS) of 2.6 mg l^{-1} for the sum of dissolved inorganic N fractions. The NO_3-N concentration remained elevated throughout the year and in November the monthly total NO_3-N load was largely offset from the normal relationship with

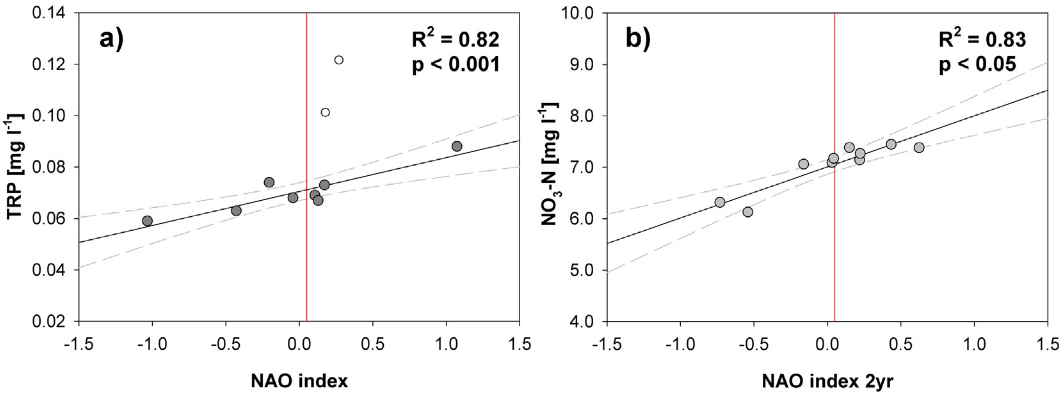

Fig. 5. North Atlantic Oscillation (NAO) as a driver for nutrient loss to water. The annual average (hydrological years 1st Oct – 30th Sep) Total Reactive Phosphorus (TRP) and nitrate (NO_3-N) concentrations correlated to the average NAO index (NAOi) and two year antecedent moving average NAOi (NAOi 2 yr) in: a) the *Ballycanew catchment*, and b) the *Castledockerell catchment*. The grey lines indicate the 95% confidence interval. Two outliers (the years 2016 and 2017) were excluded from the correlation in the *Ballycanew catchment* (open symbols) due to a temporal point-source influence. The 30-year average NAOi (1990–2019) is marked with vertical red line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

monthly discharge (Fig. 7). In that single month the NO_3-N load was offset by 6.5 kg ha^{-1} which is 51% of the annual average NO_3-N loss from this catchment.

During the summer drought in 2018 there was a clear diurnal signal of elevated P concentration monitored in the *Timoleague catchment* with high dairy cattle density. This signal was emphasized as the river flow

