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Characterization and quantification of suspended sediment sources to the Manawatu River, New Zealand

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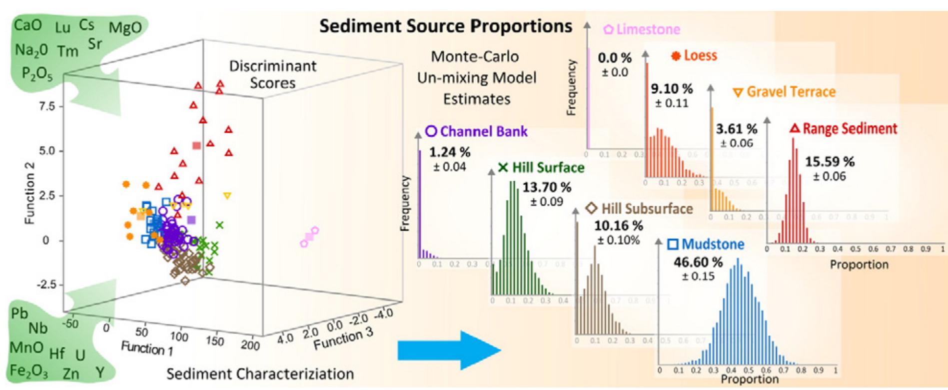
HIGHLIGHTS

- 16 geochemical variables classified 8 sediment sources with 92.6% accuracy.
- Mudstone was the dominant source of sediment of ≈38–46%.
- The four un-mixing model scenarios exhibited consistent estimates.
- Erosion process—source sediment connections remain unclear in complex environments.

GRAPHICAL ABSTRACT



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ABSTRACT

Knowledge of sediment movement throughout a catchment environment is essential due to its influence on the character and form of our landscape relating to agricultural productivity and ecological health. Sediment fingerprinting is a well-used tool for evaluating sediment sources within a fluvial catchment but still faces areas of uncertainty for applications to large catchments that have a complex arrangement of sources. Sediment fingerprinting was applied to the Manawatu River Catchment to differentiate 8 geological and geomorphological sources. The source categories were Mudstone, Hill Subsurface, Hill Surface, Channel Bank, Mountain Range, Gravel Terrace, Loess and Limestone. Geochemical analysis was conducted using XRF and LA-ICP-MS. Geochemical concentrations were analysed using Discriminant Function Analysis and sediment un-mixing models. Two mixing models were used in conjunction with GRG non-linear and Evolutionary optimization methods for comparison. Discriminant Function Analysis required 16 variables to correctly classify 92.6% of sediment sources. Geological explanations were achieved for some of the variables selected, although there is a need for mineralogical information to confirm causes for the geochemical signatures. Consistent source estimates were achieved between models with optimization techniques providing globally optimal solutions for sediment quantification. Sediment sources was attributed primarily to Mudstone, ≈38–46%; followed by the Mountain Range, ≈15–18%; Hill Surface, ≈12–16%; Hill Subsurface, ≈9–11%; Loess, ≈9–15%; Gravel Terrace, ≈0–4%; Channel Bank, ≈0–5%; and Limestone, ≈0%. Sediment source apportionment fits with the conceptual understanding of the catchment which has recognized soft sedimentary mudstone to be highly susceptible to erosion. Inference of

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the processes responsible for sediment generation can be made for processes where there is a clear relationship with the geomorphology, but is problematic for processes which occur within multiple terrains.

1. Introduction

Suspended sediment is one of the most important components of the sediment transport system (Bracken, 2010; Collins and Owens, 2006). Elevated suspended sediment loads reflect enhanced erosion processes, land instability, and often a loss of productive soils within a catchment (Owens et al., 2005; Walling and Fang, 2003), while sediment influx can impact channel morphology, water quality and aquatic ecosystems (Wood and Armitage, 1997) which are often considered a pollutant where elevated nutrients bind to sediment (Calmano et al., 1993; Horowitz and Elrick, 1987). It is therefore important to identify the key source areas responsible for sediment generation as the first step towards minimizing sediment delivery into the fluvial system. This is especially true for erosion prone areas where erosion rates have been exacerbated due to human activity and poor land management e.g. East Coast catchments in New Zealand's North Island (Page et al., 2000).

A variety of direct and indirect techniques have been developed to assess suspended sediment source information including, aerial photography (e.g. Marzolff and Poesen, 2009), erosion pins (e.g. Haigh, 1977; Lawler, 1986), sediment gauging stations (e.g. Hicks et al., 2000; Wang et al., 2007), turbidity sensors (e.g. Hicks et al., 2004; Lewis, 1996), sediment fingerprinting (e.g. Collins et al., 1997; Walling et al., 1999) and modelling (e.g. Merritt et al., 2003; Prosser et al., 2001). However, the spatial and temporal variability of suspended sediment load, coupled with the financial limitations for full catchment system monitoring, compromise the validity of many studies to provide meaningful information (Collins and Walling, 2004).

