Light attenuation – a more effective basis for the management of fine suspended sediment than mass concentration?

Robert J. Davies-Colley, Deborah J. Ballantine, Sandy H. Elliott, Andrew Swales, Andrew O. Hughes and Mark P. Gall

ABSTRACT

Fine sediment continues to be a major diffuse pollution concern with its multiple effects on aquatic ecosystems. Mass concentrations (and loads) of fine sediment are usually measured and modelled, apparently with the assumption that environmental effects of sediment are predictable from mass concentrations. However, some severe impacts of fine sediment may not correlate well with mass concentration, notably those related to light attenuation by suspended particles. Light attenuation per unit mass concentration of suspended particulate matter in waters varies widely with particle size, shape and composition. Data for suspended sediment concentration, turbidity and visual clarity (which is inversely proportional to light beam attenuation) from 77 diverse New Zealand rivers provide valuable insights into the mutual relationships of these quantities. Our analysis of these relationships, both across multiple rivers and within individual rivers, supports the proposition that light attenuation by fine sediment is a more generally meaningful basis for environmental management than sediment mass. Furthermore, optical measurements are considerably more practical, being much cheaper (by about four-fold) to measure than mass concentrations, and amenable to continuous measurement. Mass concentration can be estimated with sufficient precision for many purposes from optical surrogates locally calibrated for particular rivers.

Key words | aquatic optics, diffuse pollution, light attenuation, light penetration, suspended sediment

Robert J. Davies-Colley (corresponding author)
Sandy H. Elliott
Andrew Swales
Andrew O. Hughes
National Institute of Water and Atmospheric Research Ltd (NIWA),
Hamilton,
New Zealand
E-mail: *r.davies-colley@niwa.co.nz*

Deborah J. Ballantine
Department of Environmental Science,
Xi'an Jiaotong Liverpool University,
Dushu Lake Higher Education Town,
Suzhou Industrial Park,
Jiangsu,
China

Mark P. Gall
National Institute of Water and Atmospheric Research Ltd (NIWA),
Wellington,
New Zealand

INTRODUCTION

Fine sediment remains a particularly important diffuse pollutant. Sediment is sometimes referred to as the 'universal' pollutant because of its mobilisation wherever soils or vegetation are disturbed (e.g., Campbell *et al.* 2004). Fine sediment has a wide range of effects once deposited, including shoaling or infilling of receiving water bodies such as lakes, reservoirs and estuaries, smothering of benthic organisms notably in estuaries (Thrush *et al.* 2004), and inhibition of exchange of water and fine particles between bed sediment pores and overlying water in rivers (Packman *et al.* 2000). The depositional impacts of fine sediment may be expected to correlate, broadly, with its deposited mass, which may be why most environmental scientists and managers seem to default to measuring mass concentrations and loads of sediment in rivers. However, while sediment mass concentrations and loads are often relevant, there are numerous impacts of fine sediment while still suspended that may be poorly predicted by its mass concentration (Davies-Colley & Smith 2001).

An obvious feature of fine suspended sediment is the cloudiness (turbidity) induced in water by (multiple) light scattering. Related to this is the reduction in visual range (visual clarity) in waters (Davies-Colley *et al.* 2003). Reduced visual range can severely constrain the 'visual habitat' of fish (Newcombe 2003) and aquatic birds. Human recreationalists are also severely impacted by reduced visual clarity in 'muddy' sediment-laden water, which is both aesthetically unappealing and may mask

doi: 10.2166/wst.2014.096

submerged hazards such as trash and snags that could be avoided in clearer water (Smith *et al.* 1995; Davies-Colley *et al.* 2003). As well as reducing visual range, suspended particulate matter (SPM) also reduces light penetration into waters. Kirk (1985) recognised that the main mechanism of reduced light penetration into muddy water is the tortuous (extended) path taken by light owing to multiple scattering, which increases the proportion of photons extinguished by absorption over a given depth interval. Reduced light exposure reduces photosynthesis and the vigour of benthic plants, such as macrophytes in lakes and sea grasses in estuaries (Davies-Colley *et al.* 2003) – sometimes causing or contributing to catastrophic collapses of these keystone plant communities (Burkholder *et al.* 2007; Schallenberg & Sorrell 2009).