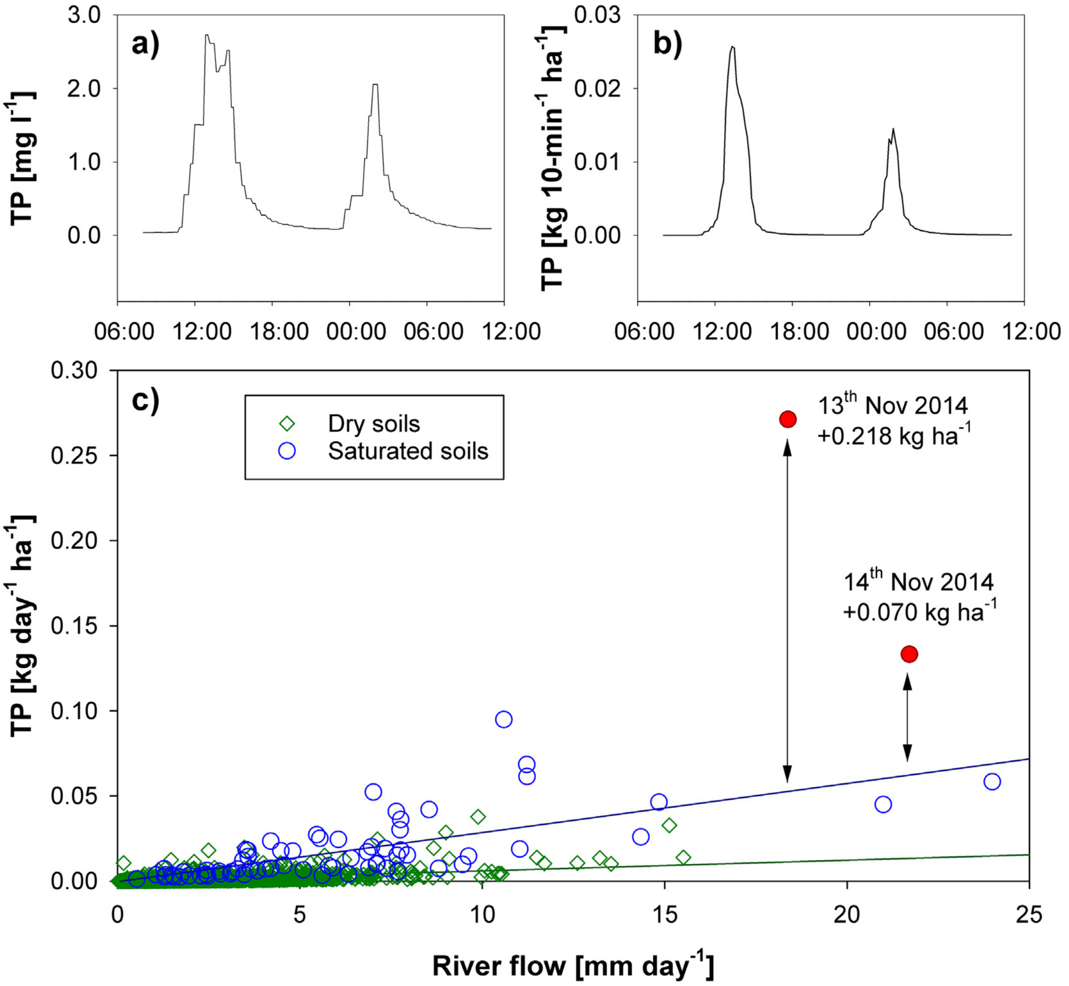

Fig. 6. Phosphorus loss from bare, saturated arable land during two large rain events. a) 10-min Total Phosphorus (TP) concentrations, b) 10-min TP mass loads during two large rain events, and c) daily total TP mass load correlated to daily total river flow for large rain events (daily effective rainfall larger than 15 mm) on soils in field capacity (saturated soils = blue circles) and below field capacity (dry soils = green diamonds). The two large rain events (13th and 14th November 2014) on saturated soils elevated the TP loss with 0.218 and 0.070 kg ha^{-1} from the expected loss based on the river discharge TP load correlation for soils in field capacity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

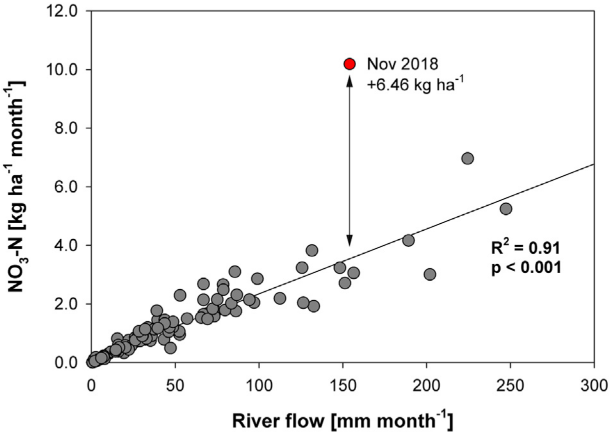

Fig. 7. Monthly total nitrate-N mass load correlated to the monthly total river discharge over 10 years (2010–2019) in the *Ballycanew catchment*. In November 2018, there was a flush-out of a large soil N pool, built up during the summer drought in the same year. This caused an offset of 6.46 kg NO_3-N ha^{-1} being lost in in that month compared to the expected loss based on the river discharge NO_3-N load correlation.

started to decrease in June (Fig. 8a). The P concentrations showed two distinct peaks typically occurring at ca. 10 h and 20 h and corresponded with a delay to the morning and evening milking and associated washing of a dairy platform (Fig. 8b) and not normally revealed in time-series data.

