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Dominant mechanisms for the delivery of fine sediment and phosphorus to fluvial networks draining grassland dominated headwater catchments

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HIGHLIGHTS

- We assess how sediment and phosphorus is transported in an agricultural catchment
- Multiple pathways are observed for particulate and soluble constituents
- Delivery is complicated by dominance & variability of erosive processes & pathways
- Large challenges faced in mitigating delivery of contaminants to headwater rivers

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ABSTRACT

Recent advances in monitoring technology have enabled high frequency, in-situ measurements of total phosphorus and total reactive phosphorus to be undertaken with high precision, whilst turbidity can provide an excellent surrogate for suspended sediment. Despite these measurements being fundamental to understanding the mechanisms and flow paths that deliver these constituents to river networks, there is a paucity of such data for headwater agricultural catchments. The aim of this paper is to deduce the dominant mechanisms for the delivery of fine sediment and phosphorus to an upland river network in the UK through characterisation of the temporal variability of hydrological fluxes, and associated soluble and particulate concentrations for the period spanning March 2012–February 2013. An assessment of the factors producing constituent hysteresis is undertaken following factor analysis (FA) on a suite of measured environmental variables representing the fluvial and wider catchment conditions prior to, and during catchment-wide hydrological events. Analysis indicates that suspended sediment is delivered to the fluvial system predominantly via rapidly responding pathways driven by event hydrology. However, evidence of complex, figure-of-eight hysteresis is observed following periods of hydrological quiescence, highlighting the importance of preparatory processes. Sediment delivery via a slow moving, probably sub-surface pathway does occur, albeit infrequently and during low magnitude events at the catchment outlet. Phosphorus is revealed to have a distinct hysteretic response to that of suspended sediment, with sub-surface pathways dominating. However, high magnitude events were observed to exhibit threshold-like behaviour, whereby activation and connection of usually disconnected depositional zones to the fluvial networks results in the movement of vast phosphorus fluxes. Multiple pathways are observed for particulate and soluble constituents, highlighting the challenges faced in mitigating the delivery of contaminant fluxes to headwater river systems.

1. Introduction

Understanding the hydrological and pollutant dynamics of headwater catchments, and the implicit connections between the land and the river is of great importance (Bishop et al., 2008). These rivers account for 60 to 80% of the entire river network (Benda et al., 2005), providing

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potable drinking water (Sturdee et al., 2007), buffering capacity for flood risk (Posthumus et al., 2008), dilution of nutrient rich waters downstream (Bowes et al., 2003) and ecological habitats fundamental to the health of the aquatic ecosystems (Meyer et al., 2007). Maintaining the quality of headwater resources is thus essential for the sustainability of the water environment (Soulsby et al., 2002). A significant risk to the systems' functional integrity is the presence of surface sediment sources that are enriched with phosphorus (P) following years of excessive fertiliser inputs (Heathwaite et al., 2006; Withers et al., 2001, 2007), which may be exacerbated by land-use conflicts (Pacheco et al., 2014; Valle Junior et al., 2014) and accelerating rates of terrestrial erosion (Mainstone et al., 2008; McHugh, 2007). The delivery of these materials to hydrological networks is augmented by the relatively low filter resistance and restricted potential for temporary storage in these small catchments. Resultantly, the catchment export of sediment and P may be closely related to the magnitude of erosion and land degradation (Kovacs et al., 2012), with adverse impacts on the aquatic habitats ensuing (Collins and Walling, 2004; Haygarth et al., 2005a,b; Holden et al., 2007; Valle Junior et al., 2015).

To moderate the number of watercourses failing to produce ecologically sustainable habitats as a result of enhanced erosion and delivery of pollutants to sensitive headwater fluvial networks, identification of the fine sediment and nutrient sources, and the pathways of delivery is firstly required (Jarvie et al., 2008), with management efforts subsequently focussing on restoring natural attenuation within catchments and disconnecting the identified Critical Source Areas (CSAs), or hotspots from the fluvial networks (Heathwaite et al., 2005; Kovacs et al., 2012; Newson, 2010; Pionke et al., 1996). Many well established factors act to define the CSAs of fine sediment and P, however, our understanding of how and when these areas are connected to the fluvial networks is limited by the heterogeneity of factors governing process rates (Dean et al., 2009). These factors include antecedent moisture conditions, runoff mechanisms, spatial variation of rainfall intensity, and land management operations. These process controls influence the mechanisms of mobilisation, pathways of transfer, and the complex biogeochemical processes occurring along the land–water continuum, yet, they are diffuse, difficult to quantify at the catchment-scale, and vary on an event basis. Understanding of how pollutant transmission varies in response to temporal and spatial constraints may however provide key information about connectivity of pollutant sources, pathways of delivery and pollutant transfer in a catchment (Lexartza-Artza and Wainwright, 2009).