In this paper we use data from New Zealand's National Rivers Water Quality Network (NRWQN) to examine the mutual relationships of visual clarity (inversely related to light attenuation), turbidity and SPM mass concentration. This analysis supports the proposition that light attenuation is a better basis than sediment mass concentration for management, including enumeration of environmental limits and standards. Furthermore, optical measurements are generally more practical than sediment mass concentration for environmental monitoring, being appreciably cheaper, and amenable to continuous measurement.

THEORETICAL BACKGROUND

Optical aspects of waters have been discussed by Davies-Colley *et al.* (2003), and a more fundamental discussion is given by Kirk (2011). Here we give a brief over-view, emphasizing the optics of fine SPM which typically dominates light attenuation (absorption plus scattering of light) in natural waters and thus controls water clarity (Davies-Colley & Smith 2001).

Light beam attenuation is quantified by a coefficient (symbol c, unit m^{-1}) defined as the proportional loss of photons from a light beam by absorption plus scattering, per unit length of light path. Light absorption and light scattering are separately quantified by an absorption coefficient (a) and scattering coefficient (b) respectively, such that $c = a + b$.

Fine mineral sediments are strongly light attenuating, mainly by light scattering, which explains why sediment-laden water typically has low visual clarity. Mineral sediments absorb light relatively weakly, with the notable exception of ferric iron minerals (Bowers & Binding 2006). However, organic coatings, particularly of aquatic humic matter, can render mineral sediments appreciably light absorbing (Davies-Colley *et al.* 2003).

Organic particles are strongly light absorbing as well as light scattering. Light absorption by organic matter (and organic coatings on minerals) is usually stronger at the blue (short-wave) end of the visible spectrum, resulting in yellow–red hues in waters. Rivers in flood typically appear brown-coloured as well as very turbid because of entrainment of organic particles and organic-coated mineral particles (Smith *et al.* 1997). Similarly, shallow lakes and estuaries subject to turbidity events during windstorms, or when receiving river flood plumes, also typically appear very 'muddy' and brown in colour. Turbidity maxima occur where rivers inflow to certain estuaries, owing to the entrapment of organic-rich SPM for extended times by estuarine circulation (Mitchell 2013).

Light attenuation by both mineral and organic particles is a strong function of particle size (van de Hulst 1957). Light beam attenuation per unit mass of near-spherical mineral particles (attenuation cross-section, symbol C, unit $m^{-1}/(g\,m^{-3}) = m^2\,g^{-1}$) peaks at a particle diameter of about 1.2 μm diameter (for quartz). As particle diameter increases above this size of maximally efficient light attenuation, C declines as an inverse function of particle diameter (D, m) (Davies-Colley & Smith 2001). This is a consequence of light beam attenuation being dependent on the projected surface area of particles (which varies as the square of particle diameter), while particle mass is proportional to particle volume (which varies as the cube of particle diameter): $C–D^2/D^3 = D^{-1}$. At smaller particle diameters than the maximally efficient size, attenuation cross-section falls off rapidly because the particles become increasingly small compared to the wavelength of light (0.4–0.7 μm in a vacuum). (Wave phenomena characteristically interact only weakly with objects that are small compared with their wavelength.)

The attenuation cross-section curve for different minerals shifts subtly due to small changes in both refractive index and density, although the overall pattern remains very similar to that for quartz. But organic particles contrast very strongly with mineral particles in both density and refractive index, resulting in a major shift in the position of the attenuation cross-section curve, with the peak occurring at around 5 μm for organic particles (Davies-Colley & Smith 2001). Eutrophic waters characteristically have low visual clarity because of dense concentrations of organic particles (phytoplankton cells and detritus) which, being ~5 μm in diameter, are strongly light-attenuating.

