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An evaluation of high frequency turbidity as a proxy for riverine total phosphorus concentrations

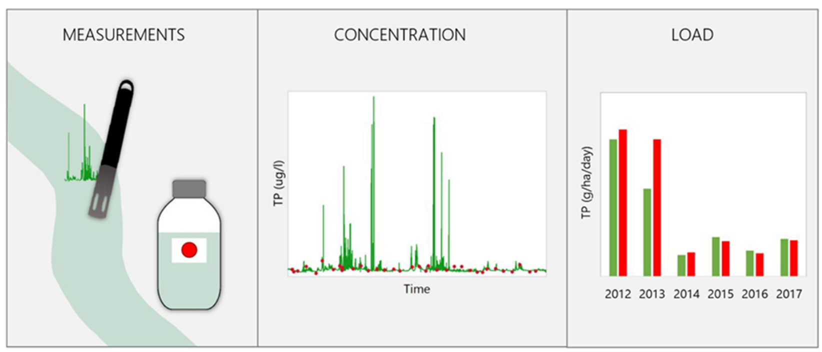
Emma E. Lannergård *, José L.J. Ledesma, Jens Fölster, Martyn N. Futter

Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, P.O. Box 7050, 75007 Uppsala, Sweden

HIGHLIGHTS

- Good linear transfer function between TP and high frequency turbidity
- Similar high frequency and grab sample estimated fluxes, except one year.
- Caution should be taken when transforming data.
- High stream discharge episodes, e.g. spring flood, are important to capture.
- Sensors can be deployed under ice for the entire winter.

GRAPHICAL ABSTRACT



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ABSTRACT

Surface water eutrophication resulting from excessive phosphorus (P) inputs is one of today's most challenging environmental issues. Riverine total phosphorus (TP) concentrations have high temporal variability, which complicates flux estimation. We evaluated the usefulness of high frequency in-situ turbidity measurements as a proxy for TP in Sävjaån, a river draining a mixed land use catchment (722 km^2) in central Sweden. Turbidity was monitored every 10th–15th minute during 6 consecutive years (2012–2017). Linear regression showed a good relationship between high frequency turbidity and TP ($r^2 = 0.64$) and could hence be used for comparison of flux estimation methods. Predictive power of the turbidity-TP relationship was not improved by adding seasons, hydrograph rising/falling limb or high/low stream discharge to the model which argues for a single transfer function relating turbidity and TP. Both TP and turbidity were log-normally distributed. However, flux estimates were sensitive to data transformation; predicted TP concentrations and fluxes based on log-transformed data were biased towards lower concentrations and fluxes compared to non-transformed data. In five of six years grab sample and high frequency estimated TP fluxes were similar (grab sample estimates −10% to +13% P transport compared to high frequency flux estimates). The exception was in 2013, when a 50-year spring flood occurred, and the grab sample estimated flux was 56% larger than that estimated from high frequency data. Thus, the flux comparisons were mostly affected by stream discharge, which underlines the importance of capturing high discharge episodes with, e.g. in situ sensors. While uncertainties regarding the use of turbidity as a proxy for TP remain, it is clear that credible water chemistry data can be obtained with current high frequency sensors. We conclude that high frequency data can be used to better understand catchment response to external pressures and gain insights into water quality that will be missed with grab sampling.

* Corresponding author.
E-mail address: emma.lannergard@slu.se (E.E. Lannergård).

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1. Introduction

Despite large efforts to control nutrient inputs to surface waters, eutrophication is an ongoing problem in many parts of the world (Sharpley et al., 2013), and is considered to be one of today's most challenging water quality issues in developed countries (Cassidy and Jordan, 2011). Freshwater and marine productivity is usually limited by either nitrogen or phosphorus (P) (Elser et al., 2007) and nutrient enrichment results in increased abundance of algae and aquatic weeds (Carpenter et al., 1998; Smith et al., 1999). The increased production can lead to low oxygen levels due to decay of aquatic vegetation, as well as biodiversity loss.

Rivers are the link transporting nutrients from land to coastal areas (van der Struijk and Kroeze, 2010). In rivers, P concentrations are highly variable over time, with high concentration events potentially contributing significantly to overall fluxes (Jordan et al., 2007; Cassidy and Jordan, 2011). Adequate monitoring of different forms of P and other highly variable parameters, e.g., total suspended solids (TSS), with traditional methods such as regular (e.g. monthly) grab sampling can be a challenge (Coynel et al., 2004; Skarbøvik and Roseth, 2015). Fluxes are typically estimated using temporally interpolated water quality parameters derived from relatively infrequent grab sampling and continuous flow measurements, with risk of missing high concentration events associated with high flows (Jones et al., 2011) and loss of contaminant delivery behaviour information. To reduce uncertainty to the degree needed to properly characterize temporal trends in water quality, a logistically infeasible number of samples would be required (Gippel, 1995; Coynel et al., 2004; Jones et al., 2012). This is especially relevant in streams with flashy hydrology (Johnes, 2007). Uncertainties in P concentrations during unmonitored time periods relate to the drivers controlling P transport, the proportion of total phosphorus (TP) derived from diffuse and point sources and how much of the P is transported in the different forms (Johnes, 2007).

