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Evaluating the use of *in-situ* turbidity measurements to quantify fluvial sediment and phosphorus concentrations and fluxes in agricultural streams

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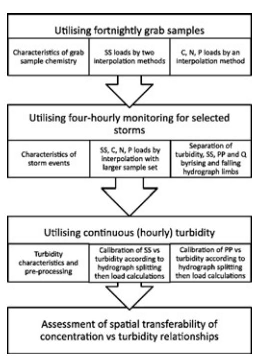
HIGHLIGHTS

- Turbidity sensors can improve temporal knowledge of river mass loads.
- *In-situ* turbidity was calibrated for assessing sediment and P transport.
- Calibrations were improved by splitting rising and falling hydrograph periods.
- Calibrations for one catchment were not transferable to a neighbouring catchment.

GRAPHICAL ABSTRACT



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ABSTRACT

Accurate quantification of suspended sediments (SS) and particulate phosphorus (PP) concentrations and loads is complex due to episodic delivery associated with storms and management activities often missed by infrequent sampling. Surrogate measurements such as turbidity can improve understanding of pollutant behaviour, providing calibrations can be made cost-effectively and with quantified uncertainties. Here, we compared fortnightly and storm intensive water quality sampling with semi-continuous turbidity monitoring calibrated against spot samples as three potential methods for determining SS and PP concentrations and loads in an agricultural catchment over two-years. In the second year of sampling we evaluated the transferability of turbidity calibration relationships to an adjacent catchment with similar soils and land cover. When data from nine storm events were pooled, both SS and PP concentrations (all in log space) were better related to turbidity than they were to discharge. Developing separate calibration relationship for the rising and falling limbs of the hydrograph provided further improvement. However, the ability to transfer calibrations between adjacent catchments was not evident as the relationships of both SS and PP with turbidity differed both in gradient and intercept on the rising limb of the hydrograph between the two catchments. We conclude that the reduced uncertainty in load estimation derived from the use of turbidity as a proxy for specific water quality parameters

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in long-term regulatory monitoring programmes, must be considered alongside the increased capital and maintenance costs of turbidity equipment, potentially noisy turbidity data and the need for site-specific prolonged storm calibration periods.

1. Introduction

Better understanding and predictive capability of sediment and nutrient mobilisation and transport will assist in managing diffuse pollution of surface waters (Jarritt and Lawrence, 2007; Udeigwe et al., 2007; Strömqvist et al., 2008). The accurate *in-situ* quantification of suspended sediments (SS) and co-transported particulate phosphorus (PP) is essential for model calibration, to identify sediment and nutrient delivery pathways, determine nutrient fluxes and evaluate management mitigation strategies within individual catchments (Kronvang et al., 1997; Owens and Walling, 2002; Minella et al., 2008; Perks et al., 2015). Whilst understanding of SS delivery behaviour in intensively studied research catchments has improved significantly over the past decades, the quantification of SS concentrations in most surface waters remains based on infrequent sampling and load calculations use SS rating curves (Walling, 1977; Jarritt and Lawrence, 2007, Minella et al., 2008). The use of turbidity measurements to characterise fluvial sediment and carbon transport has increased (Glendell and Brazier, 2014; Lloyd et al., 2016; Skarbovik and Roseth, 2015; Slaets et al., 2014), but there remains a need to assess the accuracy, limitations and cost-effectiveness of this approach (Sherriff et al., 2015). The ability to use turbidity as a surrogate for determining of particulate phosphorus (PP) concentrations and the transferability of resulting calibrations for mass load determination between adjacent catchments require further study.

Increased supplies of SS to watercourses occur where intensive agriculture, development or commercial forestry are done without appropriate practices to control erosion (Dawson and Smith, 2007; Strömqvist et al., 2008). Within waterbodies SS reduces light penetration, impacts on macro-invertebrate and fish communities, increases biochemical oxygen demand and contributes to diffuse pollution by controlling export of sediment-associated nutrients, pathogens and other contaminants (Kronvang et al., 1997; Lawler et al., 2006; Jarritt and Lawrence, 2007; Collins and Anthony, 2008; Bilotta and Brazier, 2008). The delivery of SS, PP and the contribution of the PP component to overall P flux will vary between catchments in response to local climate, land use and management (Owens and Walling, 2002; Bechmann et al., 2008; Strömqvist et al., 2008). Increased PP associated with SS is often an important link to dissolved P concentrations that form the basis of regulatory water quality thresholds for rivers (for example, in the European Water Framework Directive). In addition, many land management mitigation actions target the PP pathway, whilst the legislation is based on soluble reactive P concentrations. The identification of critical source areas of SS and PP through more accurate high-resolution direct and indirect monitoring methods will help to target land management mitigation (Strömqvist et al., 2008; McDowell and Srinivasan, 2009) and improve water quality risk assessment (Djodjic and Villa, 2015; Thomas et al., 2016). Furthermore, these methods are also required to understand the effectiveness of the management changes that can be put in place.

