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Original Research

Stream turbidity responses to storm events in a pristine rainforest watershed on the Coral Coast of southern Fiji

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A B S T R A C T

On the Coral Coast of Viti Levu Island in Fiji, inadequate knowledge of suspended sediment delivery patterns in small pristine coastal watersheds hinders any future assessment of accelerated erosion in disturbed areas nearby. This study adopts a rainfall–stream turbidity monitoring approach in the Votua Creek, which drains a small, steep but minimally-disturbed coastal rainforest catchment. Storm rainfall characteristics, stream depth and water turbidity were continuously monitored over one complete Fiji wet season from October 2009 to April 2010. The aim was to evaluate whether these parameters provide sufficient information to illustrate basic features of storm–sediment transport responses, in the case of limited stream gauging and very simple sediment rating curves. This is important because Pacific Island nations like Fiji do not have the resources to initiate long-term gauging and sediment sampling programmes across numerous small catchments.

A significant power function demonstrates that turbidity (T) is a suitable proxy for total suspended solids (TSS) for turbidity measurements above 5 NTU, with $TSS=0.930T^{1.111}$ ($r=0.98$, $P<0.001$). Over the study period, 10 individual storms 11.2–120.1 mm in size produced a 'significant turbidity response' (STR) in the Votua Creek. Rainfall parameters (totals and intensities) showed positive linear relationships ($r=0.72$–0.94) with stream turbidity parameters (mean, maximum, duration), whilst relationships of similar strength ($r=0.76$–0.98) were also derived between stream flow depth and turbidity. This implies that for small rainforest watersheds in Fiji, rainfall parameters offer no substantial disadvantage over flow as predictors of stream sediment responses to major storms. Event-based analysis revealed that negative (anticlockwise) hysteresis is a typical flow–turbidity pattern for STR events. Negative hysteresis is produced when secondary episodes of renewed (heavy) rainfall occur after maximum intensity, in the later phase of storm events. Tropical Cyclone Mick in December 2009 generated the largest flood and the greatest turbidity response ($T_{max}=1021$ NTU, $T_{mean}=207$ NTU). This concurs with earlier work confirming that tropical cyclones are the most important events for sediment transport in Fiji stream networks.

1. Introduction

1.1. Background

Sedimentation due to increasing soil erosion resulting from changing land use practices is one of the major influences on deteriorating water quality and a decline in marine productivity in many coastal regions worldwide (Bartley et al., 2014; Fabricious, 2005; Yamano et al., 2015). This is particularly true for humid tropical regimes, where greater energy input results in faster rates of hydrological processes that are expected to accelerate with projected global warming (Wohl et al., 2012). Such erosion problems are currently faced in the Fiji Islands. In four major drainage basins on the largest island of Viti Levu, land cover plays a dominant role in basin hydrology. Land use change over 1993 to 2007 has therefore had the greatest impact on surface runoff and erosion (Ankita & Kazuo, 2014). Cultivation of export crops such as ginger, taro, cassava and sugarcane cause relatively high rates of catchment erosion (Barbour & Terry, 1998; Cochrane, 1969; Mahadevan, 2008). Intensive farming practices on steep slopes, combined with uncontrolled grazing, burning, deforestation, and commercial forestry in some areas has thus led to increased sediment delivery into waterways, especially during large storm

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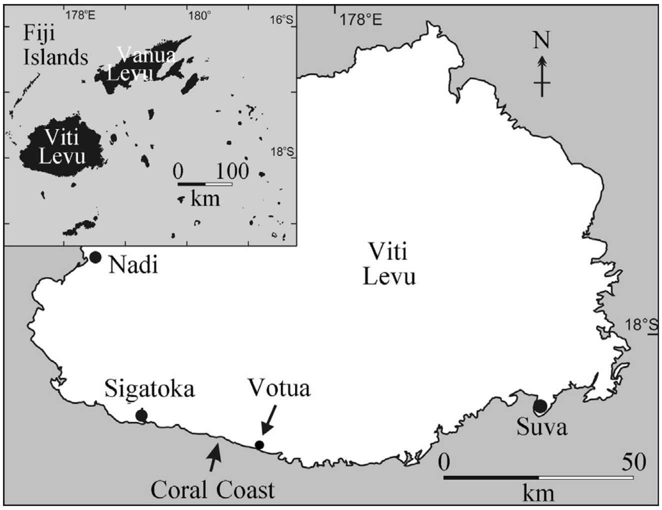

Fig. 1. Location of the Votua study area on the Coral Coast, south west Viti Levu island, Fiji.

events (Kostaschuk et al., 2003). Soil loss from small coastal watersheds is of specific concern as these occupy the majority of Fiji's coastal hinterlands. Often hilly in nature, small coastal watershed tend to exhibit a lower retention capacity for sediments compared to larger watersheds with broad, well-developed floodplains where fine sediments may be stored (Terry et al., 2008, 2011). According to Atherton et al. (2005), logging in small coastal watersheds is one of the main contributors to the degradation of coastal marine ecosystems and fisheries in Fiji, in part because coral reefs adjacent to small coastal watersheds are not adapted to periodic exposure to high sediment loads.

