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Volumetric measurement of river bank erosion from sequential historical aerial photography

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ABSTRACT

Understanding of the relative contribution of bank erosion to sediment budgets in New Zealand is limited. Few measurements of bank erosion rates exist, and this is a major limitation to the development of a locally calibrated model of bank erosion. The New Zealand sediment budget model, SedNetNZ, predicts bank erosion based on preliminary data, and this study aims to underpin the development of an improved model for bank erosion. Photogrammetric techniques and LiDAR were used to collect data on bank erosion rates for five different river reaches, ranging from 3 to 14 km in length, in the Kaipara Catchment, Northland, New Zealand. Changing river channel planform between the 1950s and 2015 was assessed using four to five well-spaced dates of historical aerial photographs. Changes in planform were combined with bank height, to calculate erosion and accretion volumes which were compared with SedNetNZ modelled estimates. Erosion and accretion is relatively evenly balanced in the study sites. The largest difference in terms of relative proportions of erosion and accretion are found along the Tangowahine River (13.4 km reach length), where 492,000 m^3 of sediment eroded between 1956 and 2015 compared to 364,000 m^3 of accretion. Lateral migration rates (erosion) for the five river reaches range between 0.14 m yr^{-1} and 0.21 m yr^{-1} and are comparable with those measured by previous assessments in New Zealand. The migration rates in channel widths per year for the three larger rivers (stream order 5–6) range between 0.4% and 0.8% of channel width per year. In contrast, the smaller streams (stream order 3–4) are retreating more rapidly, with width-averaged rates of 1.7% and 3.0%. Current SedNetNZ modelling tends to underestimate the bank height and greatly overestimates the migration rate.

1. Introduction

River bank erosion can constitute a significant proportion of river loads (Walling et al., 1999; Walling, 2005; Henshaw et al., 2013; Neal and Anders, 2015) and is usually a result of lateral migration of meandering streams and rivers. International studies estimate that sediment derived from channel sources can contribute up to 90% of catchment yields (Caitcheon et al., 2012; Kronvang et al., 2013; Olley et al., 2013). The extent and rates of erosion are a function of multiple controlling factors, such as scale (Lawler, 1995), riparian vegetation (Thorne, 1990; Beeson and Doyle, 1995; Micheli and Kirchner, 2002; Simon and Collison, 2002; Hughes, 2016), adjacent land use (Trimble, 1994; Micheli et al., 2004; Zaimes et al., 2004; DeRose and Basher, 2011a), bank material composition (Hooke, 1980; Couper, 2003; Julian and Torres, 2006; Konsoer et al., 2016), topography and channel confinement (Janes et al., 2017a), frequency and magnitude of peak discharges, as well as extreme geomorphological events that affect hydrology and sediment supply processes (Gautier et al., 2007; Hsu and Hsu, 2009; DeRose and Basher, 2011a; Henshaw et al., 2013). Anthropogenic factors can also severely impact bank erosion rates. In New Zealand, deforestation following European settlement in the nineteenth century accelerated rates of erosion and sedimentation (Page et al., 2000; Kasai et al., 2005; Marden et al., 2014). In more recent times, stock trampling in mid and upper catchments has also caused an increase in bank erosion (Hughes, 2016).

Although stream bank erosion in New Zealand is acknowledged as a significant source of sediment in waterways (Basher et al., 2012; Hughes, 2016), a lack of data has constrained the parameterisation of bank erosion for modelling purposes. Previous studies on river bank instability in New Zealand include:

- Measurements of channel changes following large floods (Collier and Quinn, 2003; Fuller and Heerdegen, 2005; Fuller, 2007, 2008).
- Analysis of bank erosion processes and long-term contribution to sediment yield in the Waikohu (Rosser, 2008) and Pohangina rivers (Rosser et al., 2008). In both rivers it was estimated bank erosion contributed <10% of catchment sediment yield.
- Measurements of bank and cliff erosion in the Waipaoa River using LiDAR and historical aerial photography (DeRose and Basher,

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2011a) suggested bank erosion contributed <2% of catchment sediment yield.
- By contrast, Hughes and Hoyle (2014) used sediment fingerprinting to determine that bank erosion contributed ~95% of sediment load of the Kopurererua Stream.

Hughes (2016) reviewed nine available studies of bank erosion in New Zealand and concluded most used qualitative or semi-quantitative analysis methods and highlighted the need for quantitative methods for measuring bank erosion.

Measurements of bank erosion rates internationally have shown bank erosion to be both spatially and temporally highly variable and a challenge to incorporate into models because of the range of hydraulic and mass failure processes contributing to bank erosion and the varying influence of controlling factors (e.g., Hooke, 1980; Lawler et al., 1999; Janes et al., 2017b). The recently developed SedNetNZ sediment budget model (Dymond et al., 2016), based on the original Australian SedNet model (Wilkinson et al., 2004), includes bank erosion as a core component. Currently, bank erosion is estimated by a simple model relating the volumetric rate of erosion per unit channel length to the product of bank height and the bank retreat rate. DeRose and Basher (2011b), using a small data set of bank retreat rates, found that the bank retreat rate is positively correlated with the annual flood discharge, allowing the bank retreat rate to be predicted from the mean annual flood discharge (Dymond et al., 2016). Since the bank erosion model is largely based on measurements at sites with limited woody vegetation, the model assumes the absence of riparian woody vegetation cover. SedNetNZ also assumes 80% of the modelled bank erosion is redeposited (i.e., as accretion) within the channel, based on a single study of the Waipaoa River (DeRose and Basher, 2011a). The reliability of these predictions has not been thoroughly tested owing to a paucity of volumetric bank erosion measurements (Basher, 2013).

