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Changing climate and nutrient transfers: Evidence from high temporal resolution concentration-flow dynamics in headwater catchments

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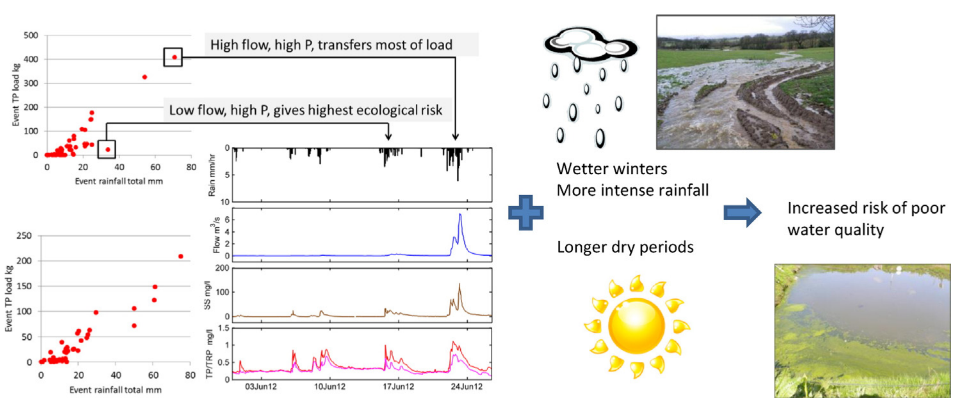
HIGHLIGHTS

- Climate change may increase pollutant transfers from agricultural land.
- High temporal resolution data enabled present day nutrient dynamics to be analysed.
- High flow events (>Q10) transported >90% of sediment, >80% of phosphorus
- Longer periods of low flow and high concentration will increase ecological risk.
- Average phosphorus loads may increase by 9% with higher rainfall volume and intensity.

GRAPHICAL ABSTRACT



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ABSTRACT

We hypothesise that climate change, together with intensive agricultural systems, will increase the transfer of pollutants from land to water and impact on stream health. This study builds, for the first time, an integrated assessment of nutrient transfers, bringing together a) high-frequency data from the outlets of two surface water-dominated, headwater (~10 km^2) agricultural catchments, b) event-by-event analysis of nutrient transfers, c) concentration duration curves for comparison with EU Water Framework Directive water quality targets, d) event analysis of location-specific, sub-daily rainfall projections (UKCP, 2009), and e) a linear model relating storm rainfall to phosphorus load. These components, in combination, bring innovation and new insight into

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the estimation of future phosphorus transfers, which was not available from individual components. The data demonstrated two features of particular concern for climate change impacts. Firstly, the bulk of the suspended sediment and total phosphorus (TP) load (greater than 90% and 80% respectively) was transferred during the highest discharge events. The linear model of rainfall-driven TP transfers estimated that, with the projected increase in winter rainfall (+8% to +17% in the catchments by 2050s), annual event loads might increase by around 9% on average, if agricultural practices remain unchanged. Secondly, events following dry periods of several weeks, particularly in summer, were responsible for high concentrations of phosphorus, but relatively low loads. The high concentrations, associated with low flow, could become more frequent or last longer in the future, with a corresponding increase in the length of time that threshold concentrations (e.g. for water quality status) are exceeded. The results suggest that in order to build resilience in stream health and help mitigate potential increases in diffuse agricultural water pollution due to climate change, land management practices should target controllable risk factors, such as soil nutrient status, soil condition and crop cover.

1. Introduction

Freshwater systems throughout the world provide many essential services to the global population. There are multiple stressors on this valuable resource (Heathwaite, 2010), including those on both water quantity (Vorosmarty et al., 2000) and quality (Onda et al., 2012; Seitzinger et al., 2010). In the future, these pressures will continue to increase, with larger populations making greater demands for food production, and, consequently, more intensive farming practices. The pressures are further exacerbated by the effect of a changing climate, which is predicted to bring more frequent extreme events (Kendon et al., 2014; Murphy et al., 2009), resulting in the likelihood of more winter runoff and longer periods of low flow (Bell et al., 2012; Wilby et al., 2006), although still with much uncertainty (Arnell, 2011; Kay and Jones, 2012; Prudhomme et al., 2012). In conjunction with projected climatic changes, previous studies have indicated likely increases in sediment and nutrient loads (Crossman et al., 2014; El-Khoury et al., 2015; Jeppesen et al., 2009; Jeppesen et al., 2011; Macleod et al., 2012; Rankinen et al., 2015; Whitehead et al., 2009).