Light attenuation also depends strongly on particle shape. This is particularly relevant to clay minerals (plate-shaped particles of layer silicates), which scatter light appreciably more intensely, and with a different angular dependence, compared with equi-dimensional particles (Pak *et al.* 1971; Gibbs 1978). Clay minerals also contribute strongly to light attenuation in natural waters because they remain suspended for extended times owing to very low settling velocities (Davies-Colley *et al.* 2003).

Water clarity is very strongly affected by SPM and has two main aspects: (1) visual clarity – that is, sighting range as it affects human recreational users and visual habitat for fish and aquatic birds; and (2) light penetration as it affects, particularly, photosynthesis of both phytoplankton and benthic aquatic plants. These two distinct aspects of water clarity depend differently on the fundamental absorption and scattering properties of water such that one cannot be estimated from the other without further information. That is to say, knowing visual clarity does not permit one to infer light penetration or vice versa.

Visual clarity strongly influences several water values, notably recreation and aquatic habitat, and is inversely related to light beam attenuation (Davies-Colley *et al.* 2003). Visual clarity is best indexed by the horizontal sighting range of a black target (y_{BD}) because this quantity is an 'exact' inverse function of only one parameter – the light beam attenuation coefficient (at the wavelength of peak sensitivity of the human eye at around 550 nm) (Davies-Colley 1988):

$$y_{BD} = 4.8/c(550) \tag{1}$$

The value of the coefficient in Equation (1) accords with theory based on contrast thresholds for the human eye, and has been confirmed to high precision with modern optical instrumentation (Zanevald & Pegau 2003). Visual range in waters for humans turns out to be very little different from that for fish and aquatic birds despite the adaptation of animals to their visual environment. Therefore y_{BD} is an excellent index for protecting the visual ecology of waters, as well as their suitability for human recreational use.

Light penetration into waters is indexed by a different attenuation coefficient, the irradiance attenuation coefficient (K_d) – defined as the proportional decline of (downwelling) irradiance over a depth interval in a water body (Kirk 2011). Irradiance attenuation is not simply (numerically) related to beam attenuation, consistent with visual clarity being distinct from light penetration. K_d, in contrast to c and y_{BD}, depends on the characteristics of the incident light field from the Sun as well as (in a rather more complicated way) on the absorption and scattering of light (Kirk 2011), and on SPM content, and is not considered further here.

METHODS

The NRWQN (Davies-Colley *et al.* 2011) is a valuable test bed for studying the optics of SPM in rivers. The NRWQN, operated by the National Institute for Water and Atmospheric Research Ltd (NIWA), comprises routine (monthly) measurements of 14 'basic' water quality variables at 77 river sites on 35 river systems draining half of New Zealand's land area (Figure 1). The catchments of NRWQN rivers range widely in geology, climate, soils and vegetation cover.

Three optical variables are measured routinely in the NRWQN: visual clarity, nephelometric turbidity, and coloured dissolved organic matter (CDOM). Sediment mass concentration (total suspended solids; TSS) has *not* been measured routinely in the NRWQN for all 25 years since its inception in 1989, mainly for reasons of cost and because simple optical correlates (visual clarity and turbidity) are available (Davies-Colley *et al.* 2011). However, recently sediment assays were temporarily 'piggy-backed' on the routine monthly NRWQN monitoring so as to pair sediment mass concentrations with water quality including optical measurements. Measurements of TSS made for 12 months in 2011 are used here.

Visual clarity is measured in the NRWQN during routine sampling visits by the *in-situ* black disc (field) method introduced by Davies-Colley (1988). Briefly, the observer wades into the river and records the extinction distance of a black disc viewed horizontally under the water surface using a simple periscope fitted with a 45° mirror (Davies-Colley *et al.* 2003). Water samples collected within a few minutes of visual clarity observations are sent to the NIWA laboratory in Hamilton for measurement of water quality, including turbidity, using a Hach 2100AN nephelometer (Davies-Colley *et al.* 2011). CDOM is indexed by the absorption coefficients of membrane-filtered (0.45 μm) water sub-samples (from the same sample used for turbidity) measured on a spectrophotometer (Shimadzu UV-1800, with 40 mm matched silica cuvettes) at both 340 nm (in the UV range) and 440 nm (blue light), using near-infra-red absorbance to correct for residual light scattering (Davies-Colley *et al.* 2003).