A large amount of research has been conducted to improve our understanding of the timing and mechanisms responsible for the transport of aquatic pollutants in surface and sub-surface runoff from agricultural land, with investigations into the fluvial export of suspended sediment from small agricultural catchments enabling exploration of the processes responsible for its delivery (e.g., Glendell and Brazier, 2014; Steegen et al., 2000; Thompson et al., 2013). Likewise, studies have sought to characterise the nature of P losses from headwater agricultural catchments (e.g., Haygarth et al., 2005b; Hodgkinson and Withers, 2007; Pionke et al., 1996; Soulsby et al., 2002; Stutter et al., 2008). However, there is currently a dearth of continuous, high-temporal resolution hydro-chemical and suspended sediment monitoring datasets available for rivers draining sensitive headwater catchments. Such high-frequency datasets of discharge, suspended sediment (SS), total phosphorous (TP) and total reactive phosphorus (TRP) enable characterisation of the complex non-linear responses of the monitored determinands at sub-hourly timescales.

Non-linear concentration–discharge relationships have been widely acknowledged for many contaminants, with assessment of this hysteresis being used as a means of interpreting probable pollutant pathways and origins (e.g., Lefrançois et al., 2007; Naden, 2010; Outram et al., 2014; Smith and Dragovich, 2009). Small scale experiments, in which the pollutant transport processes are controlled, have successfully produced the expected hysteresis dynamics, offering support for this indirect approach (e.g., Chanat et al., 2002; Eder et al., 2014). Analysis of the process dynamics of multiple contaminants using this hysteresis framework enables commonalities in transport systems to be assessed, and maximum information to be extracted about pollutant and catchment response to hydrological events (e.g., Halliday et al., 2014; Mellander et al., 2012; Outram et al., 2014; Owen et al., 2012; Wade et al., 2012). Specifically, this framework enables an assessment of the complicating factors and influences on SS and P transfer at multiple scales (e.g., Haygarth et al., 2012); and, the interaction between catchment structure, connectivity, and pathway dominance under varying environmental conditions (Bilotta et al., 2007, 2010; Bracken et al., 2014).

Such information is valuable and necessary to inform mitigation strategies for reducing diffuse water pollution from agriculture (DWPA) in the UK (McGonigle et al., 2014). The development of a solid evidence base prior to the implementation of mitigation measures is required to: a) determine the effectiveness of control measures (e.g., Wilkinson et al., 2014); b) assess the cost-effectiveness of resource allocation (e.g., Posthumus et al., 2013); and c) enable reliable and transparent decisions to be made about future catchment operations (Collins et al., 2012).

In this present study, high resolution hydro-meteorological, SS and P data collected during a range of low and moderate magnitude runoff events over one year are analysed to determine the intra-storm hysteresis dynamics of SS, TP and TRP concentrations. Analysis of the environmental factors associated with observed pollutant dynamics is conducted using factor analysis (FA) which incorporates a suite of environmental variables representing the event storm conditions and antecedent hydro-meteorological conditions. The aim of this analysis is to extract fundamental information describing the transport pathways and pollutant dynamics of the system, providing the basis for examining the key components driving the transfer of SS and P at multiple scales across a small agricultural catchment in the UK.

2. Materials and methods

2.1. Study area

This research was conducted in the upper reaches of the Newby Beck sub-catchment of the River Eden, NW England, UK (Fig. 1). Newby Beck is a predominantly upland catchment with moderate slopes (7.4%) and a mean elevation of 234 m. The catchment is underlain by steeply dipping, fractured limestone and sandstone units with interbedded siliciclastic argillaceous rock of the Carboniferous period. The soils draining the headwaters in the south of the catchment are well drained, locally deep, fine loamy soils with slowly permeable and seasonally wet acid loamy and clayey soils through the middle reaches, moving towards slowly permeable, seasonally waterlogged reddish fine and coarse loamy soils in the north of the catchment (Cranfield University, 2014). The catchment was designated as a priority under the England Catchment Sensitive Farming Delivery Initiative (ECSFDI) to reduce diffuse water pollution resulting from farming activity. Improved grassland dominates the catchment (76% by area), along with acid grassland (10%) and arable land (6%), with 2.88 livestock units (LU) ha^{-1} (cattle and sheep). The average Olsen P concentration from across 38 fields (14% of catchment) is 23.6 mg kg^{-1} ($\sigma = 9.9$ mg kg^{-1}) with a range of 8–46 mg kg^{-1}. The climate of this region is cool temperate maritime with a long-term average rainfall of 1187 mm ($\sigma = 184$ mm) (Met Office, 2009). The catchment responds relatively rapidly with a time-to-peak of 3 h (Houghton-Carr, 1999) and the standard percentage runoff (SPR) is estimated to be 35% based on the Hydrology of Soil Types (HOST) classification.