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A turbidity-based method to continuously monitor sediment, carbon and nitrogen flows in mountainous watersheds

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SUMMARY

The aim of this study was to develop a method to continuously monitor sediment, carbon and nitrogen concentrations in streams using turbidity sensors. Field experiments were conducted in an irrigated and intensely cultivated watershed in Northwest Vietnam. Turbidity, discharge and rainfall were monitored during two successive rainy seasons from 2010 to 2011, and manual water samples were collected using a storm-based approach. Samples were analyzed for concentrations of suspended sediment (SSC), particulate organic carbon (POC) and particulate nitrogen (PN). A linear mixed model was developed to account for serial correlation, with turbidity, discharge and rainfall as predictor variables. Turbidity was the most important predictor variable in all models. Fivefold cross-validation showed best model performance for POC with a Pearson's correlation coefficient of 0.91, while predictions for SSC and PN achieved a satisfying correlation of 0.86 and 0.87, respectively. Laboratory testing of the turbidity sensors showed that the turbidity signal is sensitive to differences in organic matter content, and has the smallest variance for fine textures, both of which are correlated to POC and thus supporting the higher predictive accuracy for this variable. The developed methodology is widely applicable and can be used to simultaneously obtain reliable, cost-effective and continuous estimates of SSC, POC and PN with a single sensor.

1. Introduction

Techniques to monitor sediment transport in waterways provide essential data, not only on erosion processes at watershed scale (Gao, 2008), but also on eutrophication of freshwater bodies and coastal regions (Beusen et al., 2005). Traditionally, automatic water samplers have been used to quantify suspended sediment concentrations (SSC), by sampling either at fixed time intervals or proportionally to stream flow. As the majority of sediments is typically transported during uncommon storm events with extreme rainfall, regular but infrequent sampling can lead to an underestimation of sediment loads (Walling and Webb, 1981). And frequent sampling can be impractical – especially in remote areas – being time consuming and expensive. Therefore, efforts have been made to establish relationships between sediments and other variables, in order to obtain continuous data. Initially, the focus was on discharge (e.g. Duvert et al., 2011; Porterfield, 1972; Williams, 1989). But many discharge-SSC relationships exhibit substantial scatter, due to the fact that SSC does not only vary with discharge, but also with upstream sediment availability (Gao, 2008). Typically, the variance for sediment rating curves also increases with the mean, violating the assumption of stable variance needed for simple linear regression. For this reason, Cox et al. (2008) suggested to use a generalized linear model with a gamma distribution for the errors. Moreover, in man-made channels such as irrigation channels, changes in stream flow are not necessarily related to changes in sediment and associated nutrient concentrations, because irrigation management can cause changes in discharge that are not associated with an increase in Hortonian overland flow and corresponding sediment input (Schmitter et al., 2012).

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As a solution to these limitations, turbidity has been explored extensively as an alternative to discharge as a proxy variable for SSC. Turbidity is a measure for the optical properties of a sample which cause light rays to be scattered and absorbed, rather than transmitted (Anderson, 2005) and has often been found to be proportional to the SSC in various environments: streams (e.g. Lewis and Eads, 2001; Minella et al., 2008; Navratil et al., 2011), regulated rivers (Gilvear and Petts, 1985), estuaries (Krause and Ohm, 1984), river deltas (Hung et al., 2014) and irrigation and drainage systems (Gao et al., 2008). It is generally considered the most reliable, easiest and cost-effective proxy (Lewis, 1996). Most authors used simple linear regression (e.g. Brasington and Richards, 2000; Wass and Leeks, 1999), polynomial regression (Gao et al., 2008; Lewis, 1996; Minella et al., 2008; Riley, 1998) or multiple regression, combining turbidity and discharge (Ziegler et al., 2011), to establish the relationship between turbidity and SSC.

The accuracy of the developed relationship between sediment concentrations and turbidity varied widely between studies. Regression resulted in an R^2 ranging from 0.55 (Riley, 1998) to 0.98 (Minella et al., 2008). Similar values are reported for mountainous headwater catchments: Brasington and Richards (2000) reported results of a simple linear regression with an R^2 of 0.75 for SSC for a small watershed in the Himalaya, although the authors mentioned that due to the small sample size ($n = 31$), the results should be interpreted with caution. Ziegler et al. (2011) found an R^2 of 0.96 for a simple linear SSC regression in a mountainous catchment in Thailand. Navratil et al. (2011) collected data in a mountainous headwater catchment of the Rhone (France), with badlands topography. They found it necessary to split the dataset in two. Using a quadratic regression on the one subset with 28 events, they achieved an R^2 of 0.97. The ten events in the remaining subset all showed different hysteresis effects in the SSC-turbidity relationship, requiring the development of individual relationships.