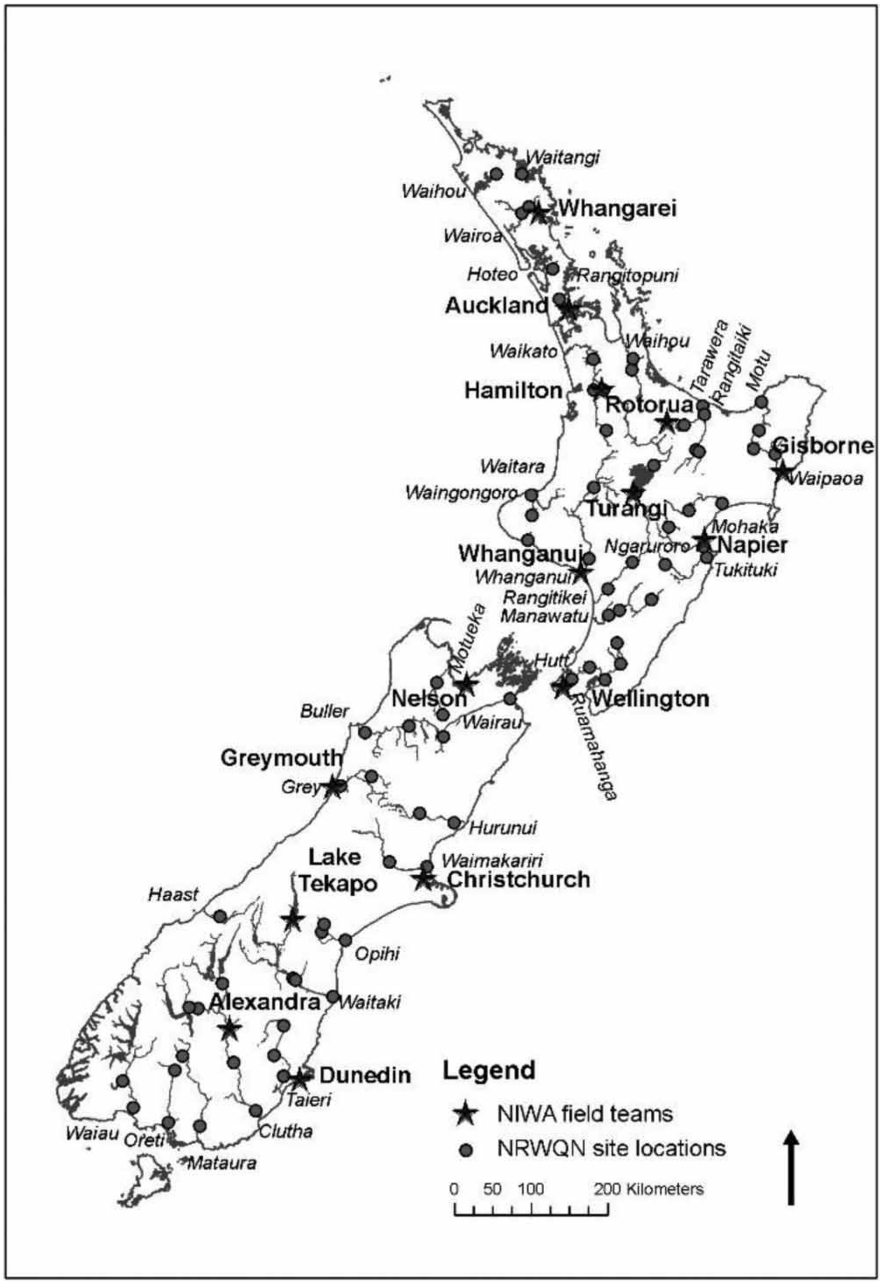

Figure 1 | Locations of monitoring sites in New Zealand's National Rivers Water Quality Network (NRWQN). The 77 monitoring sites (solid circles) are shown in relation to 35 river systems labelled near their mouths where they enter the sea. NIWA field stations that conduct the monitoring are shown as stars marking the cities or towns where they are located. (Figure from Davies-Colley *et al*. (2011) used with permission.)

