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Predicting improved optical water quality in rivers resulting from soil conservation actions on land

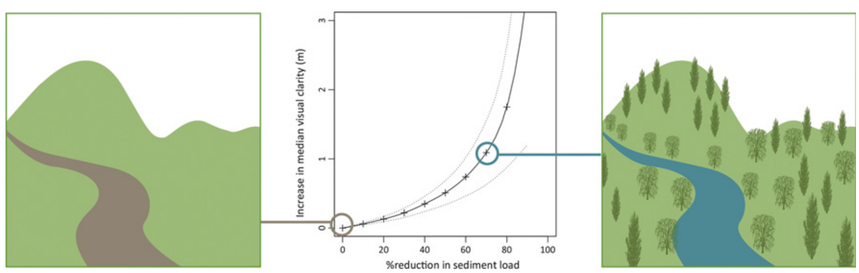
J.R. Dymond [a,*], R.J. Davies-Colley [b], A.O. Hughes [b], C.D. Matthaei [c]

[a] Landcare Research, Palmerston North, New Zealand
[b] National Institute of Water and Atmospheric Research (NIWA), Hamilton, New Zealand
[c] Department of Zoology, Otago University, Dunedin, New Zealand

HIGHLIGHTS

- Optical water quality in rivers can be related to sediment loads.
- Improved optical water quality may be predicted from soil conservation.
- In the Wairua River, visual clarity will increase 0.5 m after soil conservation.

GRAPHICAL ABSTRACT



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ABSTRACT

Deforestation in New Zealand has led to increased soil erosion and sediment loads in rivers. Increased suspended fine sediment in water reduces visual clarity for humans and aquatic animals and reduces penetration of photosynthetically available radiation to aquatic plants. To mitigate fine-sediment impacts in rivers, catchment-wide approaches to reducing soil erosion are required. Targeting soil conservation for reducing sediment loads in rivers is possible through existing models; however, relationships between sediment loads and sediment-related attributes of water that affect both ecology and human uses of water are poorly understood. We present methods for relating sediment loads to sediment concentration, visual clarity, and euphotic depth. The methods require upwards of twenty concurrent samples of sediment concentration, visual clarity, and euphotic depth at a river site where discharge is measured continuously. The sediment-related attributes are related to sediment concentration through regressions. When sediment loads are reduced by soil conservation action, percentiles of sediment concentration are necessarily reduced, and the corresponding percentiles of visual clarity and euphotic depth are increased. The approach is demonstrated on the Wairua River in the Northland region of New Zealand. For this river we show that visual clarity would increase relatively by approximately 1.4 times the relative reduction of sediment load. Median visual clarity would increase from 0.75 m to 1.25 m (making the river more often suitable for swimming) after a sediment load reduction of 50% associated with widespread soil conservation on pastoral land. Likewise euphotic depth would increase relatively by approximately 0.7 times the relative reduction of sediment load, and the median euphotic depth would increase from 1.5 m to 2.0 m with a 50% sediment load reduction.

1. Introduction

There is widespread recognition of the extent and significance of changes in land use and land cover on river ecosystems worldwide (Allan, 2004; Jones et al., 2012; Kemp et al., 2011; Wood and Armitage,

* Corresponding author.
E-mail address: dymondj@landcareresearch.co.nz (J.R. Dymond).

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1997; Meade, 1988). Since European settlement in New Zealand (c. 1840), large-scale catchment disturbance (e.g., forest clearance, establishment of agricultural land uses and stream channel modification) has led to increased erosion rates and delivery of fine sediment to rivers, lakes and estuaries (Glade, 2003; Page and Trustrum, 1997). Although the delivery of sediment to waters is likely to have reduced since the initial European settlement period due to reduction in agricultural land (Dymond et al., 2010), the sediment loads in some New Zealand rivers remain very high, even by global comparison (Jansson, 1988).

Increased sediment loads can adversely affect downstream aquatic ecosystems. River beds and benthic habitat may be smothered (Conroy et al., 2016; Thrush et al., 2004; Wood and Armitage, 1997). Increased suspended sediment can damage the gills of fish, which can limit fish growth and make them more susceptible to disease (Waters, 1995). Increased suspended sediment can also reduce visual clarity (i.e. the distance objects can be seen through water) and light penetration into water (Davies-Colley and Smith, 2001; Newcombe and MacDonald, 1991). Degraded visual clarity in rivers, lakes, and estuaries can reduce feeding opportunities for birds and fish (Davies-Colley et al., 2014; Julian et al., 2013), can cause certain migratory fish species to avoid turbid rivers (Boubée et al., 1997; Rowe and Dean, 1998), and can increase drift rates of benthic invertebrates (Bond and Downes, 2003; Larsen and Ormerod, 2010; Shaw and Richardson, 2001). Reduced light penetration can result in the decline of benthic plants (Davies-Colley and Smith, 2001; Julian et al., 2013), and can negatively affect the growth of periphyton and macrophytes on the river bed (Davies-Colley et al., 2014; Julian et al., 2013).