Regardless of their success in explaining the variability in SSC, these regression methods are based on linear models and, therefore, they require constant variance and independent errors. The first condition is often problematic as the scatter in the data typically increases with increasing turbidity (Minella et al., 2008; Riley, 1998). The second condition requires that there is no temporal correlation, which can be a problematic assumption for most hydrologic datasets, as they are normally time series (Helsel and Hirsch, 2002). Göransson et al. (2013), for example, found a temporal autocorrelation for lags of approximately 10 days for turbidity data of a large river in Sweden. But in practice, independence is often uncritically assumed. When these two conditions are not met, alternatives to simple linear or non-linear regression are required. This study aims to develop a method to reliably estimate SSC concentrations using turbidity in conditions, where simple regression does not provide satisfying predictions, where the errors are not constant but increasing with the mean, and where samples are taken so closely together in time that observations cannot be assumed to be independent.

Not only sediment concentrations require quantifying, but also nutrient concentrations are of interest: to study nutrient depletion through erosion from the uplands (Gao, 2008) but also to monitor stream quality and nutrient redistribution through irrigation (Gao et al., 2008; Schmitter et al., 2012) and nutrient export to and eutrophication of oceans (Beusen et al., 2005; Seitzinger et al., 2005). Southeast Asia in particular is considered a key region for C and N export (Beusen et al., 2005; Ludwig et al., 1996; Seitzinger et al., 2005), having been especially subject to population increase and associated land cover changes (Valentin et al., 2008; Ziegler et al., 2009).

Ideally, sediment and nutrient concentrations could be monitored with a single device. Turbidity sensors have already proven to be instrumental in monitoring total phosphorous (Grayson et al., 1996; Istvanovics et al., 2004; Jones et al., 2011; Kronvang et al., 1997; Rasmussen et al., 2002; Ryberg, 2006; Stubblefield et al., 2007), either directly via regression, or through establishing a relationship between SSC and turbidity, and total phosphorous and SSC. Particulate organic carbon (POC) and particulate nitrogen (PN) concentrations are traditionally either interpolated from discrete samples (Lu et al., 2012), or calculated as a function of discharge and/or other environmental predictors (Alvarez-Cobelas et al., 2012), or as a function of the sediment flux (Ludwig et al., 1996). The first method does not provide continuous data, and the results are strongly dependent on the sampling interval: too few samples potentially lead to an underestimation of nutrient loads. The second strategy, establishing a relationship between Q and POC, suffers from the same difficulties as using Q as a proxy for SSC: an increase in discharge is not necessarily related to an increase in POC or PN concentrations, especially in irrigation channels where irrigation management also affects discharge. Additionally environmental predictors such as discharge and rainfall generally perform poorer for smaller catchments (Alvarez-Cobelas et al., 2012). Finally establishing a relationship between SSC and POC is also not necessarily straightforward, as POC content of the sediment often decreases with increasing SSC (Lu et al., 2012; Ludwig et al., 1996). Turbidity sensors could provide an alternative. Némery et al. (2013) have successfully used turbidity indirectly to predict POC, by establishing a relationship between turbidity and SSC, and SSC and POC. Additionally, several authors discussed the effect of particle size on turbidity (Foster et al., 1992; Lewis, 1996; Pfannkuche and Schmidt, 2003; Teixeira and Caliari, 2005; Thollet et al., 2013; Wass and Leeks, 1999), showing that for the same SSC, a coarse fraction will result in a lower turbidity than a fine fraction. Foster et al. (1992) reported that at high concentrations of dissolved organic matter, turbidity is often a poor predictor for the mineral fraction. All this suggests that turbidity signals are sensitive to particle size and organic matter content, both related to nutrient content, and therefore turbidity sensors could potentially provide a continuous estimate of sediment-associated nutrient content – in particular of POC and PN. However, a direct relationship between turbidity and particulate nutrient content is to date missing.

The specific aims of this paper were (i) to investigate the factors influencing the turbidity signal in laboratory conditions, in particular the influence of organic matter, thereby testing the theoretical feasibility of using turbidity as a direct proxy for sediment POC and PN content, (ii) to develop a statistical model that accurately predicts the suspended sediment concentration when regression is not appropriate, and (iii) to assess the possibility of using turbidity as a direct predictor for POC and PN in field conditions.

2. Materials and methods

2.1. Exploratory laboratory test: effect of texture and organic matter on turbidity signal

Prior to deployment in the field, the turbidity sensors (ANALITE NEP395, McVan, Australia) were tank tested. The measuring range of the sensors is 0 to 3500 NTU. The aim was to enhance the understanding of the sensor's response to different qualities of sediment material in terms of particle size composition and organic matter content: if the turbidity sensor would be able to detect differences in organic matter content for the same SSC and particle size, that would indicate that turbidity is a potential predictor variable for POC. Therefore three soils with contrasting dominant textures (a sandy Podzol, a loamy Luvisol and a clayey Gleysol) were selected from a reference library at the Soil Science Institute of the University of Hohenheim. The particle size distribution was