TSS was measured (by standard gravimetric methods; APHA (2005): Method 2540D) on separate water samples collected within a few minutes (i.e., from the same water mass) as an add-on to routine NRWQN monitoring throughout 2011. To cope with the low particulate concentrations in clear rivers at base flow, oceanographic protocols were used with large-volume subsamples (up to 5 l) being filtered through 25 mm diameter GF/F filters.

RESULTS

Mutual scatter-plots of TSS, visual clarity and turbidity measured at 77 river sites on the 12 monthly visits in 2011 are shown in Figure 2. As expected, these variables are all inter-correlated, but there is considerable data scatter, particularly in the plots of the optical variables versus TSS (Pearson's $r = -0.92$ for visual clarity versus TSS; $r = 0.89$

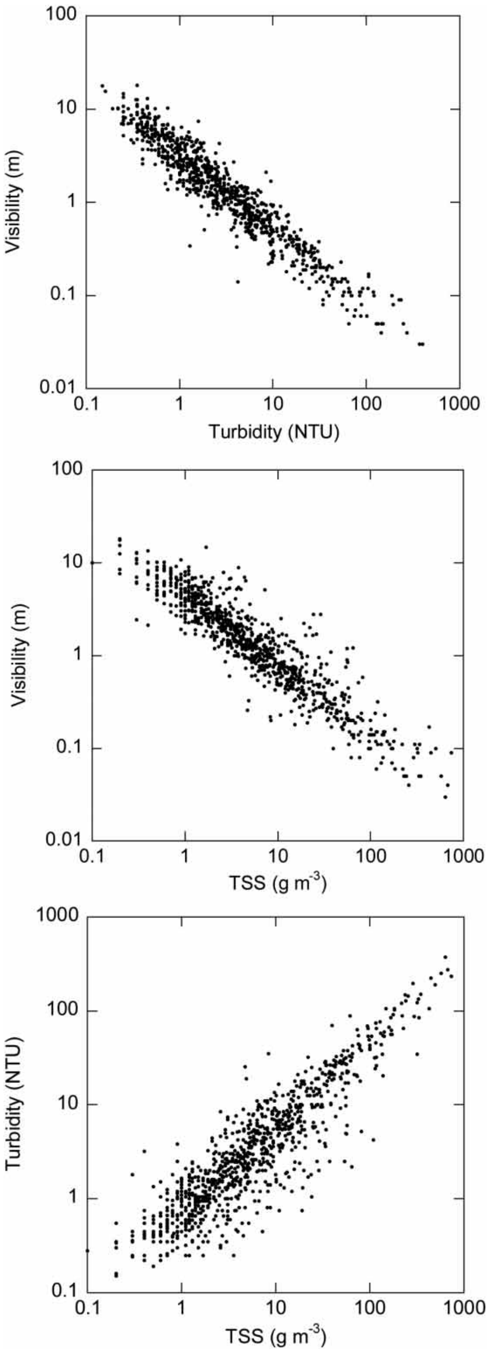

Figure 2 | Mutual relationships of visual clarity, turbidity and TSS at 77 river sites in New Zealand's NRWQN, each sampled monthly for 12 months in 2011.

for turbidity versus TSS). Visual clarity and turbidity are more closely (inversely) related ($r = -0.95$), although the wide range of clarity (nearly three orders of magnitude) belies the closeness of the relationship (standard error of the regression is about 35%). The maximum observed visual clarity was 18.1 m (0.35 NTU turbidity) in the Motueka River (upstream site at the gorge; northern South Island near Nelson; Figure 1), while the lowest clarity observed was 0.03 m (400 NTU) in the Waipaoa River (eastern North Island near Gisborne; Figure 1).