To reduce the amount of sediment being delivered to streams and their downstream receiving environments, catchment-wide approaches for reducing soil erosion are required. In recent decades, catchment rehabilitation measures, such as land use change, riparian management, and erosion control planting, have been used to improve the water quality and manage suspended sediment contributions to downstream environments (Alexander and Allan, 2007; Shah et al., 2007; Shields, 2009). These measures are costly to implement across whole catchments and so need to be targeted to achieve cost-effectiveness.

Spatially-distributed models such as SedNetNZ have been developed for relating land use change and soil conservation actions to sediment loads in rivers (Dymond et al., 2016; Kinsey-Henderson et al., 2005; Wilkinson et al., 2009). Such models enable specific targeting of soil conservation for reducing sediment loads. A range of sediment-source-tracing techniques are also available to identify important catchment sources, both in terms of key erosion processes (He and Owens, 1995; Olley et al., 2012) and spatial provenance (Collins et al., 1998; Vale et al., 2016), and these techniques are becoming more widely applied as catchment management tools (Mukundan et al., 2012).

However, the relationships between sediment loads and important sediment-related attributes of water in rivers, such as suspended sediment concentration, deposited sediment, visual clarity, and light penetration, are not well understood. Some researchers (Asselman, 2000; Lloyd et al., 2016; Thomas, 1988; Warrick, 2015; Williams, 1989) have attempted to explain the behaviour of sediment rating curves (i.e. the relationship of suspended sediment concentration to discharge), including hysteresis, but direct relationships between sediment loads and optical water quality are not well described. Other authors have interrelated visual clarity, suspended sediment concentration, and turbidity (West and Scott, 2016; Davies-Colley and Nagels, 2008), but also have not considered sediment loads. Without a knowledge of how sediment loads relate directly to optical water quality, it is difficult to target soil conservation actions for water-quality improvement.

In this paper, we present methods for relating sediment loads to sediment-related attributes of importance to freshwater values (Environment Foundation, 2015): suspended sediment concentration, visual clarity, and euphotic depth. These attributes relate strongly to water discharge (e.g., Smith et al., 1997), which varies in time, so we characterise them by percentiles of statistical distributions of occurrence. The attributes are linked to suspended sediment concentration through regressions. When sediment loads are reduced by soil conservation action, the percentiles of sediment concentration are necessarily reduced, and the corresponding percentiles of visual clarity and euphotic depth are increased. The methods are demonstrated on the Wairua River in the Northland region, New Zealand, where soil conservation action is being undertaken by the Northland Regional Council to improve water quality in the river and of the Kaipara Harbour downstream.

2. Methods

2.1. Study area

The Wairua River drains a catchment of 75,000 ha in the upper North Island of New Zealand (Fig. 1). Headwaters drain hill country comprising either greywacke/argillite, crushed argillite, which is susceptible to gully erosion, or crushed mudstone, which is susceptible to earthflow erosion. There are also pockets of volcanic rocks that are comparatively resistant to erosion. The middle reaches flow through lowland areas and drained peat swamps. Fishing and other contact recreation (swimming, kayaking) is common. Mean annual rainfall in the Wairua catchment is relatively high at 1700 mm, with some months experiencing over 500 mm of rainfall, and the mean discharge at Purua is 20 $m^3\ s^{-1}$. Sediment loads in New Zealand are driven primarily by rainfall and geology (Hicks et al., 2004), so monthly sediment loads in the Wairua are higher in the winter and early spring (June–September) when water discharges are greater (Duncan and Woods, 2004). Flooding of the Wairua floodplain is common (~3 yrs) due to high storm rainfalls combined with a low channel gradient.

Land use is predominantly pastoral farming, with sheep and beef farms being common on the hill country, and with dairy farms being common on the lowlands, floodplains, and rolling hill country. Where pastoral farming occurs on crushed-rock geology, high storm rainfalls cause high rates of soil erosion and consequently high sediment loads in streams. The mean annual sediment load of the Wairua River is 130,000 t yr^{-1} (modelled from SedNetNZ, Dymond et al., 2016), much of which makes its way to the largest estuary in New Zealand, the Kaipara Harbour, which has important habitats for fish and benthic plants and invertebrates.

Measurements of optical water quality (i.e. suspended particulate matter, visual clarity) were obtained from water samples collected from the Wairua River at Purua flow monitoring site operated by the Northland Regional Council, a local government agency responsible for catchment soil and water management. The Purua monitoring site is located in the middle to lower reaches of the Wairua River catchment and has an upstream catchment area of 54,000 ha.

2.2. Inference of suspended sediment attributes

Our approach is to infer statistical distributions of sediment-related attributes from a statistical distribution of discharge, which is calculated from the continuous measurements of discharge. The approach depends critically on establishing a relationship between sediment concentration and discharge. This relationship between sediment concentration, s, and discharge, q, is derived from measurement pairs obtained at times of sediment concentration measurement, particularly during hydrological events. This relationship is referred to as the sediment rating curve (Asselman, 2000; Warrick, 2015). This relationship is typically linear after a log transformation. Denoting $\log(q)$ as Q and $\log(s)$ as S, where log is the natural log, then the sediment rating curve may be expressed as:

$$S = a\,Q + b \qquad (1)$$

where a and b are site-specific constants.