In this example the TRP concentrations in the river frequently exceeded 0.3 mg l^{-1} (which was almost ten times larger than the EQS), occasionally 0.5 mg l^{-1} and on 22nd August there was a double peak of 4.39 and 1.48 mg l^{-1} at 15 h and 20 h.

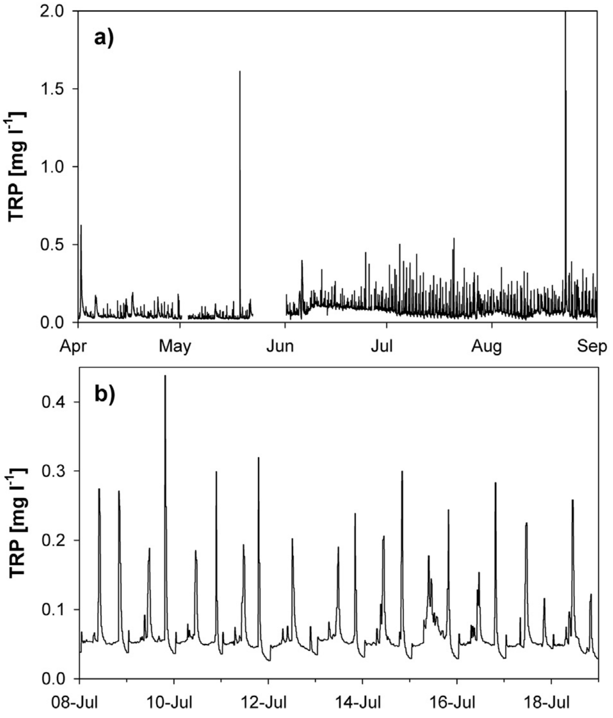

Fig. 8. Increased sensitivity to a small point source in the *Timoleague catchment* during the dry summer of 2018. a) 10-min Total Reactive Phosphorus (TRP) concentrations 1st Apr – 30th Sep 2018 as the river discharge decreased during the drought and, b) 10-min TRP concentrations during ten days of peak drought time in July 2018. An identified small point source caused diurnal spikes in TRP concentration due to less dilution during low river flow in drought condition.

4. Discussion

4.1. Changing weather and water quality

The weather changes in the most recent years, with warmer and drier summers and winters with more frequent large rain events, is typical for years with a higher NAO index in North-western Europe (Hurrell, 1995). This was consistent with the observations in the three catchments of this study. In some cases, there were inter-annual increasing trends, in other cases, there were inter-seasonal increasing or decreasing trends, or there were no clear trends at all. While the soil temperature increased inter-annually, it was mainly during the summer months that the soil became warmer. Even if there was no increase in the amounts of effective rainfall during the period, there were larger rain events occurring in winter and these have occurred more frequently in December when soils commonly are saturated and arable soils bare. Ireland has seen an increase in both the numbers of days with large rain events and high air temperatures over the last decade (Murphy et al., 2018).

Temperature and rainfall are important drivers for nutrient mobilization and transfer. Large winter rain events, when soils are more likely to be saturated, will cause large surface runoff events and cause loss of soil P stores (Haygarth et al., 2005). There is also a link between soil mineralization rates during summer droughts and higher soil temperatures (Morecroft et al., 2006) and climate change has been found to induce significant mineralization pulses (Wang et al., 2016). If this is followed by more rain in winter the soil N stores are more vulnerable to leaching and transfer to water bodies (Jiang et al., 2010). Climate projections for Ireland show a trend towards warmer, wetter, winters and hotter, drier, summers (McGrath et al., 2008). It is likely that the higher soil temperatures in summer and more frequent large rain events in winter have affected the nutrient concentrations in the streams, and differently in the three catchments due to the different physical and chemical settings (Mellander et al., 2018). Generally, the highest nutrient concentrations in the streams were in September to November. In the *Ballycanew catchment*, with the highest P and lowest N concentrations, the TP and TRP concentrations have increased in September and there were high NO_3-N outliers in this period, well above the mean concentrations. In the *Castledockerell catchment,* with the lowest P and highest N concentrations, there were higher outliers of TP concentrations in November. In the *Timoleague catchment,* with both high P and N concentrations, the TP and TRP concentrations have also increased in September and the NO_3-N concentrations have increased in a large part of the year. In that catchment there were also likely agronomic drivers influencing the nutrient concentrations.

