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Research article

Magnetic susceptibility as a simple tracer for fluvial sediment source ascription during storm events

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A R T I C L E I N F O

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A B S T R A C T

Sediment tracing using a single tracer, low frequency magnetic susceptibility (X_{lf}), was used to apportion suspended sediment to geologically defined source areas and to interpret sediment source changes during flood events in the degraded catchment of the Vuvu River, a headwater tributary of the Mzimbubu River, South Africa. The method was tested as a simple tool for use by catchment managers concerned with controlling erosion. The geology of the 58 km^2 catchment comprises two distinct formations: basalt in the upper catchment with a characteristically high magnetic susceptibility and shales with a low magnetic susceptibility in the lower catchment. Application of an unmixing model incorporating a Monte Carlo uncertainty analysis showed that X_{lf} provided a means to assign the proportion of each geological province contributing to the river's sediment load. Grab water samples were collected at ten-minute intervals during flood events for subsequent analysis of suspended sediment concentration and the magnetic susceptibility of the filtered sediment. Two floods are presented in detail, the first represents a significant event at the start of the wet season (max. discharge 32 m^3 s^{-1}); the second was a smaller flood (max discharge 14 m^3 s^{-1}) that occurred a month later. Suspended sediment concentrations during the twelve monitored events showed a characteristic decline over the wet season. The main source of suspended sediment was shown to be from the mudstones in the lower catchment, which contributed 86% of the total measured load. The sediment dynamics during the two floods monitored in detail were quite different from each other. In the first the sediment concentration was high (11 g L^{-1}), peaking after the flood peak. The X_{lf} value increased during the event, indicating that contribution to the sediment load from basalt in the upper catchment increased during the recession limb. In the second, smaller flood the sediment peak (6 g L^{-1}) coincided with the flood peak. Low X_{lf} values indicated that mudstones in the lower catchment soils dominated the sediment load throughout the entire event. Sediment tracing using a single property ($X_{lf)}$ was thus used effectively to study changing sediment sources both between and during a flood event in a catchment with strongly contrasting magnetic signatures in different areas. The results support the use of magnetic susceptibility as a simple and cheap tool to determine sediment provenance that can be used to guide catchment restoration in similar environments.

1. Introduction

The Vuvu catchment is a small catchment located in the headwaters of the Mzimvubu River in South Africa. High erosion rates result from a combination of steep slopes, erodible soils and high rural population densities. Gully erosion is prevalent throughout the area and increases connectivity in the catchment as well as being a potential sediment source (Van der Waal, 2015). As a result, there is concern about the downstream effects of sediment on water quality, aquatic habitat and reservoir sedimentation. Restoration efforts using erosion control structures have been put in place but it is important that these target the primary sources of sediment in the catchment. A number of authors have advocated the use of sediment tracing as a management tool (Hatfield and Maher, 2009; Collins et al., 2011; Mukundan et al., 2012; Guzmán et al., 2013; Koiter et al., 2013a; Walling, 2013). Koiter et al. (2013a) make a plea for the development of simple, cost effective

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tools that can be applied to river basin management, a point supported by Walling (2013). In this paper we examine the use of a simple measure of magnetic susceptibility to identify the predominant catchment scale sediment sources in the Vuvu catchment so as to better direct restoration efforts.

Sediment tracing is a well established tool for identifying source contributions to downstream sinks (Collins et al., 1997; Foster and Lees, 2000; Hassan and Ergenzinger, 2003; Walling, 2013). Walling (2005) claims it to be more efficient than alternative methods, giving an integrated catchment-wide picture. Tracing relies on identified sources having distinct properties that are conserved within the transported or deposited sediment. Walling (2013) distinguishes between source types and source provenances. Source types would include categories such as top soil, subsoil or land use types. Source provenances are spatial features, often linked to geology. In the Vuvu we consider source provinces characterised by distinctive geology.

In an investigation of flood bench chronology, Van der Waal et al. (2015) investigated the sediment sources for flood bench sediments alongside the Vuvu River, that is the coarser sediment stored locally in the valley floor. Although flood benches provide a convenient sediment sink for tracing studies there is a need to look at fine sediment carried in suspension as it is more likely to impact on downstream users through effects on water quality, stream biota and reservoir sedimentation. Suspended sediment also better reflects contemporary erosion sources. This paper traces the source of suspended sediment sampled at one point lower in the valley.