The lack of measured bank erosion rates in New Zealand is a limitation to the development of a model of bank erosion suitable for use in New Zealand. The aim of this study is (a) to collect data on erosion and accretion rates for five river reaches in Northland, New Zealand, (b) to compare measured rates of erosion with SedNetNZ bank erosion model results to further understanding of the model's current limitations, and (c) to begin improvement of the SedNetNZ bank erosion model by evaluating its current parameterisation and considering additional controlling factors to underpin future development. The assessment of river bank erosion is carried out for five reaches in the Kaipara Catchment in Northland using multi-temporal river planform mapping based on photogrammetric techniques. The study area contrasts with previous studies on bank erosion in New Zealand because it is located in an area with a subtropical climate where rivers carry fine-grained sediments and there are frequent high-intensity rainstorm events. The measurements provide a stronger basis for validating the current method used by SedNetNZ to model river bank erosion and accretion, and for further development of the model.

2. Kaipara catchment

Five river reaches were selected in the Kaipara catchment, Northland, for the analysis of river bank migration. A number of factors determined the selection of the study sites. Reasonably large river channels were required to enable the measurements using remote-sensing techniques. The sites also needed to be relatively free of woody riparian vegetation to enhance the accuracy of mapping the river banks. Finally, the availability of aerial photography determined the number of periods mapped.

Northland rivers tend to be short, with small catchments, are characterized by low-gradient meandering streams with narrow floodplains, and are typically partly confined (Richardson et al., 2013a). They drain catchments underlain by deeply weathered sedimentary and volcanic rocks that produce high levels of fine-grained suspended sediment. Current research by the National Institute of Water and Atmospheric Research (NIWA) shows that the turbidity peak during floods in the Kaipara Harbour catchment tributaries usually arrives ahead of the flow peak, which suggests fine, clay-rich sediment is coming predominantly from nearby channel sources via river bank erosion.[1] River systems in Northland have been poorly studied from a geomorphic perspective, apart from recent studies of alluvial sedimentation and Holocene floodplain development (Richardson et al., 2013a, 2013b, 2014). Floodplains are typically narrow and subject to frequent flooding and high rates of deposition (Richardson et al., 2014), which is in part because of the subtropical climate with frequent high-intensity storm events.

The selected sites are located in the upper reaches of the Wairoa catchment (sites 1–4) and the mid-reaches of the Hoteo catchment (site 5). The Wairoa is the largest catchment in Northland, draining a 3650 km^2 catchment into the northern end of the Kaipara Harbour, while the Hoteo is a 405 km^2 catchment draining to the southern Kaipara Harbour. Site 1 is in a sixth-order reach of the Wairua River, one of the largest tributaries of the Wairoa River (see Fig. 1). It is located immediately downstream of the Hikurangi swamp, where the river is extensively stopbanked and has been historically straightened. The study reach has not been modified, and the river meanders in a narrow floodplain flanked by gently rolling downland. Site 2 is in the middle reaches of the Mangakahia River, also one of the largest tributaries of the Wairoa River. It is a sixth-order reach, where the river meanders in a narrow floodplain flanked by hill country formed from volcanic rocks, crushed mudstone, and argillite. Richardson et al. (2013a) characterized the geomorphology and vertical accretion rate at sites upstream and downstream of the study reach. At the upstream site they found the floodplain had aggraded at >10 mm yr^{-1} at both sites, with 3 m of sediment having accumulated in the last 150–500 years in the upstream site and 7 m over the last c. 700 year at the downstream site. Site 3 is a third-order reach in the headwaters of the Tangowahine Stream, with a narrow, meandering, laterally confined stream flanked by hill country formed in volcanic rocks. Site 4 is downstream of site 3 in a fourth-order reach of the Tangowahine Stream. The river is highly sinuous, flowing in a relatively wide valley with floodplain and older terrace surfaces. Site 5 lies in the middle reaches of the Hoteo River, where a highly sinuous fifth-order channel is incised into a narrow floodplain, flanked by hill country formed from weathered volcaniclastic sediments. Jessen et al. (1997) identified streambank erosion as the largest contributor to stream sediment in the Hoteo River.

Table 1 provides an overview of the characteristics of the five river reaches. The reaches vary in length from 3 to 14 km; channel width is wide at sites 1, 2, and 5 (~16–18 m) compared to sites 3 and 4 (<5 m); slopes range from 0.0002 to 0.007, sinuosity from 1.28 to 2.62, and mean bank height from ~1 to 5 m. Site 3, a small, low-order tributary of the Tangowahine River, was included in the analysis to examine the behaviour of a small stream with steep slope to help improve understanding of erosional processes at different catchment scales.

The study sites can generally be characterized as meandering, sinuous streams and rivers in transfer zones and with varying degrees of entrenchment. Fig. 1 shows the location of the river reaches. Bank erosion is characterized (Fig. 2) by both hydraulic (bank undercutting, basal cleanout) and mass movement failures (rotational slips, slab and cantilever failures, soil fall). Because the sites were chosen to be largely free of riparian vegetation, the calculated bank erosion rates represent the maximum rates that could be expected.

3. Materials and methods

3.1. Assessment of historical channel changes

Channel change was measured using a combination of contemporary colour aerial photography and LiDAR, along with historic multi-

[1] https://www.niwa.co.nz/freshwater-and-estuaries/freshwater-and-estuaries-update/freshwater-update-55-october-2012/multiple-effects-of-fine-suspended.