Linking nutrient loss to water to changing hydro-meteorological patterns appears to be complex and may require looking into both inter-annual and inter-seasonal changes. It is important, therefore, to consider both long-term changes, such as those incorporated in anthropogenic warming and large-scale systems such as the NAO, and short-term offsets.

4.2. Shift in long-term drivers for water quality

A sharp increase in the NAO index was found previously to have influenced the annual trends in N and P concentrations differently in terrestrial waters in Ireland, Norway and France (Mellander et al., 2018). This trend remained when extended to the 10-year time-series in the two Irish catchments in this study (Fig. 5a and b) illustrating different nutrient loss vulnerability types mainly due to different physical and chemical controls. The *Ballycanew catchment* was likely to have high denitrification rates and low risk for N loss to water due to its heavy clay soils with low permeability. This catchment is instead “P loss risky” due to a “flashy” hydrology and erosive surface runoff (Jordan et al., 2012; Mellander et al., 2015; Sherriff et al., 2016). The *Castledockerell catchment*, in contrast, is typically “N loss risky”, due to N leaching through its freely draining soils, permeable bedrock and with high saturated conductivity (0.4–5.3 m day^{-1}) and low (1–15%) denitrification (Mellander et al., 2014; McAleer et al., 2017).

In 2018, when the NAO index was at its highest (1.08), the TRP concentration in the river of the *Ballycanew catchment* was 0.051 mg l^{-1} higher than typical concentrations observed when the NAO index (0.050) was at the 30-year average (1990–2019) (Fig. 5a). This suggests that, in P transfer risky catchments, such as *Ballycanew*, measures need to mitigate an additional >40% of reactive P loss during extreme high NAO index years. This follows predicted increased P losses from agricultural catchments up to 30% by 2050s due to the effects of climate change on weather patterns (Ockenden et al., 2017).

In the *Castledockerell catchment* the intensified NAO in 2018 increased the average N concentration in the river by 0.32 mg l^{-1} compared to average NAO index (Fig. 5b). This suggests that, in an N transfer risky catchment, such as *Castledockerell*, measures need to mitigate an additional 4% of NO_3-N loss during extreme high NAO index years. These changes may influence the interpretation of trends in monitored time-series of water quality in rivers. While these decadal changes influence the nutrient concentrations in terrestrial waters differently due to the dominating physical and chemical controls and be evident on annual scales, shorter-term weather extremes may drastically offset these trends.

4.3. Short-term offsets in nutrient loss and risk switching

4.3.1. Phosphorus loss in winter storms

During large rain events, when well drained soils are saturated in winter, the otherwise “N loss risky” *Castledockerel catchment* temporarily switched to “P loss risky”. Such events typically occurred when the SMD was 0 mm for two days or more, daily effective rain was 15 mm or more and soils were bare. Under such conditions the turbidity and proportion of particulate P (not presented) were high in the river and reflecting higher erosion. During the same conditions in summer, under crop cover, the turbidity and proportion of (PP) were lower in the river and reflecting the positive effect of a green cover. These types of weather impacts that can cause annual average P loss over a few days require targeted mitigation strategies and are likely to be dissimilar to those aimed at mitigating the effects of the long-term weather shifts.

4.3.2. Build-up and loss of the soil N pool in summer drought

Summer droughts can lead to the build-up of a large N pool in the soils due to a number of reasons; i) water limitation will negatively influence the grass growth and therefore causing reduced N uptake from fertilizers applied in spring, ii) summer droughts can enhance the soil N mineralization and nitrification rates (Morecroft et al., 2006; Wang et al., 2016), and iii) in some cases, not recognizing the water limitation, more mineral N fertilizers are applied in order to compensate for poor growth. Soil cracking caused by the drought was widespread in 2018 and likely also enhanced the potential for preferential flow paths (Nagy et al., 2020) that connected a built up soil N pool to water during the autumn/winter rains. The drought in summer 2018 was the most severe in Ireland over a 37 year period and resulted in a reduced grass growth of 5–10% (Falzoi et al., 2019). Under those conditions the daily average NO_3-N concentration was elevated well above the EQS in the *Ballycanew catchment* and the otherwise “P loss risky” catchment switched to “N loss risky”.