Sediment fingerprinting provides a means of directly quantifying sediment contribution from unique sources within catchments. This is achieved by sampling a range of sediment sources throughout the catchment system, differentiating the sources using inherent geochemical properties, and then quantifying the relative contributions to the suspended sediment load from the identified sources. A considerable range of tracers has been employed in sediment fingerprinting research including; mineralogy (e.g. Eberl, 2004; Gingele and De Deckker, 2005), mineral magnetic signatures (e.g. Blake et al., 2006; Caitcheon, 1998), geochemical compositions (e.g. Collins et al., 1998; Collins et al., 2013; Hardy et al., 2010; Lamba et al., 2015; Zhang et al., 2012), isotopic ratios (e.g. Douglas et al., 1995; Gingele and De Deckker, 2005), radionuclides (e.g. Olley et al., 2013; Porto et al., 2013; Wilkinson et al., 2013), organic elements (Evrard et al., 2013; Fox and Papanicolaou, 2008), and compound specific isotopes (e.g. Blake et al., 2012; Gibbs, 2008; Hancock and Revill, 2013).

Sediment fingerprinting research has expanded dramatically, advancing from early studies, which employed a limited array of tracers (e.g. Peart, 1993; Walling et al., 1979), to comprehensive geochemical suites relying on statistical analysis and un-mixing models for sediment source evaluation (e.g. Cooper et al., 2014; Haddadchi et al., 2014; Laceby and Olley, 2014). Despite the increasing use of sediment fingerprinting, there have been a number of ongoing challenges within the approach. Recent research has drawn attention to uncertainties with sediment un-mixing models (e.g. Haddadchi et al., 2014), tracer selection (e.g. Pulley et al., 2015), source classification and within-source geochemical variability (e.g. Collins et al., 2010a).

Changes in sediment geochemistry can occur from chemical, biological and physical modification throughout transportation. The extent of these changes is poorly constrained, referred to as a 'black-box' by Koiter et al. (2013), which raises implications for retention of sediment source signatures in the suspended sediment load. Furthermore, typical sediment fingerprinting approaches assume a directly connected transport pathway from source to sink, which is not the case in many circumstances as sediment is transported along a 'jerky conveyor'(Ferguson, 1981). Belmont et al. (2014), explored the nature of some of these changes through measuring and modelling $^{210}Pb_{ex}$ and ^{137}Cs decay through floodplain storage and understanding the geomorphic processes that fractionate sediments, concluding that there is a need to better understand the relationships between the process and geochemical signature of the sediment. The specific suite of tracers employed also accounts for significant uncertainty, as most sediment fingerprinting approaches use a different array of tracers and select the ones which provide the best discrimination between sources. This was demonstrated by Pulley et al. (2015), who identified a mean difference of ≈24% between predictions arising from different tracer groups.

Quantitative un-mixing models have also come under scrutiny as the number of un-mixing models to choose from increases. Some models use local optimization techniques, while others use global optimization, the latter, in theory is more likely to produce an appropriate solution but can also take considerably longer to run (Frontline Systems Inc., 2010). In addition, the use of Genetic or Evolutionary Algorithms has been used in recent studies (e.g. Collins et al., 2010b) as a form of global optimization. Haddadchi et al. (2014) tested different models using the same dataset and showed that source contribution displayed a dependence on the selected mixing model. Incorporation of weighting and correction factors has been used in some studies to improve performance (e.g. Collins et al., 2010a), however, Laceby and Olley (2014) found incorporation of some of these factors in unmixing models does not necessarily improve the model performance. Pulley et al. (2015) also highlight this point, finding that organic matter and particle size distribution, were not likely causes for uncertainties. This highlights the need to carefully consider using adjustments within un-mixing models as they can generate unquantifiable errors (Smith and Blake, 2014).

In this study a sediment fingerprint is applied to a New Zealand sedimentary dominated catchment with a variety of geological and geomorphological sources. The aim is to identify discrete fine-sediment sources within the catchment and distinguish the geochemical tracers which can provide source differentiation; identify and relate the geological and geomorphological processes with the statistical outcomes and tracer selection; and compare optimization techniques for the two unmixing models applied.

2. Study site

The Manawatu River drains a ≈5870 km^2 catchment situated in the lower North Island, New Zealand (Fig. 1) which is underlain by a sedimentary geology consisting of mudstone and sandstone. The headwaters drain the eastern flanks of an uplifted greywacke block forming the Tararua and Ruahine Ranges, before flowing west through the main drainage divide via the Manawatu Gorge, incorporating flow from the western flanks of the mountain range and continuing through to the Tasman Sea (Fig. 1). Steep hillslope terrain is common throughout the eastern sub-catchments e.g. Tiraumea (Table 1), underlain primarily by soft mudstone while the middle reaches occur semi-confined through contact with mudstone bedrock cliffs and alluvial terraces. The lower reaches flow through extensive alluvial floodplains and range from wandering to pseudo-meandering. Many of the channels have undergone straightening and narrowing of the channel, transitioning to laterally-confined single thread channels as evidenced in the Pohangina River (Fuller, 2009).