Elevated SS and PP concentrations are generally more episodic than river solutes, hence their assessment benefits from higher-resolution information brought by semi-continuous monitoring (van Geer et al., 2016). This requires that the relationships calibrating surrogate parameters such as turbidity to the target parameters of interest are transparently derived and uncertainties determined. High discharge events enhance soil and bank erosion due to entrainment of soil particles, increased scouring and re-suspension of benthic material (Evans and Johnes, 2004; Lawler et al., 2006). Sediment-associated P concentrations have also been shown to increase markedly during storm events (Kronvang et al., 1997; Evans and Johnes, 2004; Edwards and Withers, 2008), often showing strong concentration-discharge hysteresis (Lloyd et al., 2016; Mellander et al., 2015; Slaets et al., 2014). Together, these factors lead to underestimation of SS concentrations and fluxes when limited sampling frequencies are used (Walling and Webb, 1985; Kronvang et al., 1997; Minella et al., 2008; McDowell and Srinivasan, 2009). Therefore, turbidity has been utilised since the 1960's as a surrogate for estimating SS concentrations from continuous recordings (using *in-situ* photo-electric probes), allowing fluxes and concentration exceedance curves to be quantified more accurately (Walling, 1977; Walling and Webb, 1985; Minella et al., 2008). However, the use of turbidity probes to estimate SS concentrations has its limitations and associated errors, as describe by Minella et al. (2008) and Bilotta and Brazier (2008).

Measures to improve land management practices in agricultural catchments to minimise water pollution require evidence of changes in SS and PP concentrations, loads and timing of delivery to evaluate their benefits for water quality and ecological condition (Udeigwe et al., 2007; Bechmann et al., 2008; Collins and Anthony, 2008; Strömqvist et al., 2008). Pollutant mobilisation can occur during low as well as high flows and seasonal patterns in the accumulation and remobilisation of SS and PP remain uncertain. Temporal trends in PP transport may be distinct from those of SS (Evans and Johnes, 2004; McDowell and Wilcock, 2007), as spatio-temporal variability in different sources of SS and PP may occur (Edwards and Withers, 2008). These aspects need to be informed by high resolution monitoring that is cost-effective, but well calibrated and with constrained uncertainties. Relationships between SS and turbidity from *in-situ* studies have been published, based on coinciding manual spot-sampling; Udeigwe et al., 2007). Furthermore, turbidity has been related to colloidal P (Heathwaite et al., 2005) and PP in simulated runoff (Udeigwe et al., 2007), opening up turbidity as an option to continuously monitor PP in surface waters (Stubblefield et al., 2007). Understanding the transferability of calibrations between seasons and locations would further enhance the utility of turbidity as a surrogate for SS and PP. Therefore, we hypothesise that transferable calibrations could be developed that would enable *in-situ* turbidity to be a surrogate for improving the characterisation of high resolution concentration-discharge behaviour and SS and PP load estimates in streams dominated by agricultural land use. To test this hypothesis, our aims were to (i) establish relationships between SS and PP with turbidity and with discharge, using combined *in-situ* turbidity probe, manual grab samples and automated storm event sampling, (ii) examine the transferability of relationships between adjacent catchments, and (iii) quantify differences in loads and load estimation uncertainties gained from different load interpolation approaches and calibration relationships.

2. Materials and methods

2.1. Study site

This study was part of a joint research scheme with the national regulator (Scottish Environment Protection Agency; SEPA) to develop cost-effective methods for the evaluation of land management policy and mitigation measures to reduce diffuse water pollution in agricultural catchments in order to fulfil the requirements of the EU Water Framework Directive. The principal study site was the 241 ha Baldardo catchment in north-east Scotland. The catchment is characterised by partially