4.3.3. Increased impact of point sources in summer drought

Drier summers lead to lower river discharges and less dilution of pollutants from point sources (Neal et al., 2010). Even relatively small sources can elevate P concentrations over EQS, and since that typically occurs during an ecologically sensitive time it may have a negative impact on aquatic ecological status (Shore et al., 2017; Davis et al., 2019). High frequency time-series monitoring identified the extent of point sources during the 2018 summer drought. Mitigation efforts at catchment scale typically prioritize high load sources, but the example from *Timoleague catchment* (Fig. 8) illustrates a situation where even a small point source may significantly elevate the concentrations well above EQS for an extended time. These situations are more likely to occur in small rivers where more frequent summer droughts may result in long lasting negative effects on aquatic ecology (Davis et al., 2019).

4.4. Building resilience into agri-environmental policies

In the EU, the review of agri-environmental policies for water quality protection falls under the Nitrates Directive (OJEU, 1991) and is reviewed on a three-yearly cycle. The efficacy of mitigation measures are compared against a basic set of ecological water body metrics, often captured at low resolution. Following consultation, changes to the measures may occur. In a climate emergency and considering how high-frequency data can inform on underlying processes and reveal the additional impact of agricultural nutrient pressures, there is a need to build additional climate resilience into mitigation policies. Addressing both source and transport issues is required and smart targeting of mitigation placement. For example, for catchments where N risk switches to P risk, winter cover crops can aid in the long term and short term alleviation of both risks, respectively (Ulén, 1997). Similarly, in catchments where P risk switches to N risk, to avoid a build-up and loss of N, the application and timing of fertilizer needs to be carefully managed in relation to plant growth and weather conditions. Split spring application of mineral N and no fertilizers applied during drought conditions is essential. The offset caused by more extreme events such as the large surface runoff events on the 13th and 14th November in 2014 would also require more targeted connectivity mitigation approaches such as e.g. riparian buffer zones (Stutter et al., 2019, 2021) or sedimentation ponds (Edwards et al., 1999) on targeted delivery points (Steele-Dunne et al., 2008). The chronic and high magnitude impacts caused by farm point sources is an urgent priority to address as summer stream-flows decrease (Shore et al., 2017) and should be considered a climate adaption within the reach and responsibility of every farmer. In addition to these considerations, as the ‘link’ between driver and state, trend reporting for the Nitrates Directive should include a deeper appraisal of the climate and weather pressures associated with the reporting period, in context with longer term averages, and in addition to land use pressures.

5. Conclusions

In a world affected by a changing climate and economic drivers there is a requirement for deeper knowledge on the behaviour of nutrient transfer from land to water to better understand the links between pressures and state of water quality. A first conclusion from this study is that this can only be realised by river nutrient concentration and hydrometric data captured at high-temporal resolution in contrasting agricultural catchments against a back-drop of land use pressures.

The analysis here showed that catchments with different controls responded differently to the large-scale weather shift and to extreme weather impacts. There were links between the NAO intensity over the decade and large shifts in baseline nutrient concentrations in two hydrologically contrasting catchments. The catchments responded differently to extreme weather impacts, including a drought and short periods of rain induced nutrient flux that exceeded the catchments average annual loads, and magnification of point source dilution at extreme low flows during a drought.

The perfect storm of pressures on water quality over a ten year period assessed here are also placed in the near future context of potential agricultural growth in a post-Brexit and post-COVID19 period, and in a nationally recognized climate emergency. Basing the findings of this study into a management, monitoring and review framework, the second conclusion is that the Driver-Pressure-State-Impact-Response model requires enhancement to account for the 'link' between Pressure and State as influenced by changing weather patterns. This will ultimately provide the resilience required by agri-environmental measures in a changing climate.

CRediT authorship contribution statement

Per-Erik Mellander: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Phil Jordan:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

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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