In his recent review of sediment tracing, Walling (2013) notes that source tracing based on suspended sediment samples taken during flood events was limited in the past by the large volumes of sample required to obtain sufficient sediment (>20 g) for radionuclide or geochemical analysis, techniques commonly applied in tracing studies. Walling (2013) also recommends the use of time integrated samplers to aid the identification of sources as used for example by Gruszowski et al. (2003), Collins et al. (2010), Koiter et al. (2013b) and Smith and Blake (2014). Although these provide a valuable means of trapping sufficient sediment to distinguish between different sources over a flood event, or multiple events, they do not provide information on variation during an individual event. Although a number of studies that present the results of spot sampling through a hydrograph are reported in the literature (eg. Motha et al., 2004; Minella et al., 2008), they seldom capture the within storm temporal variation in sediment sources in an effective way. An early exception is the work of Slattery et al. (1995) who used magnetic properties to trace suspended sediment from topsoil and stream banks sources through two storm events in the Stour catchment. Recently, Cooper et al. (2015) applied X-ray fluorescence (XRFS) and diffuse reflective infrared Fourier transform spectroscopy (DRIFTS) to sediment collected using automatic water samplers to yield high-temporal resolution fluvial sediment source data.

The use of the mineral magnetic properties of sediments as a sediment tracer was widely advocated in the 1980s and 1990s (Stott, 1986; Yu and Oldfield, 1989; Slattery et al., 1995; Caitcheon, 1993, 1998; Lees, 1997, 1999). Use of mineral magnetic tracers can provide a simple and cost effective means of ascribing sources using a small amount of sample to measure a number of properties that can distinguish for example geological provinces or topsoil from subsoil. Yu and Oldfield (1989) and Walden et al. (1997) developed two of the early un-mixing models based on magnetic properties. Lees (1997) points to problems using this method, recommending that good source ascription can be found when only two sources are considered; problems arise as the number of potential sources increases. More recently the use of mineral magnetic properties has been largely superseded by the use of geochemical properties, either in addition to magnetic properties or on their own. Collins et al. (1997) recommend that as many properties as possible are used in tracing studies. They advocate the use a suite of properties derived from geochemical analysis, mineral magnetism and others. Such a suite can include more than 30 properties. Although effective, geochemical analysis is expensive and often beyond the budget of both researchers and managers (Pulley and Rowntree, 2016a).

Despite the recent emphasis on geochemical analysis, mineral magnetism has continued to provide insight into sediment sources in a number of environments including fire prone catchments (Humphreys, 2004; Blake et al., 2006), urban environments (Charlesworth and Lees, 2001; Carter et al., 2003; Robertson et al., 2003), agricultural catchments (Royall, 2001; Blake et al., 2012), forestry roads (Croke et al., 2005), gullied catchments (Krause et al., 2003) and coastal areas (Fu et al., 2006). Hatfield and Maher (2008, 2009) applied environmental magnetism to identify sediment sources in an upland catchment and Jenkins et al. (2002) to sourcing fine bed sediment in the River Tay in Scotland.

In South Africa mineral magnetism has been used successfully as a tracer where the geology provides distinct signatures. Foster and Rowntree (2012), Rowntree and Foster (2012), Pulley et al. (2015), Pulley and Rowntree (2016b) have demonstrated its application to the Karoo where dolerite intrusions provide a clear contrast to sedimentary mudstones and sandstones. Likewise van der Waal et al. (2015) use mineral magnetic signatures to distinguish between sediments of basaltic origin and mudstones and sandstones in the flood benches of the Vuvu River.

In this paper we present the results of short term suspended sediment monitoring in the Vuvu catchment. The variation in suspended sediment loads through consecutive storm events is described. We then demonstrate how mineral magnetism can be used to apportion sources of suspended sediment. Specifically, we use a relationship established through an un-mixing model between magnetic susceptibility and the percent sediment from igneous rock sources (as compared to sedimentary rock sources) to ascribe sources to suspended sediment sampled through storm events during one wet season (2013–2014). Mineral magnetism, specifically magnetic susceptibility, is shown to be an effective tracer for the small masses of sediment that could be sampled during storm events. The results of sediment monitoring are also used to estimate suspended sediment loads by storm event.

2. Methods

2.1. The study catchment

The Vuvu River is a headwater tributary of the Thina River draining the Drakensberg Escarpment. Altitude ranges from ~1400 to ~3000 m and mean annual precipitation over the catchment is ~900 mm. Rainfall is dominated by intense thunderstorms and results in flashy flows often lasting less than two hours (Van der Waal, 2015). The Vuvu has two clearly distinguished subcatchments, the upper catchment (34 km^2) is underlain by igneous Drakensberg basalts, the lower catchment (24 km^2) by sedimentary rocks (Clarens sandstone and Elliot mudstone) (Fig. 1). Catchment characteristics are summarised in Table 1. This geological division coincides with land use; settlements and cultivation are confined to lower catchment on Elliot mudstones, the upper catchment is used for livestock grazing on steep slopes, giving rise to many cattle tracks. A smaller area of Clarens sandstones separates the mudstones and basalts. Gully erosion is ubiquitous throughout the catchment, but is slightly more pronounced on the Elliot mudstones of the lower catchment (Table 1). Van der Waal et al. (2015) report a clear distinction