Figure 3(a) shows the beam attenuation coefficient, calculated from visibility using Equation (1), plotted against TSS. The data scatter implies a fairly wide range in the light attenuation cross-section, that is, the ratio of *c* to TSS. Because CDOM and water itself also attenuate light, the particulate beam attenuation, $c_p(550)$, was calculated by subtracting contributions of these constituents from the total light beam attenuation

$$c_p(550) = c(550) - c_w(550) - c_g(550)$$

where the beam attenuation coefficient of pure water, $c_w(550) = 0.0579/\text{m}$ (Pope & Fry 1997), and beam

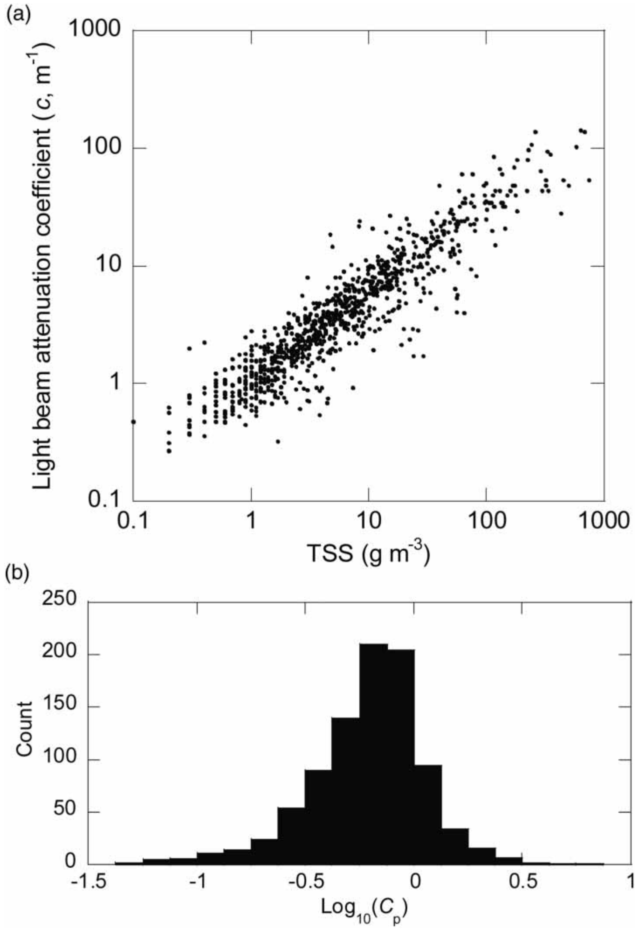

Figure 3 | Light beam attenuation in 77 rivers of the NRWQN, each sampled monthly for 12 months in 2011. (a) Light beam attenuation calculated by Equation (1) and plotted versus TSS. (b) Distribution of the beam attenuation cross-section for particulate matter, C_p, calculated as described in the text.

attenuation coefficient of CDOM is equal to its absorption coefficient, symbol a_g (because its scattering contribution is negligible), $c_g(550) = a_g(550) = 0.168{*}a_g(440)$. (The conversion factor of 0.168 was calculated from the filtrate absorption measurements at 340 and 440 nm, assuming, reasonably, that the exponential shape of the CDOM absorption spectrum extends into the 440–550 nm spectral range.) A histogram showing the (rather wide) distribution of the particulate beam attenuation cross-section calculated as ($c_p(550)$/TSS) (median = 0.66 m^2/g, interquartile range = 0.43 m^2/g) is given in Figure 3(b).

In individual rivers there is usually much less data scatter in the mutual relationships of visibility, turbidity and TSS because the optical diversity of light-attenuating material, particularly SPM, is much reduced. For instance, Figure 4 shows a close (predictive) relationship of TSS versus y_{BD} at three different river sites in the NRWQN. The linear regression lines in Figure 4 are appreciably steeper than 1:1 in log–log space (i.e., negative power law exponents are appreciably greater than 1.0, averaging 1.3), which we consider may reflect the systematic reduction in attenuation cross-section with increasing flow in rivers as coarser (less efficiently light attenuating) material is thrown into suspension.