To support water policy and make informed management decisions, significant resources are expended on producing reliable data to assess surface waters, for example to comply with the Water Framework Directive (WFD) (Allan et al., 2006) and the Convention on the Protection of the Marine Environment of the Baltic Sea (Baltic Marine Environment Protection Commission-Helsinki Commission HELCOM, 2013). Accordingly, selection of the best sampling strategy is critical, which justifies the evaluation of different monitoring methods, use of proxies and sampling frequencies.

It is necessary to quantify the TP flux in rivers discharging to the marine environment to identify nutrient sources (Coynel et al., 2004) and to evaluate the effectiveness of nutrient control measures (Kronvang and Bruhn, 1996). Multiple methods have been proposed for estimating fluxes from infrequent water quality samples and continuous flow measurements (e.g. Walling and Webb, 1985; Kauppila and Koskiaho, 2003; Johnes, 2007). Kronvang and Bruhn (1996) used daily or sub-daily chemistry sampling and instantaneous flow measurements to compare different flux estimation methods. These comparisons were regarding both sampling frequency (discrete and flow-weighted storm sampling) and flux estimation methods. The conclusion was that nearly all methods investigated underestimated fluxes of TP and P bound to particles. Furthermore, when samples are collected weekly or monthly, detailed temporal resolution is lost and peaks in concentration are commonly overlooked (Jones et al., 2012). Hence, more accurate flux estimates are likely to be associated with increased sampling frequency (Kronvang and Bruhn, 1996). Flow weighted sampling, where storm events are intensively monitored and integrated into composite samples, is a widely used and viable option for increasing accuracy in flux for a comparably low cost (Cassidy et al., 2018). However, only conservative parameters (e.g. TP) can be analysed with this method due to e.g. exchange between particulate and soluble forms. Short term changes in parameter concentrations are also lost since water from different time periods is combined into one sample.

Given the difficulties and costs of characterising concentrations based solely on measurements of the parameter of interest, there is a common use of proxies in which inexpensive or readily available measurements are used as predictors in transfer functions to predict values. There is a long history, starting in the 1940s, of efforts to use flow measurements as proxies for concentrations of water quality parameters (Walling, 1977). Other hydrological parameters, e.g. antecedent soil moisture (Zhang and Ball, 2017) have also been proposed as predictors suitable for use in transfer functions. Typically, a regression is used to create a transfer function which quantifies the relationship between the proxy and parameter of interest, although simple statistical (Seibert et al., 2009) and complex process-based (Lu et al., 2016) models have also been used. Data used in a regression are often transformed so as to achieve multivariate normality. When data are transformed, there is a risk that the hypothesis being tested will change (Changyong et al., 2014) and that the necessary back transformations to control for bias in the proxy relationship are not applied (Newman, 1993). For example, a regression using log-transformed data of Eq. 1 tests a non-linear model of the form of Eq. 2, for which the least squares estimator of the slope of the log-transformed data (β in Eq. 1) is a biased estimator of the linear slope (for mathematical details, see Newman, 1993).

$$\ln(y) = \alpha + \beta \times \ln(x) \tag{1}$$

$$y = e^{\alpha} \times \beta^{x} \tag{2}$$

One available method for generating high frequency proxy data suitable for monitoring trends in water quality is to deploy an in situ sensor in a water body to explore temporal dynamics in the concentrations and fluxes of particles. Not all water quality parameters can be measured by the current generation of high frequency in situ sensors. However, turbidity can be measured and it has the potential to be used as a proxy for other water quality parameters of interest, e.g. TP or TSS (gravimetrically determined on filtration).

Earlier studies have demonstrated the potential for using high frequency turbidity measurements as a proxy for TSS and TP (Grayson et al., 1996; Stubblefield et al., 2007; Jones et al., 2011; Ruzycki et al., 2014; Koskiaho et al., 2015; Skarbøvik and Roseth, 2015; Stutter et al., 2017; Villa et al., In review) (Table 1). Results show significant correlations between turbidity and the parameters of interest, which indicate that high frequency turbidity data could be useful when assessing eutrophication. Based on current knowledge, correlations between turbidity and TP or TSS are always site specific and thus non-transferable between catchments (Jones et al., 2012; Stutter et al., 2017). Yet, studies evaluating the reasons for site specific correlations are scarce. Furthermore there is a lack of studies predicting and evaluating the suitability of proxy parameters for e.g. P concentrations in different kinds of waterbodies (Skarbøvik and Roseth, 2015). The relation between turbidity and other parameters is affected by particle composition (Gippel, 1995) and particle size distribution (Jones et al., 2011; Stubblefield et al., 2007; Ruzycki et al., 2014). The particle size distribution is important since the turbidity signal is more sensitive to fines (<63 μm) than sand sized material (63–125 μm) (Lewis, 1996). The composition and size distribution of suspended particles in rivers is in turn connected with storm events (Walling and Moorehead, 1987; Pfannkuche and Schmidt, 2003) and season (Bogen, 1992). Colloids and nanoparticles (clay minerals, Fe oxides and organic matter) are also carriers of P (Edzwald et al., 1976; Gottselig et al., 2017). Colloidal P concentrations have previously been shown to have good correlations with turbidity (Heathwaite et al., 2005).

The aims of this study were to (1) evaluate the potential for high frequency turbidity measurements to be used as a proxy for riverine TP concentrations, (2) quantify hydrologic and seasonal controls on the turbidity-TP relationship, and (3) compare TP flux estimates calculated from high frequency measurements and grab samples to analyse