In Europe, the Water Framework Directive (WFD) (2000/60/EC: European Union, 2000) continues to drive the requirement to meet national-level water quality targets in individual water bodies (rivers and lakes). Despite this, in England, 73% of water bodies fail to meet good ecological status (Defra et al., 2015), and many of the condition assessments cite 'diffuse water pollution from agriculture', especially agricultural losses of phosphorus (P) and nitrogen (N), as key pressures.

The response of a surface water catchment (in temperate areas) to rainfall is dominated by the processes in the headwater sub-catchments comprising the network of first and second order streams (Strahler order). These first and second order streams make up most of the channel length and basin area of a larger catchment (Burt, 1997), and contribute at least 60–70% of the water (Alexander et al., 2007; Decamps et al., 1999). Many researchers (e.g. Harris and Heathwaite, 2005; Heathwaite, 2010; Johnes, 2007; Jordan et al., 2005a) have identified the need for small scale and short timestep data in order to unravel the complex processes of nutrient cycling in headwaters. Headwater catchments are very dynamic and their responses may be misrepresented by infrequent, low intensity sampling regimes (Cassidy and Jordan, 2011; Defew et al., 2013).

Hydrological event or campaign focussed sampling, particularly in short-term research studies, has demonstrated the importance of high resolution monitoring and of rainfall-driven events in the transfer of diffuse pollution from agriculture (e.g. Bilotta et al., 2008; Deasy et al., 2008; Haygarth et al., 2006; Haygarth et al., 2012; Heathwaite and Dils, 2000; Preedy et al., 2001; Sharpley et al., 2001), with the phytobenthic community suggesting a direct impact on water quality (Snell et al., 2014). However, for many water bodies, the only available water quality data are the standard condition assessments and the Environment Agency national level programme of routine monitoring at main river (large catchment scale) locations, at fortnightly or monthly resolution. These can provide valuable information for the identification of sites that are under pressure, but do not capture the high frequency dynamics of the system. The problems associated with infrequent sampling are well documented (e.g. Cassidy and Jordan, 2011) and can lead to large uncertainty in annual load calculations of sediment and nutrients (Defew et al., 2013). There is, therefore, increasing interest in the use of in-stream high resolution water quality monitoring to assemble higher resolution catchment-scale datasets (e.g. Bowes et al., 2015; Halliday et al., 2012; Jordan et al., 2012; Melland et al., 2012; Mellander et al., 2012; Mellander et al., 2014; Outram et al., 2014; Skeffington et al., 2015; Wade et al., 2012), which can be used to understand key catchment processes in terms of hydrology, diffuse pollution transfer and trophic impacts and how these may alter under a changing climate.

For much of the UK, climate change is expected to bring warmer, wetter winters, with fewer but more intense rain days, and hotter, drier summers (Murphy et al., 2009) and an increase in extreme events, including summer storms (Kendon et al., 2014). We hypothesise that climate change will alter the transfer of nutrients from land to water, and this study makes an integrated assessment of nutrient transfers, bringing together, for the first time:

- high-frequency data from the outlets of two surface water-dominated, headwater (~10 km^2) agricultural catchments within the River Eden catchment, Cumbria, UK
- event-by-event analysis of suspended sediment (SS), total phosphorus (TP), total reactive phosphorus (TRP) and nitrate (NO_3^-) transfers
- concentration duration curves for each season for comparison with EU Water Framework Directive water quality targets
- event analysis of location-specific, sub-daily rainfall projections (UKCP, 2009)
- a linear model relating storm rainfall to phosphorus load

The unique combination of these components brings new insight into the estimation of future phosphorus transfers, which was not available from individual components.

2. Materials and methods

2.1. Site description

The field dataset was generated as part of the Demonstration Test Catchments (DTC) programme (McGonigle et al., 2014). Newby Beck (12.5 km^2) and Pow Beck (10.5 km^2) are two rural headwater catchments within the Eden river catchment, in Cumbria, UK (Fig. 1). Newby Beck Fig. 1b) is generally steeper (23% of catchment area steeper than 5°) and at higher altitude (range 150–345 m above sea level) than Pow Beck (<1% steeper than 5°; altitude 60–155 m, (Fig. 1c)).

The bedrock of the larger Eden catchment comprises Permian and Triassic sandstones in the valley bottom, overlying rocks of the Carboniferous Series. The valley sides are mainly Carboniferous limestone and limestone/mudstone layers (Fig. 2). The sandstones are