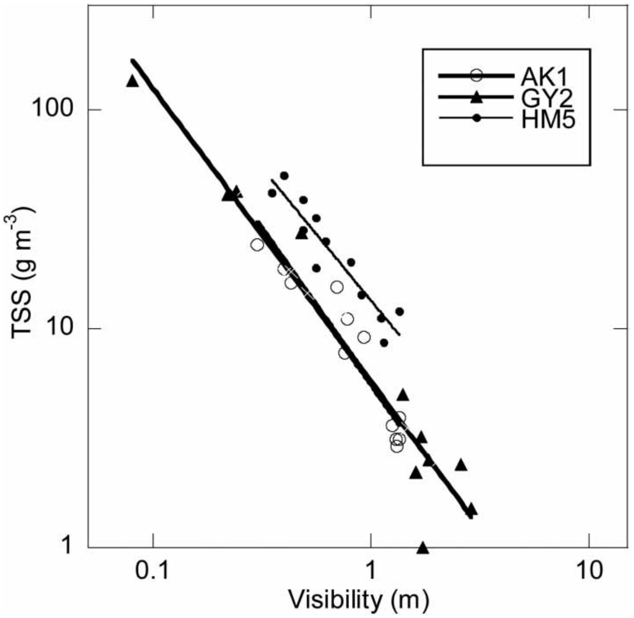

Figure 4 | TSS plotted versus visibility at three sites in the NRWQN. Suspended particulates at Site AK1 (Hoteo R; northern NI) and Site GY2 (Grey R; western SI) are fairly strongly light attenuating, and corresponding power-law curve fits are very similar and contrast with that for Site HM5 (Waihou R; northern NI) in which suspended particulates are much less strongly light attenuating. (Site and river locations are indicated in Figure 1.)

DISCUSSION

Visual clarity and turbidity observations in NRWQN rivers are distributed in an approximately log-symmetric pattern over nearly three orders of magnitude range (Figure 2). Numerous reports are given in the literature of the relationship between TSS and turbidity, particularly in the context of the use of turbidity as a surrogate for TSS. However, correlations of TSS and visual clarity (Figure 2) or, equivalently, light attenuation (Figure 3) are considerably less common, which highlights a novel contribution of our paper.

Despite the high correlations (for a very wide clarity range), there is appreciable data scatter in Figure 2. The (separate) samples for TSS and turbidity, and visual clarity observations, were taken within a few minutes of each other and are expected to be from virtually the same water mass within the river. Therefore we attribute the data scatter mainly to the optical diversity of SPM in river waters – specifically, the variation in light attenuation per unit mass, depending on grain size distribution, shape and composition (Davies-Colley & Smith 2001). Clearly, TSS is not satisfactory as a general indicator of optical effects, as well as (downstream) depositional effects, of fine suspended matter. Where there are concerns regarding optical effects of fine sediment, such as on visual clarity, then optical variables should be measured. Furthermore, guidelines and limits are needed for management of optical effects as well as sediment mass effects.

The (approximately inverse) relationship between visual clarity and turbidity supports the concept that turbidity provides a rough surrogate for visual clarity and *vice versa*. Davies-Colley & Smith (2001) have argued that measurement of visual clarity or, equivalently, beam attenuation, is theoretically preferable to turbidity. But, as we discuss below, there are practicalities favouring turbidity for continuous monitoring, ideally with (local) calibration to visibility or light beam attenuation in particular waters.

In individual rivers there is usually a close (albeit appreciably non-linear) relationship of sediment mass concentration (TSS) with the two optical variables, visual clarity and turbidity. Indeed, typically the (power law) relationships are sufficiently close to be predictive (Figure 4). Therefore, at particular sites TSS can be estimated with sufficient precision for many purposes from visual clarity or turbidity, once the relationship has been established. This is important because the optical variables are much cheaper (by about four-fold) to measure than TSS (Davies-Colley & Smith 2001) so it should be appreciably more cost-effective to estimate TSS from optical surrogates than directly. Furthermore, optical variables can be measured continuously if desired (Davies-Colley & Smith 2001). Therefore, measurement of TSS seems redundant in routine work, including state-of-environment monitoring. Indeed it was for precisely such reasons that TSS was not included among routinely measured variables in the NRWQN (Davies-Colley *et al.* 2011). This finding has important ramifications for routine on-going monitoring, because there are major cost savings to be achieved by monitoring optical variables in preference to TSS.