It might therefore be argued that issues of coastal water quality in Fiji need to be addressed at the watershed scale, since watershed health is inextricably linked to the well-being of natural coastal systems. However, a lack of information on temporal patterns of stream suspended sediment delivery from both pristine and disturbed small watersheds in Fiji is one of the major impediments hindering the identification of vulnerable areas, which might otherwise promote the implementation of watershed restoration efforts. The Coral Coast (Fig. 1) has been identified as an area of generally low levels of watershed management and disturbance, although there is increasing pressure for logging and land-use conversion to agriculture, so threatening offshore coral reefs (see Section 2). Yet, in spite of this threat, no previous studies have investigated stream sediment transport on the Coral Coast in order to understand conditions typical of undisturbed watersheds, which will be necessary for assessing the scale of any future disturbance by logging or land cover change.

1.2. *Stream suspended sediment and turbidity proxy*

Storms are natural events responsible for increasing the transport of sediments into streams and rivers. Nevertheless, some major questions in soil erosion remain unanswered for large events, owing to inadequate data from most areas of the world (Boardman, 2006; García-Ruiz et al., 2015). Although various conceptual, physically-based and empirical models exist for estimating erosion and predicting catchment sediment yield (e.g. Brooks et al., 2016; de Vente & Poesen, 2005; Morgan et al., 1998; Sarangi et al., 2007), de Vente et al. (2013) cautioned that results are not always reliable, in part because models do not incorporate all sediment producing and transport processes. Furthermore, many models have demanding data requirements for calibration, and hence cannot be consistently used in developing countries where data may be scarce. Stream monitoring therefore offers an alternative approach. A common goal has been to use relationships between discharge (Q) and suspended sediment concentrations (*SSC*) to estimate the suspended sediment load in rivers and streams (Araujo et al., 2012), and it is now widely accepted that different rainfall regimes exhibit contrasting patterns in sediment dynamics (Navratil et al., 2012). That being said, the situation persists that stream discharge and sediment yield from coastal watersheds are generally underrepresented in global databases (Milliman & Farnsworth, 2011; Warrick et al., 2015).

This investigation relies on a rainfall–turbidity monitoring approach. Various studies have established rainfall variables to be significantly linked with stream turbidity (Nadal-Romero et al., 2008a, 2008b; Ramos et al., 2015; Zabaleta et al., 2007). Water turbidity (T) is a useful parameter in stream monitoring programmes because it offers a suitable proxy for *SSC* (Göransson et al., 2013). Turbidity is a broad measure of stream water clarity and is normally recorded in nephelometric turbidity units (NTU) (George et al., 1996; Miller et al., 2015). Automated probes for in-stream installation measure turbidity as the amount of light backscatter from suspended particles. The main advantages of turbidity measurement are threefold. First, close relationships have been demonstrated between turbidity and *SSC*, allowing conversion (Chanson et al., 2008; Ochiai & Kashiwaya, 2010; Pavanelli & Bigi, 2005; Williamson & Crawford, 2011). Second, fixed probe installations for *in situ* turbidity monitoring are cost-effective compared to elaborate methods involving direct sampling and subsequent laboratory analysis for determining sediment concentrations (Pavanelli & Bigi, 2005; Pavanelli & Pagliarani, 2002). Third, after calibrating site-specific relationships between T and *TSS* (total suspended solids), normally through statistical regression, continuous in-stream turbidity data can then be employed to construct time series of *TSS* for individual study catchments (Rasmussen et al., 2011; Ziegler et al., 2014). This overcomes traditional problems associated with infrequent sampling (Gippel, 1995).

1.3. *Aims and objectives*

The first aim of the present study is to provide primary information on relationships between storm events and stream suspended sediment transport in a small, undisturbed forested watershed on the Coral Coast of south west Viti Levu island in Fiji. Investigating the transport of suspended sediment is considered a priority over bedload sediment, because silt and clay fractions are carried into the nearshore marine environment where they may smother coral reefs. Any observations will improve on the limited current knowledge of sediment delivery behaviour on the Coral Coast. It is anticipated that findings will serve as comparison against the few published studies on Fiji rivers and for any future erosion assessments in neighbouring watersheds where land use is becoming more intensive.

It should be stressed that the study is not designed as an in-depth examination of either stream discharge behaviour or catchment sediment yields. As with many developing countries, financial and resource constraints in Fiji restrict the number of watersheds that can be effectively monitored. Although all Fiji's major rivers have long-term hydrometric stations (Applied Geoscience and Technology Division of the Pacific Community [SOPAC], 2010), most small watersheds across Fiji are not systematically gauged, except in an *ad hoc* fashion during short-term projects, so stage–discharge relationships do not exist. In contrast, a wide network of climate stations is maintained by the Fiji Meteorological Services (www.met.gov.fj/). Within this context, the second aim is to make a preliminary assessment on whether or not storm rainfall (R), stream depth (D) and turbidity (T) measurements provide enough information to observe the key

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