TSS is mainly of concern in rivers from the perspective of mass loads on (and sedimentation in) downstream waters. Such loads are dominated by high flow events which are seldom intercepted by routine monitoring, for example, at monthly intervals. Storm flows are probably best characterised for their contribution to loads by special event-triggered automatic sampling for TSS assay supported by continuous monitoring of optical surrogates. Measuring TSS in routine monitoring is seldom efficient for load estimation because regular monitoring visits usually miss the high flow events that transport the great majority of the mass load, albeit less of the optical load, in rivers.

The most broadly appropriate optical variable for monitoring (and for expressing environmental limits) is usually the beam attenuation coefficient, c, not least because this inherent optical property can be converted easily and accurately to visual clarity (or, less precisely, to TSS). Beam attenuation can be measured directly (including continuously) by a beam transmissometer (Davies-Colley & Smith 2001; Zanevald & Pegau 2003). However, continuous measurement of turbidity by nephelometry is often more practical, because modern turbidity sensors are appreciably cheaper than transmissometers and can cope with a wider dynamic range (up to 10,000-fold) as can occur in rivers in widely varying flow condition. Turbidity records can be locally calibrated to beam attenuation (hence visibility), light penetration, or suspended sediment mass, as desired.

We are continuing to explore the relationship between optical properties of SPM and its mass concentration, with the goal of developing limits (environmental targets) for managing optical effects of fine sediment in rivers and downstream receiving waters. More specifically, we are undertaking further testing of the proposition that 'light attenuation provides a better basis for managing effects of fine sediment than its mass concentration'. A far-reaching ramification that follows from this proposition is that light attenuation should be used as the basis of management (including enumeration of guidelines and limits) rather than sediment mass concentration. Our main research testbed is the Kaipara Harbour and its catchment in northern North Island, New Zealand, where muddy rivers such as the Hoteo (NRWQN site indicated in Figure 1) discharge fine sediment and associated pollutants from diffuse sources on clay-rich soils, particularly under livestock pasture.

CONCLUSIONS

Monitoring data from NZ's NRWQN confirms that visual clarity, turbidity, and TSS are inter-correlated. However, there is considerable data scatter in the relationships, particularly of TSS versus the two optical variables. This data scatter, reflecting the optical diversity of SPM in diverse rivers, suggests that measuring sediment mass concentration is not very useful when the optical impacts of fine sediment are of concern. Optical variables need to be measured to protect water values dependent on key optical attributes such as visual clarity and light penetration.

In individual rivers, in which the optical character of suspended particles is fairly consistent and trends systematically with flow condition, the data scatter is much reduced such that TSS, if needed, can be estimated fairly reliably from light attenuation (visual clarity) or turbidity. Furthermore, because light attenuation and turbidity are much cheaper to measure than TSS, and can be monitored continuously if desired, it follows that monitoring and managing the optical variables is usually preferable for managing sediment mass effects (i.e., depositional effects) as well as optical impacts. Visual clarity, a key attribute of waters that strongly affects water values, can be estimated from measurements of light attenuation (or turbidity – with suitable calibration). Light penetration can also be estimated from optical surrogates with suitable calibration (e.g., Davies-Colley & Nagels 2008). TSS is most relevant in the context of sediment loads on downstream waters, which is dominated by storm flows. Therefore, flood 'chasing' is preferred to quantify the event-related fluxes that dominate overall sediment mass loads.

Emphasising light attenuation of fine sediment instead of its mass concentration is expected to advance the management of fine sediment impacts in waters. In particular, considering light attenuation by SPM should engender more relevant and effective environmental limit setting and encourage monitoring by continuous instrumental (optical) methods.

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First received 24 October 2013; accepted in revised form 11 February 2014. Available online 24 February 2014